Preface

This textbook is intended as a lifeline to physics students (of either the traditional or the autodidactic variety) who have had some preliminary exposure to quantum mechanics but who want to actually try to make physical and conceptual *sense* of the theory in the same way that they have been trained and expected to do when learning about other areas of physics. Its main goals are (i) to help students appreciate and understand the concerns that people like Einstein, Schrödinger, and Bell have had with traditional formulations of the theory and (ii) to introduce students to the several extant formulations of quantum theory which purport to address at least some of the concerns and provide candidate accounts of what quantum theory might actually imply about how the micro-physical world works.

The book grew out of, and its structure in many ways reflects, the "special topics in physics" course on the *Foundations of Quantum Mechanics* that I taught at Smith College in the Spring of 2016. In this seminar-style course, students would read through each new chapter (and attempt a few of the end-of-chapter Projects that I recommended as appropriate pre-class exercises) prior to our weekly three-hour meeting. During our time together in class, we would discuss the more difficult concepts and derivations from the text, students would share their (sometimes only partial) solutions to the assigned pre-class projects (and we would discuss and complete those as needed), and then we would tackle some additional projects.

Not surprisingly, then, I envision the book being most straightforwardly useful for a similarly structured elective course in a physics department (or perhaps for a philosophy-of-physics course focused on the *Foundations of Quantum Mechanics* in a philosophy department). But the fact that the chapters were created as pre-class readings (as opposed to transcripts of "lecture notes") perhaps makes this, compared to most physics textbooks, unusually readable and accessible to individuals for whom it is not the textbook for any official course—e.g., interested physics students who are not lucky enough to find themselves in a department that offers an elective course on the *Foundations of Quantum Mechanics*, or just anyone with an interest in the puzzling and fascinating history, philosophy, and, really, *physics* of quantum physics.

The book begins with two introductory chapters. Chapter 1 ("Pre-Quantum Theories") introduces a number of important concepts and ideas in the context of classical physics theories such as Newtonian gravity and Maxwellian electrodynamics. Chapter 2 ("Quantum Examples") then provides a lightning overview of some quantum mechanical formalism and examples that serve as a foundation for later discussions. The level of these two chapters (as well as the rest of the book) reflects the background preparation I was able to expect for the students in my course at Smith College: they had taken a sophomore-level "modern physics" course including exposure to Schrödinger's equation and 1-D wave mechanics (but had not yet taken, or were in some cases taking concurrently, a junior-level "quantum mechanics" course using, for example, the text by Griffiths); similarly, they had seen Maxwell's equations before (in a 100-level introductory course and perhaps also a 300-level E&M course) and had a fairly strong prior exposure to vector calculus and differential equations. Still, the students found some of the material in the two introductory chapters quite fresh and challenging.

Readers who are missing one or more of the prerequisites I just mentioned (or readers who are pursuing physics outside of, or perhaps decades beyond, any organized undergraduate physics curriculum) should thus anticipate some struggle with some mathematical details in the first two chapters. However, I want to reassure people in this category that it will be OK, and that they should get what they can out of the first two chapters and press forward into the rest of the book. Let me explain my attitude here with an example. I don't think you can fully appreciate Bell's Theorem (the subject of Chap. 8) without digesting, in Chap. 1, the reasonableness of Bell's formulation of "locality" as a generalization of the specifically deterministic sort of local causality exhibited by Maxwellian electrodynamics (in contrast to Newtonian gravitation). But for readers for whom understanding the mathematical details is too big a stretch, it will suffice to merely accept *that* Bell's formulation purports to be a natural generalization of the important relativistic locality of classical E&M.

After the two introductory chapters, the book turns toward the first goal mentioned above: Helping students appreciate and understand the concerns that people like Einstein, Schrödinger, and Bell had with traditional formulations of quantum theory. We begin in Chap. 3 by studying "The Measurement Problem" which was most famously illustrated by Schrödinger's infamous cat and then emphasized and significantly clarified by Bell. Chapter 4 tackles "The Locality Problem" which was most famously brought out in the 1935 paper of Einstein, Podolsky, and Rosen—although, as we will discuss in detail, this canonical presentation does not perfectly capture Einstein's fundamental objection to the orthodox interpretation. Finally, Chap. 5 introduces "The Ontology Problem"—a concern that was intensely worrying to Schrödinger, Einstein, and others in the early days of quantum mechanics, but which has, unfortunately, been largely forgotten in the instrumentalist and anti-realist wake of the Copenhagen orthodoxy (and which, again unfortunately, remains under-appreciated even by certain schools of anti-Copenhagen quantum realism). One of the things I like best about this book is that it gives the ontology problem pride of place alongside the (more widely recognized) measurement and locality problems as one of the “big three” concerns that clearheaded physicists should have in mind when they are evaluating and developing candidate theories.

Having thus surveyed the central problems that one would hope to see resolved, the book turns to reviewing and assessing the menu of available resolutions. We cover, in particular, what I consider the four most important perspectives on quantum mechanics that curious and intelligent physics students should understand. These include: in Chap. 6, “The Copenhagen Interpretation” (which is a self-confessed non-candidate for genuinely explaining micro-physics in an ordinary, realist way, but is of historical and sociological interest nevertheless since it has been the official, if only superficially understood and half-heartedly accepted, orthodoxy of the physics community for nearly a century); in Chap. 7, “The Pilot-Wave Theory” of de Broglie and Bohm; in Chap. 9, “The Spontaneous Collapse Theory” of Ghirardi, Rimini, Weber, and Pearle; and, finally, in Chap. 10, “The Many-Worlds Theory” of Everett. Chapter 8, on “Bell’s Theorem,” is a kind of sequel to Chap. 4 which explains the Earth-shattering advance that Bell was led to from his study of the pilot-wave theory.

