# Computer Storage Systems and Technology

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**Richard E. Matick**

*International Business Machines*
*Yorktown Heights, New York*

**A Wiley-Interscience Publication**
**JOHN WILEY & SONS**
**New York • London • Sydney • Toronto**

**Library of Congress Cataloging in Publication Data**

Matick, Richard E. 1933-
Computer storage systems and technology.

"A Wiley-Interscience publication."
Bibliography: p.
Includes index.
1. Computer storage devices. 2. File organization (Computer science) 3. Data structures (Computer science) I. Title.

TK7895.M4M37 621.3819'533 77-5812
ISBN 0-471-57629-8

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

# Preface

Since the inception of the modern computer in the late 1940s, computing systems have continually grown in complexity, both in hardware and in the associated systems programming. This complexity is by and large due to two factors: first, the tradeoffs in cost/performance versus size for various memory technologies, and second, the way human beings organize and use data. If technology could produce an infinitely fast, infinitely large, random access memory at a low cost, many of the problems faced by systems designers would disappear. There would be no need for memory hierarchies, virtual systems, or storage management. In addition, technology could be aimed at producing only one type of memory (i.e., random access), rather than a seemingly infinite variety of memory designs, each with its own advantages and disadvantages. Unfortunately it is not possible to make this ideal random access memory, and there will always be a spectrum of memory systems having varying cost/performance characteristics and different sizes. Thus memory presents an interesting and difficult challenge to designers, not only technologically but from the entire perspective of a memory–storage system.

This book, which confronts the challenge just noted, has grown out of a series of courses taught at the University of Colorado at Boulder, Stanford University, and various IBM locations. The students' backgrounds have ranged from sophomores, juniors, seniors, and graduate students, to engineers, programmers, physicists, metallurgists, and others. As a result, the book is organized as a textbook, although it is intended also for self-study and as a reference for those working in this or related areas. This book requires general familiarity with computers, preferably some courses on programming, computer logic, and introductory computer science or computer architecture. Certain sections assume some physics, device, or circuit background, although those not so oriented should be able to grasp the essential points with little difficulty.

The book is written in terms of the fundamentals as nearly as possible. In many cases, the fundamentals had to be articulated, if not discovered, since there appear to have been no previous attempts to establish the fundamental requirements for storage devices, organization, writing, retrieval, and so on. Thus after having worked in the field for more than 15 years, I realized that the area has never received a comprehensive fundamental treatment, and I have attempted to rectify the situation.

This book has two main purposes: first, to bring together all related aspects of computer storage systems and technology in one volume, and second, to relate the various aspects of data structure and usage to the hardware design and tradeoffs. There are several reasons for undertaking this task; first, if one wishes to learn about computer memory and storage, it is necessary to search through countless books, papers, and scattered literature. Even then many significant gaps exist. In addition, there are sharp distinctions drawn in practice between main memory, storage, mass storage, data structuring and file organization, memory hierarchy, virtual systems, and other aspects of a complex system. In the past, these distinctions also established the boundaries between technologies (i.e., magnetic cores, magnetic disks, tapes, etc.). However these boundaries are becoming less clear, particularly in the new advanced technologies being considered for memory and storage. It is not certain, for instance, whether an advanced technology such as magnetic bubbles is useful strictly for storage or memory, or whether it is applicable at some point in between within the file gap. Even less advanced technologies such as transistorized integrated circuits are currently used in memory and are being studied for large backup storage. Furthermore, the size of main memory in use on third and fourth generation systems today exceeds that of "storage" used on older first and second generation systems. Thus these boundaries are not only arbitrary and unnecessary, but they promote misunderstanding of the overall problems, such as similarity and tradeoffs between memory technologies and the relationship between the way in which people use data and the possible means of storing and retrieving data usefully and economically. When all these topics are covered in one volume, the hardware designer can better understand not only other technologies but also the relationship of the overall systems and programming problems to the technology at hand. In a like manner, the systems or machine level applications programmer can acquire a deeper understanding and broader perspective of the various technology tradeoffs and how they relate to data storage and retrieval requirements.

The major technology problem in computing systems today lies mainly in providing large, fast, inexpensive storage. The CPU itself is no longer the major problem, since there are ways to achieve faster logic; but the directions for memory and storage are less clear. Much of what systems programmers do is a result of the large discrepancies between speed, size, and cost of the various storage technologies. Programming systems expend considerable effort to bridge and smooth the gaps that technology has not been able to eliminate at a competitive cost; that is, it is cheaper to bridge gaps with programming and system architecture rather than new intermediate technologies. How long or how far this can be done is an important question that is not considered in this book; only the marketplace can provide an answer.

This book is interdisciplinary to the extent that it deals with the various disciplines that are directly related to storage. It is a further aim to permit the scientist to acquire a fundamental understanding of memory, to be better able to see where new inventions, discoveries, or understanding may be useful in this field, which needs new ideas continuously.

Chapter 1 presents a brief history of memory storage technology to show the speed gap between the CPU and main memory, how we arrived at the present state of the art, and why storage systems are important. The various memory systems and cost/performance gaps are covered briefly, to show a very wide range. Several sections are devoted to relationships between the main memory and CPU (e.g., the connection between CPU and memory clocking period in terms of an instruction execution period). A study of the size of main memory versus the speed of the CPU has revealed some important relationships and "universal constants" that have not previously been recognized. The effects of limited storage capacity on the problem size is treated in a separate section. Some current requirements for storage both in scientific and commercial data processing are included, as well as some future hardware needs for weather forecasting. An important question often asked but hitherto not answered is, With the advent of large-scale integration of memory devices, why can't we just make the entire storage system a random access memory? A fundamental treatment of this question in terms of the size of random access memory relative to the number of logic gates in the central processor is presented in a separate section, along with the concept of the one level store. A brief discussion of the human memory system reveals a number of very interesting relationships to a computer memory hierarchy. Chapter 1 thus places the entire storage area into perspective and sets the stage for the remainder of the book.

