QUANTUM ONTOLOGY

A Guide to the Metaphysics of Quantum Mechanics

PETER J. LEWIS

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To my parents, Pat and John Lewis

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PREFACE

This book is intended as a guide to quantum mechanics for the philosophical consumer. Quantum mechanics is a rich source of metaphysical insight—about the nature of individuals and of properties, about supervenience and space and causation, about determinacy and determinism. This is not to say that physics holds all the answers. Quantum mechanics is notoriously slippery territory: Multiple interpretations of its basic mathematical formulation are possible, with very different implications about the nature of the world. In general, any metaphysical claim of the form "Quantum mechanics entails X" is likely to be false. But despite the lack of definitive answers, quantum mechanics is very important to metaphysics, because of the way it broadens the range of metaphysical possibilities, because of the way it challenges our classically tutored intuitions, and because of the way it reshapes metaphysical debates in surprising, empirically informed ways.

There are many things that this book is not. It is not a user's guide to quantum mechanics: Physicists need no help from philosophers like me, and the business of using quantum mechanics goes on largely independently of foundational metaphysical concerns. It is not a physics textbook: While I explain the bare bones of the theory and a couple of applications, the exposition of the physics is limited to what I need to get the metaphysical points across. There are plenty of good physics textbooks out there, some of which I mention along the way. It is not a polemic, or an argument in favor of one interpretation of quantum mechanics over the others, or an attempt to construct a new interpretation: There are plenty of good examples of these genres out there, too, many of which I mention.

While I have opinions about the various interpretations on offer, I try to remain even-handed for present purposes, and just lay out the options.

So if you are a philosopher (professional, student, or amateur) who wants to find out how quantum mechanics might be relevant to your metaphysical views, this book is for you. It is intended to be self-contained: I explain the physics, as well as the philosophy, along the way. I don't shy away from equations when necessary: Quantum mechanics is written in the language of mathematics, and to understand the theory you have to see for yourself what it says. But you don't need much math to understand the basics of quantum mechanics, and all the equations are fully explained, often with diagrams. Similarly, you don't need prior acquaintance with any particular metaphysical tradition—not least because the quantum-inspired debates are often quite distinct from the traditional ones.

I would like to acknowledge the generous support of the University of Miami in helping me to free up time to write this book: a Provost's Research Award in the summer of 2012, a Humanities Center Fellowship for 2012–2013, and a research leave under the College of Arts and Sciences Associate Professor Pilot Program during spring 2014.

I would also like to thank the many people who have helped me with this project. The 2012–2013 fellows of the University of Miami Humanities Center provided me with invaluable feedback about my attempts to make quantum mechanics accessible to the nonspecialist. Jenann Ismael gave insightful counsel about how to organize the material, as well as much-needed encouragement. The students in my *Philosophy and Quantum Mechanics* seminar in spring 2015 (David DiDomenico, Lou Enos, Iago Bozza Francisco, Wei Huang, Nihel Jhou, and Rina Tzinman) picked lots of holes in a draft of the book, as well as finding an embarrassing number of typos. Craig Callender, Roman Frigg, Jonathan Schaffer, and Eric Schwitzgebel gave me useful feedback on drafts of various chapters. Finally, my special thanks to Jeff Barrett, for teaching me how to think about and write about quantum mechanics, and for insightful comments on the whole manuscript.

This book would not have been possible without the encouragement, support, and philosophical acumen of my wife, Amie Thomasson. It would definitely have been possible without our daughters, Natalie and May, but it wouldn't have been nearly so much fun.

INTRODUCTION

Why is this book about quantum mechanics? That is, why, of all the scientific theories you might study, should metaphysicians be particularly interested in quantum mechanics, rather than string theory or molecular biology? This might seem to go without saying, for at least two reasons. First, it is tempting to think that quantum mechanics is interesting to metaphysicians because it is fundamental: It describes the basic structures of the physical world. Second, it is tempting to think that quantum mechanics is interesting to metaphysicians because it is revisionary: The descriptions of the world it provides are at odds with our metaphysical intuitions. But the first of these tempting answers is hard to defend, and the second, while reasonable, is apt to be somewhat misleading unless stated more carefully. So before we get started, it is worth trying to get a little clearer on the relationship between physics and metaphysics.