The material in this second half of the book is, to a large but not perfect extent, organized historically. Thus, the Copenhagen Interpretation (largely developed in the 1930s) comes first, the pilot-wave theory (originally proposed by de Broglie in 1927 but then largely forgotten until Bohm resurrected the idea in 1952) comes second, then we turn to Bell’s theorem of 1964 (which, as mentioned, was directly stimulated by Bell’s contemplation of a seemingly troubling feature of the pilot-wave theory), and then the spontaneous collapse theories (which only began to be developed in the 1980s). Everett’s many-worlds theory is presented last, despite the fact that Everett proposed it in 1957 (between Bohm’s resurrection of the pilot-wave idea and Bell’s presentation of his important theorem), both because the theory was not widely recognized as a serious candidate account of quantum phenomena until much more recently, and also because I think it is hard to recover from studying something rather surreal and focus on something rather more mundane!

Note that it might be slightly puzzling that the Copenhagen Interpretation is only covered (in Chap. 6) *after* we have reviewed the measurement, locality, and ontology problems (in Chaps. 3, 4, and 5, respectively)—this despite the fact that these “problems” were largely raised in *response* to the interpretive pronouncements of Bohr and Heisenberg and their colleagues. I structured things this way in part because I assume that students will already have been exposed, as part of a “modern physics” type course, to the basic Copenhagen philosophy of insisting on the *completeness* of the description in terms of wave functions alone (but also, paradoxically, denying the *reality* of wave functions) and then foreclosing further discussion as somehow scientifically inappropriate. So I thought students would be able to appreciate the somewhat-reactionary concerns of, for example, Einstein and Schrödinger, without any explicit prior discussion of the Copenhagen philosophy. In addition, I think having a clear sense of the critics’ concerns can help motivate students to actually care about what, exactly, Bohr and Heisenberg said: Did they really assert what the critics reacted against, and did they have viable answers to the criticisms? Finally, I thought that giving Bohr and Heisenberg the last word (after hearing from the critics) was a good way to try to maintain the neutrality that I have aimed at throughout the book—despite, perhaps obviously, not thinking very highly of the Copenhagen philosophy.

In the Smith College course, we went through these topics at a pace of one chapter per week. That left a couple of weeks at the end of the semester, during which the students each picked a topic they were individually interested in exploring further, did some independent reading and research, and then gave a presentation back to the class summarizing what they had learned and uncovered. This structure is reflected in the present book, which closes with an "Afterword" that tries to bring an (admittedly limited) element of closure to the covered topics by summarizing where things stand and then provides an informal laundry list of recommended topics for further exploration, including pointers to some more contemporary literature.

I attempt, though, even in the ten chapters of the book, to build bridges to the primary literature. There is, for example, extensive quoting from the published papers (as well as the private correspondence) of Einstein, Lorentz, Schrödinger, Bell, Bohr, Heisenberg, etc., and many of the end-of-chapter Projects invite students to read some accessible piece of primary literature and report on things they find interesting or surprising. Indeed, one of my goals with this book is to help students appreciate the extent to which their own confusions and concerns about quantum mechanics are not something to feel ashamed of (a feeling that is too-often the result of the "shut up and calculate" attitude that quantum physics professors frequently take toward the subjects we cover). Instead, students should feel proud that they can understand, and indeed in many cases will have anticipated without realizing it, concerns that were shared by some of the giants of twentieth-century physics—concerns that have unfortunately been suppressed and forgotten rather than adequately addressed. To capture the intended spirit of the book in this respect, I can do no better than quote from an email from my friend Kenny Felder who read drafts of most of the chapters:

> Reading [this], I have I think exactly the sense that you want me to have—or perhaps the meta-sense that you want me to have—in any case it's a wonderful sense that I really have never had before. I have the sense of a group of men who are very smart but perfectly human, right at the dawn of the quantum revolution, desperately trying to figure out what the experimental evidence is actually telling them. I see them throwing ideas around, trying and rejecting theories, alone and in correspondence with each other. And I get the sense that somewhere between them and us, that search for a coherent theory more or less evaporated—not because the questions were answered, but more because people kind of forgot about them—and you're trying to revitalize that quest. It's exciting!

Let me finally say something about the end-of-chapter "Projects" which I consider to be an essential component of the book, just as they were an essential component of the course it grew out of. Some of these are rather like traditional end-of-chapter exercises, which ask students, for example, to fill in gaps in derivations from the text or apply concepts introduced in the text to simple concrete examples. But many of the Projects are considerably more challenging and open-ended. For example, as mentioned above, some invite students to read an article or essay that has been discussed in the text and report back on things they find interesting, surprising, or novel. Some projects invite students to use Mathematica or another programming language to create helpful visualizations or numerical solutions of difficult problems. There are even a few Projects (perhaps most suitable for students using the text in the context of a traditional course) asking students to interview a few physicists to get a sense of how real people think about some issue. It is hoped that the diversity and open-endedness of the Projects will allow students with many different backgrounds, technical abilities, and interests to stay actively engaged with the material (before, during, after, and/or without classroom time, as appropriate in each individual case).

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