Health Informatics

Morris F. Collen
Marion J. Ball *Editors*

The History of Medical Informatics in the United States

Second Edition

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Health Informatics

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Morris F. Collen • Marion J. Ball
Editors

The History of Medical Informatics in the United States

Springer

Editors
Morris F. Collen (deceased)

Marion J. Ball
IBM Research
Baltimore, MD, USA

Johns Hopkins University
Baltimore, MD, USA

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To the future of informatics and its evolving branches

Foreword I

How often does a person envision a new medical discipline and then live to see this vision come into reality? He not only practiced his discipline, he established professional associations to promote it, and he mentored generations of practitioners. As a result of his pioneering efforts, we now have a field of clinical informatics. Information and communication technology is now used to improve health and healthcare in our hospitals, our clinicians' offices, our places of work, our schools, and our homes. Physicians and nurses now train in clinical informatics, and physicians can be board certified in what has become a new subspecialty.

One year ago, we celebrated Dr. Collen's 100th birthday near his home in San Francisco. Luminaries from the field of clinical informatics and health service research came to reflect on their interactions with this great man and to celebrate the field he grandfathered. After a day of celebrations, Dr. Collen delivered a 20-minute talk that was insightful, modest, and caring.

The story of his life and work has been well told, by Howard Bleich at the time of his 80th birthday, by Jochen Moehr on his 90th, and by Donald Lindberg and Marion Ball on his 100th birthday. Published in *MD Computing* (1994;11(3):136–139), the *Journal of the American Medical Informatics Association* (2003;10(6):613–615), and *Methods of Information in Medicine* (2013;52(5):371–373), these accounts stand as tributes to the man identified as "pioneer in computerized medicine" in his obituary in *The New York Times* of October 5, 2014.

This book, the second edition of *A History of Medical Informatics in the United States*, is not only a labor of Dr. Collen's love for our field but is also a comprehensive updating of his original work, first published in 1995. The same luminaries who gathered to celebrate his life came forward to help to update, edit, and revise the manuscript he left behind. Like the original, it serves as an invaluable resource documenting the infrastructure that is transforming care delivery in the twenty-first century. Dr. Collen's book will serve as a reminder to future generations of the important contributions of this wonderful clinician, mentor, and gentleman.

2014 Recipient of the Morris F. Collen Award Charles Safran
Professor of Medicine, Harvard Medical School
Boston, MA, USA

Foreword II

Morris F. Collen, MD, developed his groundbreaking contributions to medical informatics amid the fertile environment of Kaiser Permanente, one of the nation's first and most renowned integrated healthcare systems. As one of the founding partners of The Permanente Medical Group, now the largest medical group in the United States, Morrie championed the principle that physicians should manage healthcare for both individual patients and large populations. He and the organization's other founders weathered controversy during the 1940s and 1950s for their beliefs. Today, the concepts of prepayment for services, comprehensive electronic medical records, and an emphasis on preventive care have been widely embraced throughout the country.

Morrie's approach to medical informatics was informed by his work as a physician providing medical care to a socioeconomically diverse group of patients. During World War II, he treated thousands of workers in the Richmond shipyards, and he later served as the physician-in-chief of Kaiser Permanente's San Francisco medical center. He related that in the late 1950s, the leader of The Permanente Medical Group, Sidney R. Garfield, MD, thought that the time had come for computers to be useful in the practice of medicine and dispatched him to figure out how.

Inspired by a major conference on medical electronics in New York in 1960, Morrie founded the group that became the Division of Research in Kaiser Permanente's Northern California region. He began to collect medical information on patients via new multiphasic preventive examinations and entered the data into a mainframe computer – using punch cards. This work and the information obtained led to major improvements in medical practice decades ahead of the rest of healthcare. Since that era, the Division of Research has grown into an internationally respected group of researchers who continue to use informatics in hundreds of ongoing studies to identify the drivers of health and disease and to find innovative ways to enhance healthcare.