Metaphysicians have been interested in physics for as long as the two disciplines have been distinct (and before that, trivially so). And this seems quite natural, at least at first glance: Metaphysics is the branch of philosophy that deals with the fundamental structures of reality, and physics is the branch of science that does the same. Indeed, a commitment to the right combination of reductionism and naturalism might lead you to the conclusion that metaphysics is just physics, perhaps expressed in more philosopher-friendly terms. On that view, since quantum mechanics is a very important part of physics, it is ipso facto a very important part of metaphysics.

Most metaphysicians, though, don't accept this combination of reductionism and naturalism—perhaps none do. So the first-glance explanation for the interest of metaphysicians in physics would at least need to be carefully hedged, and I strongly suspect it is untenable. But fortunately we can bypass these concerns, since it is relatively straightforward to establish that understanding quantum mechanics is important for metaphysicians of virtually any stripe. The argument is this: Whatever one's philosophical commitments (pretty much), metaphysics is constrained by consistency with experience. Quantum phenomena are part of experience: The experiences of the physicist in the lab are no less constraints on metaphysics than the experiences of the philosopher playing with a piece of wax. So quantum mechanics is a constraint on metaphysics.

Of course, that doesn't entail that it's an *important* constraint. Poached-egg phenomena are part of experience, too, but though these phenomena are relevant to metaphysics (Lewis, 1979, 530), nobody should write a book on the metaphysical implications of poached eggs. One might suspect quantum mechanics of being even less central to metaphysics than poached eggs: Unless you are a professional physicist, one might think, you just don't run across experiences of the quantum world. But that would be a mistake. There are everyday phenomena that can only be explained in quantum mechanical terms—the light from your laser pointer, for example. Furthermore, quantum mechanics is not limited to the behavior of the very small, or of matter under certain extreme circumstances; it holds, if it holds at all, of all material objects all the time. Most of your experience of material objects may be roughly explicable in classical terms, but if modern physics is right, a more general explanation is in terms of quantum mechanics, since classical mechanics has been superseded by quantum mechanics and subsumed as a limiting case.[1] So your experience of material objects is always experience of quantum phenomena. Quantum mechanics is important to metaphysics because quantum phenomena, unlike poached-egg phenomena, are ubiquitous in our experience of the physical world.

I stand by this above argument, but put in such stark terms it runs the risk of applying either too broadly or too narrowly. Certainly quantum mechanics is relevant to the behavior of every object that we experience, but so are any number of other theories in physics (thermodynamics, optics, etc.) and chemistry (bonding theory, reaction kinetics, etc.). Any sufficiently general theory applying to material objects constitutes a ubiquitous constraint on our experience, and hence is relevant to metaphysics according to this argument. Perhaps some or all of these theories are reducible to quantum mechanics, but I don't want to tie my argument to any particular account of intertheoretic reduction. So the argument applies too broadly: It doesn't single out quantum mechanics as especially relevant to metaphysics.

Conversely, one might argue that, strictly speaking, quantum mechanics (the standard nonrelativistic theory outlined in Chapter 1) doesn't apply to any material objects, because it too has been superseded by quantum field theory and subsumed as a limiting case. Indeed, we know that even quantum field theory cannot be the final word, as it cannot be extended to gravitational phenomena. Quantum mechanics is false: At best it is approximately true within a certain range of application (Monton, 2013, 154). But in that case, quantum mechanics *isn't* the underlying explanation for the behavior of objects. So the argument applies too narrowly: Only the ultimate physical "theory of everything" (if there is such a thing) is relevant to metaphysics.

