FOREWORD

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In the nineteenth century, life was transformed by the conscious application of classical mechanics, in the form of Newton's equations (and, later, thermodynamics) to the engines of the industrial revolution. In this century, a similar transformation has been wrought by electromagnetism, in generating and distributing electric power and communicating words and pictures across the world at the speed of light, in what should be seen as the conscious application of Maxwell's equations. It is easy to predict that in the twenty-first century it will be quantum mechanics that influences all our lives.

There is a sense in which quantum mechanics is already having profound effects. Leon Lederman claims that a large part of the gross national product of the industrialized countries stems from quantum mechanics. I suppose he is referring to transistors—the 'fundamental particles' of modern electronics—that depend on properties of semiconducting materials designed by applying quantum mechanics to electrons in solids, and to lasers, where the Bose-Einstein statistics of identical particles generates coherent avalanches of photons to read the bar-codes in our supermarkets and guide delicate surgery in our eyes.

The most dramatic influences are, however, likely to come from the deliberate manipulation of entangled states. These arise naturally when Thomas Young's superposition principle, familiar throughout wave physics since 1800, is generalized to states of more than one particle. Entanglement lies at the heart of the microscopic world as described by quantum mechanics, and makes it weirdly different from the world of our immediate experience. Schrödinger invented the idea of entanglement more than sixty years ago (although a version of it had appeared before, in the quantum states of identical particles); but only now, in a remarkable flowering of fin de siècle quantum mechanics, are its full implications being thoroughly and energetically explored. There is much to understand; even a convincing measure of entanglement is lacking.

In an entangled state of several particles, measurements on one particle can affect all the others, even if they are too far apart for a causal influence to propagate between them. These nonlocal (but not relativity-violating) actions are being incorporated into proposals for technologies that were hardly imagined twenty years ago. Most of the attention is being focused on quantum computing, quantum cryptography, and teleportation.

In quantum computing, information is manipulated not discretely, in the classical way, as a series of zeros and ones (bits), but as continuous superpositions (qubits) where the number of possibilities is vastly greater. In effect, many computations are performed simultaneously, and calculations that would be intractable classically (for example, factoring large integers) become feasible quantally. In this way, the theory of computation—indeed information science itself—is becoming a branch of physics rather than mathematics.

Easy factorization would destroy one of the commonly-used methods of encryption. However, the same entanglement employed in quantum computing makes possible the development of unbreakable shared codes, incorporating the intrinsic randomness of quantum mechanics. To my mind, this particular emphasis in the application of fundamental physics is depressing, because I regard the obsession with secrets in public life (as opposed to a commendable discretion about private matters) as one of the less attractive preoccupations of our fellow human beings.

Teleportation is the dissolution of an object in one place in a way that enables it to be perfectly reconstituted elsewhere. On the finest scale, the most complete specification of an object is its quantum state, but complete knowledge of that cannot be had: measurement of one property of the state irrevocably destroys information about complementary properties. However, suitable measurements can entangle the teleportee (whose state is unknown) with one of a previously entangled pair of systems, and thereby transfer the state to the other member of the pair, however far away that is, where another measurement (requiring information sent conventionally) can reconstruct it.

Each of these projects is visionary—technological fantasy, some say—but the principles have been demonstrated experimentally. The big obstacle to further developments is 'decoherence', in which uncontrolled effects of the environment scramble the delicate phase correlations that embody quantum entanglement. Decoherence has plagued wave physics from its beginnings; it is what made Thomas Young's superpositions, in his double-slit experiments with light, so hard to create and maintain (his experiments were carried out with candles!). States of many particles are even more fragile. Recent work suggests that the effects of decoherence might be reduced or eliminated by cleverly correcting errors as they arise.

This book is a record of these modern developments, a self-contained pedagogical account—perhaps the first—written by the world's leading experts. Most of the chapters were 'battle-tested' in a series of lectures at Hewlett-Packard's Basic Research Institute in the Mathematical Sciences (BRIMS) in Bristol, United Kingdom. That the lectures were sponsored by Hewlett-

Packard indicates the intense industrial interest in a branch of theoretical, and, increasingly, experimental, physics that optimists (including me) believe is also a nascent technology.