Chapter 2 presents the fundamental device and system requirements for storing and retrieving information as well as the fundamental differences and similarities between storage systems of various types (random access, sequential, etc.). The important engineering fundamentals that are applicable on a general scale to memory design are included in the areas of magnetism and magnetic circuits, semiconductor technology, superconductivity (including the Josephson effect), and certain electrical properties of array conductors. There is a separate section on the "ultimate" limits on storage density.

Chapter 3 focuses on the principles of operation, characteristics, and design of the major cells and devices that have been implemented in either commercial or experimental random access memories. Included are ferrite cores, thin films, junction and field effect transistors, superconducting cells, ferroelectric cells, and read-only memory devices. Important design parameter and tradeoffs are presented.

Chapter 4 covers random access memory systems with particular emphasis on the advantages and disadvantages of various types of organization. It discusses design principles, important parameters, and organization methods, as well as limitations of magnetic cores, thin films, and transistor and other memories. A section on associative memory is included.

Chapter 5, which is devoted to magnetic recording principles, serves as a stepping stone to Chapters 6 and 7. Chapter 5 covers the basic principles associated with all digital magnetic recording techniques, as well as materials and systems parameters. Chapter 6 consists mainly of a discussion of magnetic tape and related systems; Chapter 7 covers disks, drums, and related systems. Although a significant amount of technology is worked into these two chapters, the basic problems of addressing and retrieving information, including the amount of "stored addressing" information; are considered in detail. The importance of this factor is often overlooked, yet it represents a fundamental tradeoff in achieving low cost at the expense of nonlocal, nonrandom access of data.

Chapter 8 reviews file organization techniques and the major difficulties as related to storage systems (e.g., disks and tapes). The reader is led through several fundamental examples to explore the various ways a given file might be organized, with the tradeoffs in terms of storage space, access time, and ability to insert and delete records.

Chapter 9 is a fundamental discussion of memory hierarchy systems and storage system architecture. Particular attention is given to virtual memory, including cache, showing the tradeoffs in buffer size, page size, and replacement algorithms, in addition to the design concepts that are possible. Examples of commercial systems are discussed in terms of the fundamental requirements. This chapter is unlike any other book dealing with virtual memory and should be of interest to memory system designers as well as to systems programmers.

This book was originally written by pulling together all the aspects of memory and storage that I considered important. In addition to more details and other topics, this included a chapter on advanced concepts for shift register storage, including magnetic bubbles, charge coupled semiconductor devices, beam-addressed storage, and dynamic reordering for improved access time. Unfortunately, this would have resulted in an enormous book with additional delays and hence were removed. A brief discussion of shift register storage with numerous references can be found in Matick (1975).

An earnest attempt has been made to keep this book at a fundamental level and dissociated from any particular computer organization or design. However this is not always possible, and specific examples sometimes relate to one type of organization. When this occurs, the type of organization assumed is specifically indicated to prevent any misconceptions from arising. This fundamental approach avoids the common pitfall of introducing a subject by describing the typical commercial implementation. Rather—the fundamental requirements for any system or part of a system are first established; then typical examples are described in terms of implementing the fundamentals. This is a major departure from the approach of other books dealing with related subjects.

RICHARD E. MATICK

*Peekskill, New York*

*April 1977*

# Acknowledgments

Many persons have contributed to this book in various ways, and their efforts are most sincerely appreciated.

I am especially indebted to Ralph Gomory, IBM Vice-President and Director of Research, for providing me the opportunity for a teaching sabbatical in 1972–1973. It was during this time that I formulated the basic subject matter of this book and decided how it was to be organized. No less a debt of gratitude is due to William Turner, who in early 1972, having learned of my impending teaching sabbatical, planted the idea of a book.

Frank Barnes, Chairman of the Department of Electrical Engineering, University of Colorado, Boulder, gave me the opportunity to teach two courses on which much of this book is based. My first students, Barbara Langdon, Tom Burrows, Ching Tuan, Kent Weldon, Clarence Ellis, Doug Johnson, Van Norred, Lee Ware, Paul Williams, and Ted Hommel, deserve special thanks for their interest and suggestions. There were many subsequent students at Stanford University, IBM, and elsewhere, too numerous to include.

The enthusiasm of one student, Hjalmer Ottesen of IBM Boulder, who continued the courses I had initiated at IBM and the University of Colorado was a source of inspiration to me.

The typing assistance of Barbara Juliano over the past three years has been above and beyond the call of duty. Without her skill and dedication, this effort would have been formidable. The drafting skills of Sally Bradford, who did most of the complex drawings, has substantially aided in communicating such a complex subject. The understanding and willingness to help on the part of Linda Callahan, Louis Kristianson, Mary LaMarre, Bob Monahon, and many others is sincerely appreciated.

An internal company text on magnetic recording by Jim Smith has been of considerable value in certain parts of Chapter 5. Countless individuals have helped over the years, and I acknowledge these efforts as being the small epsilons whose summation amounts to a large value.

I hope that this book can serve as an example for future books dealing with memory and storage, in terms of demonstrating a more fundamental approach, as well as inclusion of all aspects of memory systems.

My wife, Doris, and our children, Lisa and Jill, have been most sympathetic during this rather long and tedious undertaking.

R. E. M.

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