The response to both of these objections is basically the same: Quantum mechanics provides a level of physical theory at which a number of interrelated conceptual difficulties appear, and it is the responses to these conceptual difficulties that make quantum mechanics so metaphysically revisionary. So while it is true that many theories can be regarded as ubiquitous constraints on our experience, most of them are not terribly interesting from a metaphysical point of view.

Classical mechanics provides the most obvious case in point. Classical mechanics, like quantum mechanics, can be regarded as approximately true within a certain range of application, and indeed most of the observed behavior of macroscopic objects can be given classical mechanical explanations. But classical mechanics is not metaphysically revisionary; indeed, you might regard the description of the world provided by classical mechanics as the received metaphysical view. If philosophers wish to gesture at the physical reality underlying everyday phenomena, they typically do so in terms of a classical particle ontology—in terms of little billiard balls flying around according to Newton's laws of motion. A representative example is Merricks's analysis of ordinary objects: A statue, says Merricks, is nothing but "atoms arranged statuewise," where the atoms are "the atoms of physics, not Democritus" (Merricks, 2001, 3). This is not to single out Merricks: Such examples are commonplace. Admittedly, they are often accompanied by a disclaimer to the effect that claims about particles or atoms are "really placeholders for claims about whatever microscopic entities are actually down there" (Merricks, 2001, 3). But this disclaimer is itself couched in classical terms: There is no guarantee that physics will produce a fundamental ontology that is anything like microscopic entities arranged in three-dimensional space, and indeed quantum mechanics has been taken to show otherwise. Hence, a metaphysical exposition of classical mechanics would be otiose, since it would be merely telling metaphysicians what they intuitively assume, but a metaphysical exposition of quantum mechanics has the potential to reveal where those intuitions fail.

To an extent, every scientific theory (that is roughly empirically adequate) is metaphysically relevant, since every such theory rests on empirical phenomena, and every empirical phenomenon is a constraint on metaphysics. But most of these constraints are unsurprising, since they are already built into our standard metaphysical intuitions. What makes quantum mechanics exciting is that the phenomena on which it is based seem to *undermine* those intuitions. Note that it is an advantage of this phenomena-based motivation for the study of quantum mechanics that it is independent of whether quantum mechanics is a *fundamental* theory. Quantum mechanics, at least in the standard nonrelativistic form to be covered in this book, is surely not a fundamental or ultimate theory in any sense, but the argument developed here for its metaphysical interest does not depend on any such claim. A case can be made that evolutionary biology is also metaphysically revisionary, in that the phenomena of speciation cannot be captured by our intuitive species ontology (Okasha, 2002). So there is no "physics first" or reductionist agenda here: The metaphysical interest of quantum mechanics does not rest on its being an important part of modern *physics* per se. Rather, the claim is just that one particular set of empirical phenomena—those associated with quantum mechanics—provides a fertile area for metaphysical investigation.

So it doesn't matter that quantum mechanics isn't the final word in physical theory, and it doesn't matter that quantum mechanics doesn't reveal the ultimate constituents of matter. Perhaps those ultimate entities are the strings described by string theory; perhaps they are something else entirely. We don't really know, in large part because there are as yet no empirical results that bear on the matter. But what we do know is that whatever the ultimate entities are, they must exhibit the characteristic phenomena of quantum mechanics at the relevant level of description. At the level of electrons, atoms, and the like, we know from the results of extensive experimentation that quantum mechanics makes just the right predictions. It is these predictions that generate the metaphysical difficulties to be explored in this book. At the end of the day, it is quantum *phenomena* that are metaphysically problematic; these phenomena are well explored experimentally, and theoretical developments are not going to make them go away.

So much for the claim that quantum mechanics is interesting because it is fundamental. What about the claim that it is interesting because it is revisionary? As should be clear from the earlier discussion, I endorse this claim. But note the stress on the quantum phenomena rather than the theory of quantum mechanics. This is not accidental. The theory of quantum mechanics is notoriously difficult to interpret, to such an extent that several prominent physicists and philosophers have denied that it provides us with any description of the physical world at all. And even if one does take it as descriptive, there is no consensus about the nature of the description it provides us with. So it is certainly not straightforwardly true that quantum mechanics is metaphysically revisionary in the sense that it provides us with a theoretical description of the world that undermines our classically tutored intuitions.

