Preface

Entanglement was initially thought by some to be an oddity restricted to the realm of thought experiments. However, Bell's inequality delimiting local behavior and the experimental demonstration of its violation more than 25 years ago made it entirely clear that non-local properties of pure quantum states are more than an intellectual curiosity. Entanglement and non-locality are now understood to figure prominently in the microphysical world, a realm into which technology is rapidly hurtling. Information theory is also increasingly recognized by physicists and philosophers as intimately related to the foundations of mechanics. The clearest indicator of this relationship is that between quantum information and entanglement. To some degree, a deep relationship between information and mechanics in the quantum context was already there to be seen upon the introduction by Max Born and Wolfgang Pauli of the idea that the essence of pure quantum states lies in their provision of probabilities regarding the behavior of quantum systems, via what has come to be known as the *Born rule*. The significance of the relationship between mechanics and information became even clearer with Leo Szilard's analysis of James Clerk Maxwell's infamous demon thought experiment.

Here, in addition to examining both entanglement and quantum information and their relationship, I endeavor to critically assess the influence of the study of these subjects on the interpretation of quantum theory. The deepest implications of quantum phenomena remain controversial in large part because there remains a need to more adequately interpret quantum theory itself. For example, physicists and philosophers hold a variety of increasingly subtle and radically differing interpretations of the quantum state, ranging from (i) that it is merely a representation of the knowledge of an agent regarding the world or (ii) that it merely links the preparation of systems and the registration of later measurement results without being of ontological significance, to (iii) that it directly describes a continually growing number of real universes that jointly constitute a unique 'multiverse' of incredible size or (iv) that it is the only truly real entity that can be associated with a physical system.

Because both physical and philosophical approaches to foundational problems of physics are involved in this, it is important to address the negative impressions to which the differences of methodology between the larger scientific and philosophical communities have given rise. In that regard, one can do no better than to recall the following comment of Michael Redhead in his 1993 Tarner Lectures at Cambridge. "One must admit that many physicists would dismiss the sort of questions that philosophers of physics tackle as irrelevant to what they see themselves as doing... Either these metaphysical questions arise, they would say, as a result of philosophers involving themselves with the technicalities of theoretical physics, which they, the philosophers never really understand, or it is the physicists themselves who in some cases get sidetracked and ensnared by the temptation to indulge in the subtle sophistry of the philosophers posing unanswerable questions, a subject where there is no discernable progress on premisses from which an argument could be launched, where every conceivable position has been argued for by some group of philosophers and equally refuted by another group... It may not come as a surprise to learn that philosophers generally regard physicists as naive people, who do physics in an uncritical way, rather like a child riding a bicycle, quite innocent of the subtleties of rigid-body dynamics!" [372].

Readers are requested to remove any caricatures from their minds, should they have previously entertained them. It behooves one to consider physics and philosophy as constructively coming together wherever both are deployed seriously and properly because our subjects necessitate the addressing of questions both philosophical and scientific. Physicists typically approach problems within a clearly defined mathematical framework, whereas philosophers typically emphasize logical and conceptual rigor and may be more flexible in their use of formalism in their attempts to surmount fundamental difficulties. Each approach has its strengths and weaknesses. Specialists in the foundations of physics tend to be concerned less with the department in which the office of a colleague is located than about whether he or she has presented a clear analysis of a problem. The work considered in this book provides evidence as to why this is so. I believe that work is a sufficient basis for the rejection of the forms of chauvinism to which Redhead refers, particularly on the part of some physicists toward philosophy.

