Preface

While still in high school, I learned that the tides act as a brake on the Earth's rotation, gradually slowing it down, and that the angular momentum lost by the rotating Earth is transferred to the Moon, causing it to slowly spiral outwards, away from Earth. I still vividly remember my puzzlement. How, by what mechanism or process, did angular momentum get transferred from Earth to the Moon? Just so Newton's contemporaries must have wondered at his theory of gravity. Newton's response is well known:

> I have not been able to discover the cause of those properties of gravity from phænomena, and I frame no hypotheses. . . . to us it is enough, that gravity does really exist, and act according to the laws which we have explained, and abundantly serves to account for all the motions of the celestial bodies, and of our sea. [Newton (1729)]

In Newton's theory, gravitational effects were simultaneous with their causes. The time-delay between causes and effects in classical electrodynamics and in Einstein's theory of gravity made it seem possible for a while to explain "how Nature does it." One only had to transmogrify the algorithms that served to calculate the effects of given causes into physical processes by which causes produce their effects. This is how the electromagnetic field—a calculational tool—came to be thought of as a physical entity in its own right, which is locally acted upon by charges, which locally acts on charges, and which mediates the action of charges on charges by locally acting on itself.

Today this sleight of hand no longer works. While classical states are algorithms that assign trivial probabilities—either 0 or 1—to measurement outcomes (which is why they can be re-interpreted as collections of possessed properties and described without reference to "measurement"), quantum states are algorithms that assign probabilities *between* 0 and 1 (which is why they cannot be so described). And while the classical laws correlate measurement outcomes *deterministically* (which is why they can be interpreted in causal terms and thus as descriptive of physical processes), the quantum-mechanical laws correlate measurement outcomes *probabilistically* (which is why they cannot be so interpreted). In at least one respect, therefore, physics is back to where it was in Newton's time—and this with a vengeance. According to Dennis Dieks, Professor of the Foundations and Philosophy of the Natural Sciences at Utrecht University and Editor of *Studies in History and Philosophy of Modern Physics*,

> the outcome of foundational work in the last couple of decades has been that interpretations which try to accommodate classical intuitions are impossible, on the grounds that theories that incorporate such intuitions necessarily lead to empirical predictions which are at variance with the quantum mechanical predictions. [Dieks (1996)]

But, seriously, how could anyone have hoped to get away for good with passing off computational tools—mathematical symbols or equations—as physical entities or processes? Was it the hubristic desire to feel "potentially omniscient"—capable in principle of knowing the furniture of the universe and the laws by which this is governed?

If quantum mechanics is the fundamental theoretical framework of physics—and while there are a few doubters [e.g., Penrose (2005)], nobody has the slightest idea what an alternative framework consistent with the empirical data might look like—then the quantum formalism not only defies reification but also cannot be explained in terms of a "more fundamental" framework. We sometimes speak loosely of a theory as being more fundamental than another but, strictly speaking, "fundamental" has no comparative. This is another reason why we cannot hope to explain "*how* Nature does it." What remains possible is to explain "*why* Nature does it." When efficient causation fails, teleological explanation remains viable.

The question that will be centrally pursued in this book is: what does it take to have stable objects that "occupy space" while being composed of objects that do not "occupy space"?[1] And part of the answer at which we shall arrive is: quantum mechanics.

---

[1] The existence of such objects is a well-established fact. According to the well-tested theories of particle physics, which are collectively known as the Standard Model, the objects that do not "occupy space" are the quarks and the leptons.

As said, quantum states are algorithms that assign probabilities between 0 and 1. Think of them as computing machines: you enter (i) the actual outcome(s) and time(s) of one or several measurements, as well as (ii) the possible outcomes and the time of a subsequent measurement—and out pop the probabilities of these outcomes. Even though the time dependence of a quantum state is thus clearly a dependence on the times of measurements, it is generally interpreted—even in textbooks that strive to remain metaphysically uncommitted—as a dependence on "time itself," and thus as the time dependence of something that exists at every moment of time and evolves from earlier to later times. Hence the mother of all quantum-theoretical pseudo-questions: why does a quantum state have (or appear to have) two modes of evolution—continuous and predictable between measurements, discontinuous and unpredictable whenever a measurement is made?

The problem posed by the central role played by measurements in standard axiomatizations of quantum mechanics is known as the "measurement problem." Although the actual number of a quantum state's modes of evolution is zero, most attempts to solve the measurement problem aim at reducing the number of modes from two to one. As an anonymous referee once put it to me, "to solve this problem means to design an interpretation in which measurement processes are not different in principle from ordinary physical interactions." The way I see it, to solve the measurement problem means, on the contrary, to design an interpretation in which the central role played by measurements is *understood*, rather than swept under the rug.