Nevertheless, we can say this much: The quantum phenomena (as we shall see) are such that they cannot be accommodated within a classical world. So either we have to give up on the project of describing the world behind the phenomena at all (which I don't recommend), or we have to embark on the project of modifying our classical worldview to accommodate them. It is this latter project that takes up the bulk of the book. As will become clear, we can say quite confidently that quantum mechanics is metaphysically revisionary even if it is not clear what form the revisions should take.

There are two competing dangers to taking physics as a guide to metaphysics. The first danger is that we will convince ourselves that only the final, fundamental theory has anything definitive to tell us about ontology. In that case, we end up endorsing a kind of metaphysical skepticism: We can't know anything about physical ontology until the end of physics. This seems unwarranted: We can know a lot of things about rocks and organisms and molecules without knowing anything about their ultimate constituents. So there is no reason in principle why we should not know about the entities and processes involved in quantum phenomena without waiting for the fundamental theory in which they are ultimately grounded.[2]

The second danger is that we will take some particular account of the description of the world that quantum mechanics presents us with as definitive, and hence become overly confident of the metaphysical consequences of that description. The second danger points in the opposite direction to the first: We end up saying too much rather than too little. And this is not just an idle worry, since many of the metaphysical conclusions that have been claimed on the basis of quantum mechanics (as we shall see) do so on the basis of some particular interpretation of the quantum world, when other interpretations would entail different conclusions. The goal of this book is to navigate between these competing dangers: to say what can be said about the ontological implications of quantum mechanics, without overstating the case.

The first three chapters set up the general framework for drawing metaphysical consequences from quantum mechanics. Chapter 1 presents two distinctively quantum mechanical phenomena—interference and entanglement—and lays out the theory that was devised to account for them. The notable thing about quantum mechanics is that it is remarkably silent about what the basic mathematical structures of the theory represent. Chapter 2 explores the possibility that this silence is because no descriptive account of the physical reality behind quantum phenomena is possible: Quantum mechanics is just a very good predictive recipe. If this is right, of course, then quantum mechanics tells us nothing at all about ontology. But although there are theorems that preclude some ways of describing the underlying physical reality, I argue that realism about the quantum world is perfectly tenable. Chapter 3 presents three incompatible ways of understanding the reality behind the quantum phenomena—spontaneous collapse theories, hidden variable theories, and many-worlds theories—and discusses the extent to which the choice among these theories is underdetermined by the empirical data.

The next five chapters investigate the consequences of quantum mechanics for various metaphysical issues. Chapter 4 is about indeterminacy: To what extent does quantum mechanics entail that there is vagueness in the world, as opposed to in our language? Chapter 5 looks at the consequences of quantum mechanics for the kinds of causal explanation we give for physical phenomena, and in particular, at whether quantum mechanics requires action at a distance. Chapter 6 is about determinism: Does quantum mechanics entail that the physical laws are fundamentally probabilistic, and what does it tell us about the nature of probability? Chapter 7 investigates the dimensionality of the world according to quantum mechanics and evaluates arguments that the apparent three-dimensionality of the world is an illusion. And Chapter 8 examines whether quantum mechanics requires holism—that wholes have properties that cannot be reduced to the properties of their parts—and, if so, what this tells us about the ontological priority of parts and wholes and about the existence of localized individuals. The final chapter sums it all up.

