Preface

> Would you tell me, please, which way I ought to go from here? said Alice. That depends a good deal on where you want to get to, said the Cat. I don't much care where, said Alice. Then it doesn't matter which way you go, said the Cat.
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> Lewis Carroll

In a long academic career teaching different subjects in the fields of chemistry, physics, and computer science, I noticed how many of my students finish their studies knowing how to do things, although sometimes they do not understand the basic underlying concepts that permit generalization and reasoning by analogy. In fact, I am convinced that, perhaps, our teaching efforts focus excessively on specialization. I fear that educators (and I belong to this exciting community) very frequently overlook some very interesting questions that deserve deep and abstract thinking. In other words, we center more on problem solving than on the problem itself. We also assume that our students are capable of thinking by themselves, and they are, of course, but it is also true that not all of them have the same skills when trying to find the solution to a problem that has not previously been explained. However, these skills can be fostered by the teacher and acquired by the student, and I believe that at least a part of this training is our responsibility as educators. With these ideas in mind, I decided to write this book. It is an almost speculative text in which I discuss different areas of science from a computer science perspective. This fact will be more evident in some chapters of the book than in others.

The main focus of the text is the basic unit of information and the way in which our understanding of this basic unit of information has evolved over time. Do not expect to find anything new in this book; you may even consider the way I have chosen to explain things to be extravagant. This could be due to the fact that I was inspired by my readings of two brilliant scientists and communicators: Richard P. Feynman and George Gamow. I hope that the final outcome will be to pique the reader's curiosity and lead him or her to think with the sole objective of better understanding our world. As I used to say, and according to Richard P. Feynman: "All right, I have not been the first, but at least I understand it."

The scientific material of this book covers concepts related to information, classical computing, logic, reversible computing, quantum mechanics, quantum computing, thermodynamics, and something of artificial intelligence and even biology, all approached from the point of view of the computer sciences. In some chapters, the discussion is extremely informal, even irreverent, but I think that this way of presenting difficult concepts may stimulate the curiosity of the reader. In fact, it was my own doctoral students who suggested I write a book based on my notes for the doctoral course on "Physical Models in Advanced Computing" that I teach, as I had done previously with the notes of an undergraduate course on "Artificial Intelligence." Perhaps this is why the book's layout may seem to be rather unusual, although, in the opinion of the author, this is not entirely a bad thing, as it means the reader can pick and choose chapters in no particular order and still achieve a reasonable understanding of the material.

The book can be used by graduate, postgraduate, and even doctoral students, although I suggest that it would most benefit graduate students—and people suffering from insomnia! The apparent disorganization of this book is not indeliberate. In fact, it took me a long time to properly disorganize the text so as to encourage the reader to embark on reasoning by analogy and also to force them to verify for themselves some of the stranger ideas and approaches described in the book.

The material in this book has been organized into eight chapters. Chapter 1 focuses on "classical bits." Chapter 2 explains "reversibility." Chapter 3 discusses "reversible architectures." Chapter 4 describes basic "quantum mechanics principles." Chapter 5 draws on the material presented in Chaps. 2–4 in order to introduce the "quantum computing paradigm." Chapter 6 discusses "Feynman's universal quantum machine" in depth. Chapter 7 explores key "quantum algorithms." Finally, Chap. 8 poses questions for reflection and discussion. Each chapter concludes with a summary, a glossary of terms, and an explanation of the notation used. Before the bibliography, Appendix A provides some mathematical background, and Appendix B brings together the terms used in each individual chapter in a glossary.

The book begins by asking the following question: what is a bit? This apparently trivial concept is not, in fact, so trivial and we spend several pages thinking about it. We continue with some fundamental and elementary computations with bits in, for example, binary arithmetic and binary logic and describe the implementation of a number of classical operations by means of logic gates. We then introduce the concept of reversible computing in terms of (1) a detailed description of conventional reversible logic gates, (2) a redesign of conventional logic gates so that they are reversible, (3) the construction of a simple reversible adder, (4) a fun example of reversibility, and (5) a brief analysis of the requirements imposed by reversibility. Next comes a more or less formal description of what we call reversible architectures, and we analyze two examples in depth. In one example, a great deal of disorder is generated, and in the other, none. This issue of disorder has important implications for certain phenomena related to the fundamental and basic energy required for an abstract computation. The discussion of reversibility draws greatly on the *Feynman Lectures on Computation*, which, of course, is cited in the Bibliography.

Next, we try to establish a relationship between three essential questions that justify quantum approaches in the computer sciences: (1) the energy required to perform a real-life computation, (2) the size of current processors, and (3) the reversibility of quantum operations. We then offer a historical perspective on the antecedents and basic concepts of quantum mechanics, the conundrum implied by Heisenberg's uncertainty principle for the concept of measurement, and the description of quantum states by means of Schrödinger's equation. This all lays the groundwork for what comes later in the book.

Based on the above concepts, we establish the conditions that justify the use of quantum techniques for certain kinds of computational tasks. Next, we use formal descriptions and formal argumentations—rather than a traditional approach—to introduce key quantum mechanical concepts and approaches. Nevertheless, the mathematical load is minimized as much as possible, and we adopt the axiomatic formulation of quantum mechanics. After a review of certain fundamental preliminary questions, we proceed directly to a description of the quantum unit of information, the definition of certain essential elements in quantum computational approaches, and the introduction of possible physical representations of quantum computational systems. We also describe some fundamental properties of quantum operators, explore the concept of quantum information, and suggest how to build systems capable of handling several quantum bits (or qubits). Finally, we study the problem of the collapse of information associated with the measurement of qubits as a consequence of Heisenberg's uncertainty principle.

The rest of the book is formally different. Whereas the earlier chapters navigated the universe of concepts and ideas, we now enter the world of practical issues and describe the universal quantum architecture proposed by Feynman in detail. We begin with a discussion of a kind of peculiar matrices and show how these rather curious matrices can be used to represent the behavior of reversible logic gates. We also explore the Hamiltonian operator proposed by Feynman for quantum computation. The detailed approach followed here is illustrated with the original Feynman example, analyzed in depth from different points of view.

Having explored the basic concepts and a universal architecture, we next consider some remarkable quantum algorithms. The approach is based on "Quantum Circuit Theory," which, in our opinion, is more easily understood than, for example, the "Adiabatic Computation" approach. We begin with Deutsch's algorithm and its versions, analyzed from several different points of view. We then generalize this algorithm and introduce the Deutsch-Jozsa algorithm. We next explore the algorithm proposed by Simon, developing an alternative, more transparent version. We conclude our description of quantum algorithms with a discussion of quantum teleportation, using spies to illustrate it. We close the circle with something akin to pure speculation, based on developments in 2014 and 2015 in relation to attempts to develop quantum computers. We also refer briefly to thermodynamics, biology, and artificial intelligence and conclude with some thoughts on the material presented in the book.

Just to reiterate—although this book does not contain anything particularly new, it is to be hoped that the reader will find novelty in the way the material is presented. Enjoy!

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