An approach that rejects the very notion of quantum state evolution runs the risk of being dismissed as an ontologically sterile instrumentalism. Yet it is this notion, more than any other, that blocks our view of the ontological implications of quantum mechanics. One of these implications is that the spatiotemporal differentiation of the physical world is incomplete; it does not "go all the way down." The notion that quantum states evolve, on the other hand, implies that it does "go all the way down." This is not simply a case of one word against another, for the incomplete spatiotemporal differentiation of the physical world follows from the manner in which quantum mechanics assigns probabilities, which is *testable*, whereas the complete spatiotemporal differentiation of the physical world follows from an assumption about what is the case *between measurements*, and such an assumption is "not even wrong" in Wolfgang Pauli's famous phrase, inasmuch as it is neither verifiable nor falsifiable.

Understanding the central role played by measurements calls for a clear distinction between what measures and what is measured, and this in turn calls for a precise definition of the frequently misused and much maligned word "macroscopic." Since it is the incomplete differentiation of the physical world that makes such a definition possible, the central role played by measurements cannot be understood without dispelling the notion that quantum states evolve.

For at least twenty-five centuries, theorists—from metaphysicians to natural philosophers to physicists and philosophers of science—have tried to model reality from the bottom up, starting with an ultimate multiplicity and using concepts of composition and interaction as their basic explanatory tools. If the spatiotemporal differentiation of the physical world is incomplete, then the attempt to understand the world from the bottom up—whether on the basis of an intrinsically and completely differentiated space or spacetime, out of locally instantiated physical properties, or by aggregation, out of a multitude of individual substances—is doomed to failure. What quantum mechanics is trying to tell us is that reality is structured from the top down.

Having explained why interpretations that try to accommodate classical intuitions are impossible, Dieks goes on to say:

> However, this is a negative result that only provides us with a starting-point for what really has to be done: something conceptually new has to be found, different from what we are familiar with. It is clear that this constructive task is a particularly difficult one, in which huge barriers (partly of a psychological nature) have to be overcome. [Dieks (1996)]

Something conceptually new has been found, and is presented in this book. To make the presentation reasonably self-contained, and to make those already familiar with the subject aware of metaphysical prejudices they may have acquired in the process of studying it, the format is that of a textbook. To make the presentation accessible to a wider audience—not only students of physics and their teachers—the mathematical tools used are introduced along the way, to the point that the theoretical concepts used can be adequately grasped. In doing so, I tried to adhere to a principle that has been dubbed "Einstein's razor": everything should be made as simple as possible, but no simpler.

This textbook is based on a philosophically oriented course of contemporary physics I have been teaching for the last ten years at the Sri Aurobindo International Centre of Education (SAICE) in Puducherry (formerly Pondicherry), India. This non-compulsory course is open to higher secondary (standards 10–12) and undergraduate students, including students with negligible prior exposure to classical physics.[2]

The text is divided into three parts. After a short introduction to probability, Part 1 ("Overview") follows two routes that lead to the Schrödinger equation—the historical route and Feynman's path-integral approach. On the first route we stop once to gather the needed mathematical tools, and on the second route we stop once for an introduction to the special theory of relativity.

The first chapter of Part 2 ("A Closer Look") derives the mathematical formalism of quantum mechanics from the existence of "ordinary" objects—stable objects that "occupy space" while being composed of objects that do not "occupy space." The next two chapters are concerned with what happens if the objective fuzziness that "fluffs out" matter is ignored. (What happens is that the quantum-mechanical correlation laws degenerate into the dynamical laws of classical physics.) The remainder of Part 2 covers a number of conceptually challenging experiments and theoretical results, along with more conventional topics.

Part 3 ("Making Sense") deals with the ontological implications of the formalism of quantum mechanics. The penultimate chapter argues that quantum mechanics—whose validity is required for the existence of "ordinary" objects—in turn requires for its consistency the validity of both the Standard Model and the general theory of relativity, at least as effective theories. The final chapter hazards an answer to the question of *why* stable objects that "occupy space" are composed of objects that do not "occupy space." It is followed by an appendix containing solutions or hints for some of the problems provided in the text.

---

[2] I consider this a plus. In the first section of his brilliant Caltech lectures [Feynman *et al.* (1963)], Richard Feynman raised a question of concern to every physics teacher: "Should we teach the *correct* but unfamiliar law with its strange and difficult conceptual ideas . . . ? Or should we first teach the simple . . . law, which is only approximate, but does not involve such difficult ideas? The first is more exciting, more wonderful, and more fun, but the second is easier to get at first, and is a first step to a real understanding of the second idea." With all due respect to one of the greatest physicists of the 20th Century, I cannot bring myself to agree. How can the second approach be a step to a real understanding of the correct law if "*philosophically we are completely wrong* with the approximate law," as Feynman himself emphasized in the immediately preceding paragraph? To first teach laws that are completely wrong philosophically cannot but impart a conceptual framework that eventually stands in the way of understanding the correct laws. The damage done by imparting philosophically wrong ideas to young students is not easily repaired.

I wish to thank the SAICE for the opportunity to teach this experimental course in “quantum philosophy” and my students—the “guinea pigs”—for their valuable feedback.

Ulrich Mohrhoff
August 15, 2010