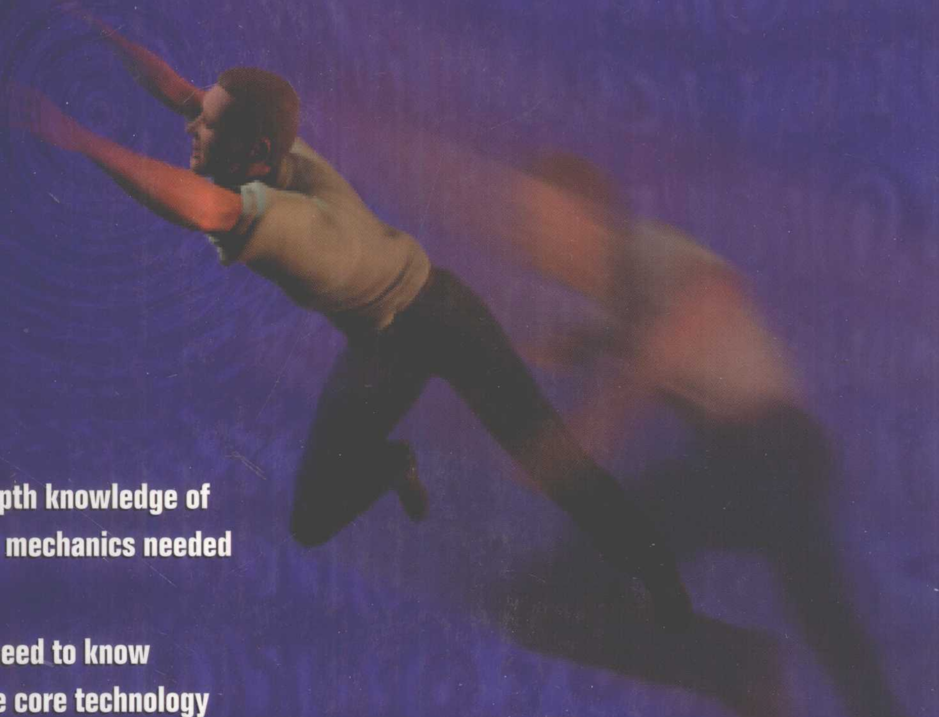
Michael Brooks (Ed.)

Quantum Computing and Communications



- No in-depth knowledge of quantum mechanics needed
- all you need to know about the core technology
- Includes contributions from researchers at: the Los Alamos National Laboratory, the Jet Propulsion Laboratory, IBM, Hewlett-Packard, and more.

Springer

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Preface

We have, in the last few years, radically improved our grasp of the quantum world. Not just intellectually, either: our ability to manipulate real quantum systems has grown in equal measure with our understanding of their fundamental behavior. These two shoots - the intellectual and the practical harnessing of the quantum world - have sprung up at a time when a third shoot - information processing - has also been experiencing explosive growth. These three shoots are now becoming intertwined. Twisted together, our understanding of information processing, quantum theory and practical quantum control make for a strong new growth with enormous potential.

One must always be careful about using the word 'revolutionary' too readily. It is, however, difficult to find another word to describe the developments that have been taking place during the second half of the 1990s. In 1986 Richard Feynman, the visionary professor of physics, made a very interesting remark:

> "...we are going to be even more ridiculous later and consider
> bits written on one atom instead of the present 1011 atoms.
> Such nonsense is very entertaining to professors like me."

It is exceptionally unfortunate that Feynman did not live to see this 'nonsense' fully transformed into reality. He, more than anybody, would enjoy the fact that it is now possible to write information onto an atom, or indeed an ion or a photon. Furthermore, theorists and experimentalists have shown that this information can be processed and transmitted in ways that allow a seemingly absurd degree of power and control over the information. It is now possible to use one quantum particle to influence another particle that it has never met. It is possible to transmit information encoded in a single photon through the air and, on detection, to verify whether that information has been read by anyone else. Experiments are just beginning to string together quantum bits of information that promise massively parallel computing power, far beyond anything that classical machines can manage. In short, we are on the verge of the quantum information revolution.

