The Physics of Information Technology

The familiar devices that we use to collect, transform, transmit, and interact with electronic information operate surprisingly close to very many fundamental physical limits. A handheld GPS receiver requires special and general relativistic corrections to the time reported by the system's atomic clocks; the typical distance between air molecules in a hard disk drive is larger than the height that the head flies above the platter; the linewidth in a VLSI circuit is approaching the size of a single atom; the performance of satellite receivers is limited by the echo of the Big Bang.

Given the economic and intellectual importance of these scaling limits, surprisingly few people are equipped to address them. Understanding how such devices work, and how they can (and cannot) be improved, requires deep insight into the character of physical law as well as engineering practice. *The Physics of Information Technology* provides this needed connection by introducing underlying governing equations and then deriving operational device principles. This self-contained volume will help both physical scientists and computer scientists see beyond the conventional division between hardware and software to understand the implications of physical theory for information manipulation. It is at this interface that many of the most dramatic advances in both domains are occurring.

The book starts with an introduction to units, forces, and the probabilistic foundations of noise and signalling, then progresses through the electromagnetics of wired and wireless communications, and the quantum mechanics of electronic, optical, and magnetic materials, to discussions of mechanisms for computation, storage, sensing, and display. Attention is drawn throughout to the remarkable opportunities associated with more closely integrating the physical and logical descriptions of classical and quantum information.

This textbook will be useful for advanced undergraduates and graduate students in physics, computer science, and electrical engineering, but its unique scope will also make it a handy reference and guide for working scientists, engineers, and technical leaders.

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Academic and industrial research has separated the description of the information in a system from its physical properties, but many of today's most compelling opportunities and obstacles lie right at this interface. From controlling the coherent dynamics of atomic nuclei to compute beyond the scaling limits of integrated circuits, to programming the expression of genetic sequences to fabricate nanostructures, evolutionary technological progress has brought us to a revolutionary integration of the most profound physical theories with their practical application in systems that detect, transform, and deliver information. This series bridges the historical gulf between the fundamental enabling research and the domain-specific description of its engineering application through studies by leading researchers of both the theory and practice in these emerging fields.

The Physics of Information Technology

Neil Gershenfeld

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for JOEL, who showed me the value of creating things
and for ALAN, who showed me the value of fixing them

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Preface

How does the bandwidth of a telephone line relate to the bit rate that can be sent through it? Modems keep getting faster; how quickly can they operate? These sensible questions have unexpectedly profound answers. At MIT, I've been asked them by people ranging from undergrads to faculty. A good engineer might know about coding theory and the concept of channel capacity, but not understand the origin of the noise that limits the capacity. Conversely, a physicist might use the fluctuation–dissipation theorem to explain why resistors are necessarily noisy, but know nothing of information theory. And the computer scientist sending data over the phone line might not understand either side. The most interesting aspects of this problem can easily be missed among these poles. I've found this pattern to recur over and over: people may not appreciate the useful applications of fundamental results in the devices they use, or the deep implications of their practical knowledge, and may not have a good sense of how their formal academic training can relate to their personal passions.

The familiar computing and communications devices that we use to manipulate information operate near many remarkable physical limits. A handheld GPS receiver applies both special- and general-relativistic corrections to its timing measurements of signals from atomic clocks in satellites in order to maintain the system's global 1 ns accuracy. The head in a high-capacity disk drive flies within a single mean-free-path of an air molecule above the platter, and so the aerodynamic design problem can no longer be solved by modeling the airflow with continuum partial differential equations. This kind of tremendous ingenuity has gone into finding practical solutions to what had appeared to be impossible technological problems. However, the exponential improvements that we've come to rely on, such as processor speeds doubling every few years, must stop when current scaling trends run into basic physical limits. Circuits cannot have wires smaller than atoms, signals faster than light, or charge carriers less than an electron. Given such constraints, a CMOS chip that can perform 10^9 floating-point operations per second (a gigaflop) is feasible, but 10^{12} (a teraflop) is unlikely. Understanding these kinds of systems requires equal familiarity with fundamental physics and with very practical engineering. Because this kind of background is hard to develop given the traditional split between basic and applied science, it's easy for students (and practitioners) to run into either the Scylla of uncritically accepting the received wisdom of past practice, or the Charybdis of enthusiastically pursuing impossible alternatives.

This book grew out of lecture notes for a course that I've developed at MIT's Media Lab. The goal is to review basic physical governing equations in a number of areas relevant to information technology, and then work up through device mechanisms to a

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quantitative examination of practical implementations. There is a companion course called *The Nature of Mathematical Modeling* that studies the possible levels of description for mathematical modeling; these can loosely be summarized as covering the rules for the logical worlds inside computers and the physical world outside them. The breadth of research at the Media Lab, coupled with the strong scientific background and personal interests of many of the students, has provided a fertile environment for me to attempt this kind of synthesis. Because there was no suitable text for such a course I started by writing lecture notes for myself to teach from, then began handing these out in response to student requests, then put them on the computer when the students couldn't read them, and eventually they grew into this book. I hope that my presumption in covering so many important areas in such a limited space is justified by the value of covering so many important areas in such a limited space.

I've taken the liberty to broadly define "physics" to mean a number of branches of physical science and the supporting mathematics, and "information technology" to cover many kinds of systems that detect, transmit, transform, store, and deliver information. The breadth of subjects covered necessitates sacrificing some detail. And although the text is self-contained, the quick review of basic governing equations such as Maxwell's equations implicitly assumes some previous familiarity. I've tried to balance these demands by including enough background to introduce the key ideas in each section, and then providing pointers to equip the interested reader to access the specialized literature as needed. Particularly useful references are given at the end of each chapter. Wherever possible, I've tried to gather together the kind of information that I routinely use but regularly need to look up.

Any mathematical techniques that might not be familiar are covered in [Gershenfeld, 1999a], and the implications and applications of these technologies are explored in [Gershenfeld, 1999b]. Of these books, this one was started first and finished last because of the challenge of including enough depth to explain any one area and enough breadth to follow rapidly advancing developments. Throughout, I've tried to abstract the timeless principles that are as applicable to string telephones as to quantum teleporters.

I am deeply grateful to the Media Lab for the opportunity to prepare and teach this material, to the great students who suffered through drafts that have ranged from incomplete to incorrect, to the valuable feedback from my many readers, to Susan Murphy-Bottari for the cheerful efficiency with which she handles the unreasonable demands of overly ambitious projects, and to the many Media Lab sponsors for their generous support of, and participation in, the research that lies behind and ahead of this book.

Cambridge, MA
March, 2000

Neil Gershenfeld