1 | Phenomena and Theory

One of the central claims of this book, outlined in the Introduction, is that it is empirical quantum *phenomena* that require us to revise our classically inspired metaphysical presuppositions. To make good on that claim, I need to describe some of these phenomena, and that is the first order of business in this chapter. I then proceed to describe the theory of quantum mechanics that was developed to account for such phenomena. Typically in scientifically informed metaphysics, we look to scientific *theories* to inform our ontology. But it quickly becomes apparent why that strategy won't work in the case of quantum mechanics. First, there are two canonical formulations of the theory, so it is not clear which we should take as metaphysically privileged. Second, it is far from clear how to take either of these theories as descriptive of the world. We are left with the project of this book: If the theory of quantum mechanics by itself doesn't tell us how to conceive of the world behind the quantum phenomena, then it is up to us to construct such a conception. Fortunately, a lot of work has already been done in this direction; this is the project of *interpreting* quantum mechanics.

I do not intend here to give a historical account of the phenomena that led to the development of quantum mechanics; an excellent informal treatment can be found in Gamow (1966). The story is fascinating in its own right, but as with the development of most theories, the development of the theory and the discovery of the phenomena that require such a theory are entangled together in complicated ways. It is much cleaner, from an expository perspective, to proceed ahistorically. So in the next two sections I will present two examples of physical phenomena that most clearly demonstrate the failure of our classical intuitions and the need for a theory like quantum mechanics. It wasn't these actual phenomena that motivated the development and adoption of quantum mechanics, but they get at the heart of quantum behavior. Then in the following two sections I present the two standard mathematical formulations of quantum theory: matrix mechanics and wave mechanics. In the final section, I make the case that the theory of quantum mechanics, perhaps uniquely in the history of science, is a theory in need of interpretation.

1.1 Interference

The first phenomenon I want to discuss is interference. Interference phenomena were known long before the quantum mechanical era, notably in the behavior of light waves. Suppose you shine a light at a screen with two slits in it, and project the result on a further screen, as shown in Figure 1.1. Initially, suppose that the left-hand slit is open but the right-hand slit is blocked; then the screen is illuminated behind the open slit, as shown in the top diagram. Similarly, if the right-hand slit is open and the left-hand slit is blocked, the screen is illuminated behind the right-hand slit, as shown in the middle diagram. But if both slits are open, the illumination on the screen is not the sum of those in the top and middle diagrams; rather, it is the pattern of light and dark bands shown in the bottom diagram.

This behavior can be readily understood in terms of the mechanics of light waves, as shown in Figure 1.2. The waves spread out from the source until they encounter the first screen, where most of the wave is blocked. When one slit is open, as in the top diagram, some of the wave passes through the open slit and spreads out until it hits the second screen. This explains the illumination of the screen behind the open slit. When both slits are open, as in the bottom diagram, some of the wave passes through each slit, and the two wave components spread out and overlap before they hit the second screen. In this overlap region, interference occurs; that is, the waves from the two slits add up in some directions and cancel out in others. The solid lines represent the wave peaks, and in some directions (marked by dashed lines) you can see that the lines emanating from each slit cross, meaning that the peaks coincide. In these directions the waves from the two slits reinforce each other, resulting in a bright band on the screen. Between these directions, the peaks from one slit coincide with the troughs from the other; here the waves from the two slits cancel each other out, resulting in a dark band on the screen.