The greatest minds behind the quantum theory worked actively with tools from both areas and used them to engage each other in valuable discussions and to define lines of research that have played an important role in our understanding of the physical world. Albert Einstein was correctly concerned that Niels Bohr was, in his subtle use of philosophically inspired concepts while building what has come to be known as the Copenhagen interpretation, perhaps *too* adept at reassuring physicists that quantum theory could be well founded by making use of ideas from outside physics proper. However, Bohr's interpretation achieved the status of an orthodoxy only *after* he was able to defend his interpretation with a remarkable degree of success against repeated logical *and* physical challenges from Einstein. Furthermore, Bohr's approach was likely so long sustained as such due to Werner Heisenberg's reworking of Bohr's approach into a helpful tool for using the quantum formalism. There should be no doubt that a useful basis for engaging the quantum world was achieved with the aid of the Copenhagen interpretation even though, from the metaphysical realist philosophical perspective traditionally assumed in physics, which itself is less easily combined with quantum mechanics, it is deficient. By contrast, more recently conceived interpretations of quantum mechanics, which may be of some practical benefit to physics in handling some newly considered situations, have yet to offer similar depth or comparable practical strength. Only Feynman's approach to quantum theory currently appears capable of supporting a new interpretation rivaling those of Dirac and von Neumann or of Bohr, Pauli, and Heisenberg.

To their credit, physicists proffering interpretations of quantum theory have often gone beyond the confines of physics when engaging fundamental problems. For example, Bohr, Heisenberg, and Pauli were engaged in modes of creative thinking physicists rarely consider. Similarly, Eugene Wigner seriously contemplated the possibility of a psychophysics. One does well to consider the methodology of the physicist–philosopher Abner Shimony, who has struggled with the deepest of foundational issues and has explained his own well informed use of philosophy in probing the foundations of quantum mechanics. "The language which we have employed for describing the conceptual innovations of quantum mechanics is quite philosophical. We have no apology for this language, because we consider it to be appropriate to the subject. We do not regard philosophy as an autonomous discipline, with a subject matter distinct from other disciplines, but rather as the general investigation of foundations questions and the general search for perspective. The change of framework in physics from classical to quantum mechanical is clearly a fundamental transformation of the conception of nature, and hence is a philosophical matter according to our usage of the term... a highly formal exposition of quantum mechanics is unclear concerning interpretation even though it is clear concerning structure, whereas the formal and philosophical expositions in combination may supplement each other and achieve a fuller clarification" ([407], p. 374).

Investigations of the foundational problems of quantum mechanics and the physics of computation have provided an important context for the emergence of quantum information science. The former two have also begun to benefit from the last, largely due to the importance of information and the possibility or impossibility of its transmission or transformation in different contexts. In my first book, *Quantum information: An overview*, I took pains to avoid engaging issues requiring substantial philosophical discussion or arguing for or against interpretations, as is appropriate in a technical overview. Here, by contrast, I take foundational issues head-on in order to elucidate the centrality of entanglement and information to quantum physics while discussing some of the same situations.

Because entanglement has long been identified as distinctive of quantum mechanics and has recently been shown to serve as an information theoretical resource, it is the primary subject of the opening chapter, which also includes a brief introduction to the mathematical formalism of quantum mechanics and an explication of fundamental concepts such as quantum interference and uncertainty in a manner emphasizing their foundational aspects and relation to information. The second chapter provides an overview of further mathematical formalism and analyses that have played an important role in clarifying the foundations of the theory. This includes a survey of quantum probability, quantum logic, some fundamental theorems of the foundation of quantum mechanics, the description and significance of quantum measurement, and important thought experiments conceived in the history of quantum theory, all of which set the stage for a careful examination of the interpretation of quantum mechanics. The third chapter critically examines the most prominent interpretations of standard quantum mechanics that have emerged in light of the results described in the first two chapters. This includes discussion of recent interpretations in which information is taken to play a dominant role. The ultimate focus of the book is the final chapter, which considers in detail quantum information and its relationship to quantum mechanics, returning to its relationship to entanglement. In addition to articulating that relationship, the final chapter includes critical assessments of the various claims regarding the nature of information and mechanics at the foundational level.

Engaging many issues in foundations of quantum mechanics at this advanced stage in the history of the subject involves formulations that some readers may find challenging. However, the reward of mastering them more than justifies the effort required.

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http://www.springer.com/978-3-540-92127-1

Entanglement, Information, and the Interpretation of Quantum Mechanics
Jaeger, G.
2009, XIV, 307 p., Hardcover
ISBN: 978-3-540-92127-1