There could have been no better time for the European Commission to fund a Pathfinder Project in Quantum Computing and Communications* to look into this subject. This Project, which was carried out with the financial support of the Commission, within the frame of the Esprit LTR Working Group 27126 QCEPP, facilitated the gathering and organization of a large amount of useful material about the field; I have freely and extensively used this material in this book. It is reproduced here with the kind permission of the Commission, but it does not necessarily reflect the views of the Commission.

It has been a great privilege for me to spend the last year being so closely involved with the Pathfinder Project. Some of the members of the Project's Working Group have laid the theoretical or experimental foundations in important areas of this field; I have taken great pleasure in working alongside them, and am grateful for all their assistance in drafting parts of this volume. As a journalist I often have to skim the surface of a subject, taking in its essence, but with little time to consider its implications or to examine its fundamental basis. My involvement with the Pathfinder Project has enabled me to investigate this fascinating area to my heart's content, often learning directly from those who have originated the concepts. I am grateful to the European Commission, and to all of the Working Group for their input and advice. However, I take full responsibility for any errors or omissions that have crept into this volume.

Finally, I would like to acknowledge the important role played by Brian Oakley, Chairman of the Pathfinder Project, and Charles Ross, its Honorary Secretary. Without their seemingly boundless energy and enthusiasm, it is likely that little of this material would ever have been gathered.

Michael Brooks, January 1999

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* The term 'Quantum Information Processing' (QIP) is also used to describe Quantum Computing and Communications throughout this book.

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Section I

A Wide Perspective

An examination of the whole field of Quantum Computing and Communications requires some decisions to be taken about where to draw divisions between the various subject areas; the placement of these divisions is a subject that could sustain infinite debate. For the purposes of this volume, the field has been split into four main fields, each covered by a chapter in this section. These four chapters are preceded by an introduction to the subject of quantum information, and are followed by a note on the problems of decoherence.

Chapter 1
Introduction

Michael Brooks

1.1 Exploiting the Quantum World

Civilization has always advanced as people discovered new ways of exploiting various physical resources, such as materials, forces and energies. In the twentieth century, information was added to the list when the invention of computers allowed complex information processing to be performed outside human brains. The history of information technology has involved a sequence of changes from one type of physical realization to another; from gears to relays to valves to transistors to integrated circuits and so on. Now, developments of quantum information processing have reached the stage where one bit of information can be encoded in quantum systems, for example using two different polarizations of light, or two different electronic states of an atom. Matter on this scale obeys the laws of quantum mechanics, which are quite different from the classical laws followed by 'conventional' technologies. If an atom is used as a physical bit then quantum mechanics shows that apart from the two distinct electronic states the atom can be also prepared in a coherent superposition of the two states. This means that the atom is both in state 0 *and* state 1. In general, a quantum two-state system, called a quantum bit or a qubit, can be prepared in a superposition of its two logical states 0 and 1. Thus one qubit can encode at a given moment of time both 0 and 1. Strings of qubits in superposition states can be 'entangled' together to simultaneously encode, in principle at least, vast amounts of information.

Entanglement is one of the distinct properties of quantum systems (together with quantum superposition and probabilistic measurement among others) that makes quantum information processing so different from classical information technology. This phenomenon refers to the joint state of two or more quantum systems and describes correlations between them that are much stronger than any classical correlations. Entangled states offer the possibility to encode information in a completely new way. Let us assume we have two qubits and we want to encode two bits of information. The straightforward approach is to encode one bit of information onto each qubit separately. But using entangled states it is possible to do it in such a way that neither of the two qubits carries any well defined information on its own: all the information is encoded in their joint properties. Entanglement makes possible quantum teleportation, quantum error correction, quantum dense coding, etc. It is closely linked to the issue of non-locality in quantum theory.

This means that quantum technology, potentially, can offer much more than cramming more and more bits on to silicon and multiplying the clock-speed of microprocessors. It can support entirely new kinds of computation with qualitatively new algorithms based on quantum principles. It also offers very significant improvements - in speed, security and quality - in the technologies of information transfer.