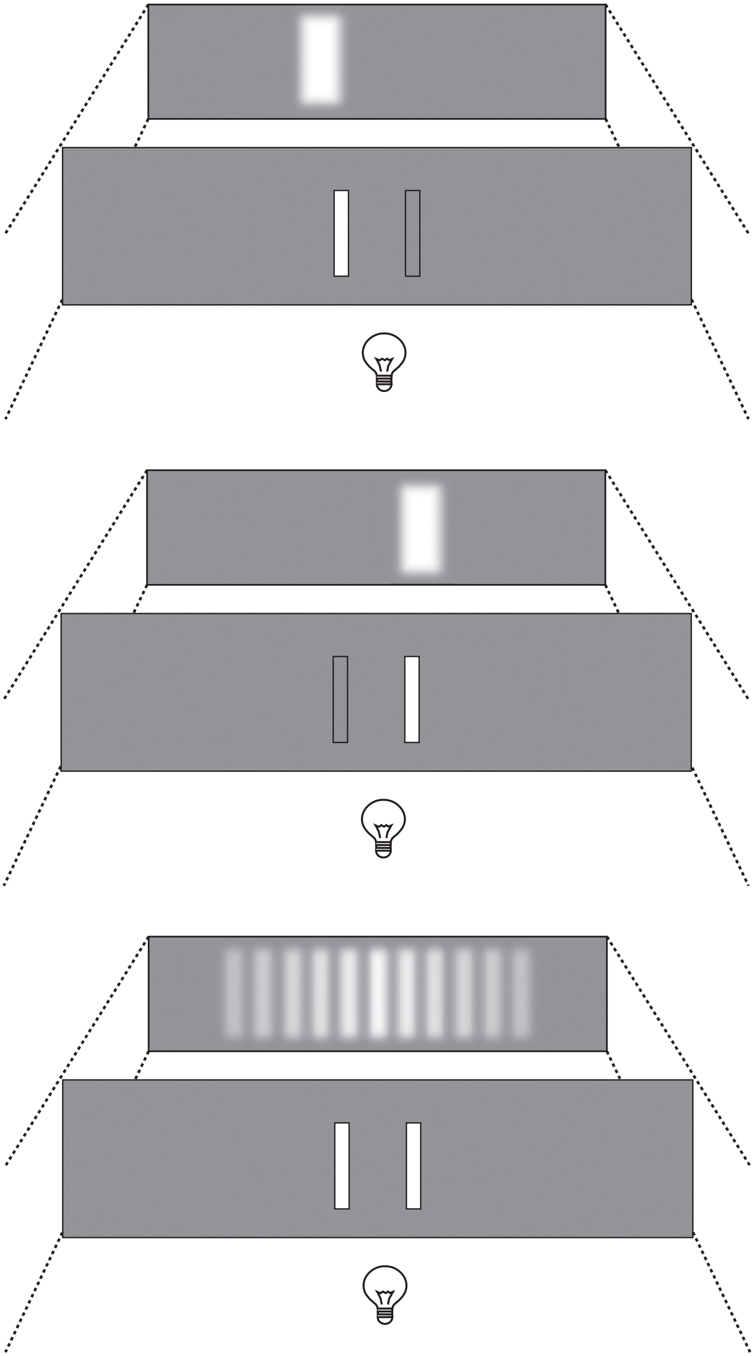

FIGURE 1.1 Two-slit interference with light.

