

# Contents

<i>Preface</i>	xi
<i>List of Figures</i>	xiii
1. Classical Mechanics	1
1.1 Quantum Mechanics and Philosophical Intuition	1
1.2 Newtonian Mechanics	4
1.3 Problems with Classical Mechanics	8
1.4 The Stability of Matter	11
2. Quantum Phenomena	15
2.1 Spin Properties	15
2.2 Basic Properties of the Boxes	17
2.3 Quantum-Mechanical Interference	20
2.4 How Electrons Move	23
2.5 Superpositions, Property Attribution, and the Total-of-Nothing Box	27
2.6 Random, Nonlocal, and Indeterminate	29
3. The Mathematics of Quantum Mechanics	30
3.1 Hilbert Space	30
3.2 Spin Space	39
4. The Standard Formulation of Quantum Mechanics	42
4.1 The von Neumann–Dirac Theory	42
4.2 Spin Boxes and the Linear Dynamics	53
4.3 Quantum Statistics	58
4.4 Combining Boxes	61
4.5 Physical Properties more Generally: <i>K</i> Mesons and Qubits	63
5. Quantum Interference	66
5.1 The Simple Two-Path Experiment	66
5.2 Measurement	68
5.3 Barriers	72
5.4 Decoherence	76
5.5 Quantum Records	81
5.6 Total-of-Nothing	84
5.7 The Wave Function	86
6. Real and/or Local	89
6.1 The EPR Argument	89
6.2 Quantum Mechanics and Relativity	93
6.3 Bell's Theorem	96



6.4	Bell-Type Theorems	98
6.5	Quantum Property Attribution Redux	101
6.6	EPR Morals	102
7.	The Quantum Measurement Problem	105
7.1	Wigner's Friend	105
7.2	The Measurement Problem	111
7.3	Why A-Type Measurements are Difficult	113
8.	The Collapse of the Quantum State	118
8.1	Wigner's Solution	118
8.2	GRW*	121
8.3	GRW	130
8.4	GRWr, GRWm, and GRWf	134
8.5	Empirical Ontology and Experience	140
9.	Pure Wave Mechanics	143
9.1	Everett's Solution to the Measurement Problem	143
9.2	The Bare Theory	145
9.3	Pure Wave Mechanics with just the Standard Interpretation of States	153
9.4	The Relative-State Formulation of Pure Wave Mechanics	154
9.5	Everett's Empiricism	158
10.	Many Worlds and Such	162
10.1	Extending Pure Wave Mechanics	162
10.2	Splitting-Worlds	163
10.3	Probability and Typical Worlds	168
10.4	Decohering Worlds	174
10.5	Single-Mind and Many-Minds Theories	181
10.6	Many Threads and Many Maps	184
10.7	Epistemological, Pragmatic, and Information-Theoretic Interpretations	187
11.	Bohmian Mechanics	190
11.1	Bohm's Theory	190
11.2	Basic Spin Experiments	193
11.3	Interference and the Two-Path Experiment	200
11.4	Measurements and Records	203
11.5	Surreal Trajectories and Decoherence	208
11.6	How the Theory Explains Experience	213
11.7	EPR and Relativity	214
11.8	Virtues and Vices	217
12.	Empirical Ontology and Explanation	220
12.1	The Explanatory Work of Metaphysics	220
12.2	Beables and Experience	222
12.3	Metaphysics and Empirical Adequacy	226



12.4 Empirical Ontology and Experience	230
12.5 Philosophical Morals	231
Appendix A: A Formal Characterization of Hilbert Space	233
<i>Bibliography</i>	235
<i>Index</i>	241

The aim of this book is to introduce the conceptual foundations of quantum mechanics. To this end, we will start with the empirical evidence that quantum mechanics is meant to explain, develop the standard formulation of quantum mechanics and discuss how it explains the empirical evidence, and then turn to the measurement problem and the various attempts to resolve it.

Since quantum mechanics is written in the language of linear algebra, we will need some basic mathematical notions in order to say precisely what the theory is. With few exceptions, almost everything should be accessible to a reader comfortable with high-school algebra.

This book owes much to the insights of David Bohm, Hugh Everett III, Eugene Wigner, John Bell, and David Albert. Everett and Wigner were the first to characterize the measurement problem in the form that we will discuss it. Bohm and Bell helped to set the stage for what a satisfactory resolution of the measurement problem might look like. And Albert's influence is evident throughout the book.

Theory selection involves a sort of cost-benefit analysis. We start with rough intuitions concerning the nature of the world and a sense of the sorts of predictions and explanations we want from a satisfactory physical theory; then we see how much we can get given the constraints of inquiry. From this perspective, this book might be thought of as a map of the conceptual options and explanatory trade-offs one faces in constructing a theory that explains and predicts quantum phenomena.

It is impossible to evaluate the conceptual foundations of quantum mechanics without reflecting on general philosophical questions concerning what we can know about the physical world and what it means for a physical theory to explain and predict. That the world is so deeply counterintuitive that one cannot trust even one's most cherished intuitions is one of the philosophical lessons of quantum mechanics. Part of the argument here is that there are nevertheless better and worse ways of understanding the quantum world.

The book is written the way I would explain quantum mechanics to a friend. While there is a natural order of events, the structure is not linear. This means that we will sometimes briefly discuss something before it is carefully explained. I have several cross-linking references in a number of places to mark this.

This book is the result of many discussions with friends and colleagues and contributions from students. Discussions with David Albert, Tom Maudlin, and David Wallace over the years were particularly salient. I would also like to thank John A. Adams, Thomas Barrett, Jeffrey Bub, Daniel Herrmann, J. B. Manchak, Michael Mauts, and Liam Pritchett for helpful comments on the book as it