Considering quantum computation first, it has been shown that quantum effects could allow the creation of a register of qubits. Such a register composed of three qubits, for example, can simultaneously represent the numbers from binary 000 to binary 111 - i.e. the decimal numbers 0 to 7. Computations performed on these entangled qubits thus have the potential to process simultaneously, offering new and exciting possibilities in information processing.

Algorithms have now been developed which show how quantum computation could lead to enormous advantages over classical computation, accomplishing tasks that are impossible, or impossibly time-consuming, to any classical computer - no matter what its clock speed or processing power. That list of tasks includes code-breaking factorization operations, which makes the development of quantum computation a matter of great importance to any institutions involved with matters of national or financial security. Practical implementation of these ideas is not without its very considerable difficulties and there can be no certainty that it will ever prove possible to build a useful quantum computer. But solutions to existing problems are continually being discovered and analyzed. Whatever the end result, the journey towards the implementation of quantum computation is already yielding valuable spin-off technologies and applications in fields such as communication security.

Entangled qubits are also at the heart of quantum communications, a field whose development is of fundamental interest to financial institutions and national security agencies. Research has demonstrated that measuring the properties of one of a pair of entangled photons would lead to an instantaneous change in the properties of the other half of the entangled pair, however far it was from the measured photon. Development of this work has taken entirely secure communications, using information encoded in entangled photon pairs, to a near-marketable development stage. The use of quantum effects are enabling new and extremely useful techniques to be discovered and implemented.

1.2 Historical Background

The subject of Quantum Information Processing is not new. In one sense the work stems from the recognition of the quantum nature of radiation by Max Planck in 1900, and the equation derived by Erwin Schrödinger in 1926 which provided a mathematical basis for quantum mechanics. This showed that if a quantum system was to operate as a computer it had to be capable of operating reversibly. The history of twentieth century computing, stemming from Turing's work in 1936, is based on a model of a computer that is not reversible. The super-computer of today is essentially of the same nature of machine as the early computers of the 1940s, as is the PC; they differ in memory and operating speed but not in fundamental operations. It has been recognized for many years that they have some practical limitations; for example in not being able to generate a truly random set of numbers; and not being able to perform certain calculations such as those that can be solved for smaller numbers, but at some point become too lengthy for any current or conceivable computer operating on the current classical principals. As the semiconductor switches, on which modern computers are based, have become smaller and smaller, it has become apparent that at some stage, probably within the next 10 to 20 years, the number of atoms in the structures will become so small that the classical laws will have to be replaced by the laws of quantum physics if their behavior is to be understood and predicted.

Perhaps the key breakthrough in quantum computation came in 1973 when Charles Bennett (IBM, Yorktown Heights) showed that a reversible Turing machine was a theoretical possibility. Then, in 1980, Paul Benioff (at that time at Argonne National Laboratory) formulated a reversible Turing machine, which could read, write and shift using quantum mechanical interactions. In 1982, Richard Feynman suggested that a quantum computer could simulate a quantum system efficiently, in a way that no classical computer could. And then, in 1985, David Deutsch (Oxford University) described how the quantum Turing machine might be built, in principle, and how the 'superposition' of 0s and 1s simultaneously led to quantum parallelism. During the 1980s, work was developing on ways of constructing the necessary quantum gates, and then experimental work on a variety of approaches to handling a limited number of quantum bits started in the 1990s. The problem of decoherence seemed to create a practical limitation on the use of quantum information processing, but work at various centers in the 1990s has shown how this might be overcome by error correction techniques. A very considerable boost to the practical interest in the subject came in 1994 when Peter Shor (then at Bell Labs) demonstrated an algorithm which showed how the superpolynomial time process for factorizing a large number on a classical computer could be reduced to an efficient polynomial time process on a quantum computer, a result of considerable interest to the cryptography community.

And amongst the algorithms for quantum computers that followed this breakthrough, Lov Grover developed in 1996 an algorithm that would reduce the time required to find a single item in an unsorted list in the square root of the time