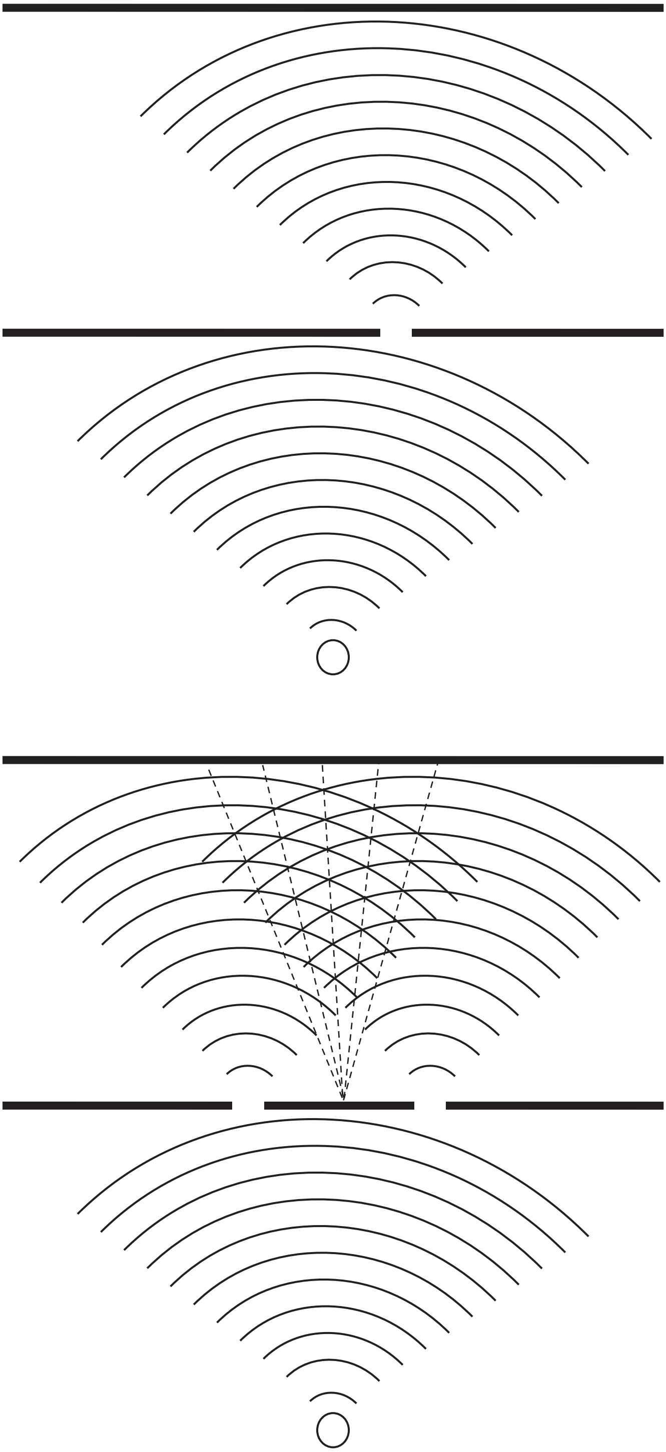

FIGURE 1.2 Wave diagrams for two-slit interference.

So far, this is just a classical wave phenomenon. A more surprising phenomenon—and a paradigmatically quantum mechanical one—is the production of an interference pattern like this using a stream of electrons instead of a beam of light. Suppose that the light source is replaced by an electron gun like that at the back of an old-fashioned television, and the display screen is replaced by a fluorescent screen like that on the front of such a television. Then you can produce interference effects exactly like those produced by light: When only one slit is open, the screen is illuminated behind the relevant slit, but when both slits are open, the screen displays a pattern of light and dark bands. This behavior is utterly inexplicable from a classical point of view. Classically, electrons are viewed as particles—essentially as like little billiard balls traveling through space. Whereas a wave can pass through both slits and then interfere, a particle, by its nature, has to pass through one slit or the other, so any explanation of interference is ruled out. That is, if the electron passes through the left-hand slit, then it can make no difference to the path of the electron whether the right-hand slit is open or not, so the pattern when both slits are open *has* to be simply the sum of the single-slit patterns.

So perhaps we were wrong about the nature of electrons: Perhaps they are really waves, not particles. This is what Louis de Broglie (1924) proposed—that every so-called particle can be treated as a wave with wavelength $\lambda = h/mv$, where m is the mass of the particle, v is its velocity, and h is a fundamental constant called Planck's constant. These wavelengths are very small; for an electron at typical lab velocities, the de Broglie wavelength is around a nanometer (a billionth of a meter), compared to several hundred nanometers for visible light. This means that to actually observe interference effects for electrons, one needs to use a slit spacing of atomic dimensions; typically, the lattice of atoms in a crystal is used in place of slits.

So far, the explanation of electron interference doesn't require any fundamental metaphysical reorientation: Electrons are reclassified as waves rather than particles, but the basic classical ontology of waves and particles remains intact. In fact, though, the situation is far more mysterious than it at first appears. Suppose we reduce the firing rate of the electron gun so that the electrons pass through the slits one at a time. Each electron produces a flash at a single precise point on the fluorescent screen, but if we look at the distribution of the flashes over time, we see that it forms an interference pattern. A typical cumulative pattern of flashes is shown in Figure 1.3. Note that the interference pattern is present even though the electrons pass through the apparatus singly; each electron interferes with *itself*, not with other electrons. But more problematically, the explanation