This book reflects Morrie's visionary leadership as well as the dedication of his many colleagues, especially his beloved editor, Marion Ball, EdD. At a time when the most advanced computers had less power than a watch today, he saw what was possible and the ultimate potential for big data to revolutionize medical care. In sharing ways we can harness information to take better care of patients in real-world settings, this work stands as a beacon on the path to better healthcare for modern society.

Director of the Division of Research Tracy Lieu
Kaiser Permanente Northern California
Oakland, CA, USA

Executive Director and CEO, The Permanente Medical Group Robert Pearl
Kaiser Permanente, Oakland, CA, USA

Preface

This volume is the legacy of Morris F. Collen, a vital force in medical informatics in the United States since its birth. In the last years of his life, up until his death at age 100 in September 2014, Dr. Collen – Morrie to many of us – worked every day to update his *History of Medical Informatics in the United States*, published in 1995. In the original edition, Morrie compiled a meticulously detailed chronological record of significant events in the history of medical informatics and their impact on direct patient care and clinical research. His intent was to offer a representative sampling of published contributions to the field; his vision was that this would serve as a useful bridge between medical informatics of the past and of the future.

As he revised his *History*, Morrie restructured the book, replacing the original seven chapters with eighteen to reflect the transformation medical informatics had undergone in the years since 1990. The systems that were once exclusively institutionally driven – hospital, multihospital, and outpatient information systems – are today joined by systems that are driven by clinical subspecialties, nursing, pathology, clinical laboratory, pharmacy, imaging, and more. At the core is the person – not the clinician, not the institution – whose health all these systems are designed to serve, a foundational belief that guided Morrie throughout his career, from his early work with multiphasic health testing, with the computer-based patient record at the height of his career, and finally to the completion of this new *History*.

Of course he knew that time was not on his side and enlisted me to help. He worked on the manuscript each day, and we spoke every evening by telephone. The review was exacting, adding new material was time-consuming, and in the summer before Morrie died, he asked me to assume control of the project and do what needed to be done to see the *History* into print when he was no longer here. I realized this was a daunting task with an ambitious goal, and, upon his death, I asked his colleagues, the medical informatics community, for help.

Nineteen informaticians, whose names appear on the chapters in the finished book, agreed to help. Most of them had known him for years. Several had been leaders, along with Morrie, when the field was in its infancy, not yet named; others met him and worked with him as the field grew and matured; and a lucky few claimed him as their mentor. Recognized leaders in medical informatics today (and many of them recipients of the Morris F. Collen Award in Medical Informatics), they carefully reviewed the draft chapters, editing and updating the material Morrie left behind. They gave of their time and expertise to bring Morrie's work to completion – a task that proved more difficult than I and my colleagues had initially imagined.

The chapters in the manuscript Morrie left behind were in different states of completion and posed different challenges. Some colleagues edited chapters that Morrie had spent considerable time revising; their task, as they saw it, was to do a final edit on his behalf, smoothing or restructuring for clarity and, in some instances, adding to and commenting on Morrie's text. Other colleagues took on chapters that Morrie was in the midst of revising; for them, the challenge was to add their insights to Morrie's while maintaining his vision. And three colleagues contributed the chapter on imaging that Morrie had planned but not yet developed. All their efforts honor Morrie and serve the field. To them I owe heartfelt thanks.

Like the field of medical informatics it describes, this new *History* reflects the changes made possible by information technology. Like the earlier version that sits on bookshelves around the country, it is available as a hardcover book. Comprehensive in its coverage, it preserves much of the history recounted in the first edition – history now growing ever more distant and difficult to trace. This new *History* provides an unrivaled repository of the literature – much of it in hard-to-locate proceedings and reports from professional and industry groups – that guided informatics as it matured. Yet it is much more than a repository. It sets forth Morrie's last assessments of the field he pioneered and cultivated, and it is enriched by the contributions of his colleagues who reviewed his chapters and helped bring this volume to completion. Always collegial, Morrie himself would welcome these new perspectives on the work that engaged him so completely up to the end of his life.

Mirroring the advances in healthcare computing it describes, this new *History* is available as an e-book in its entirety or as individual chapters. Morrie prepared each chapter to be complete unto itself, including all the information the reader needed to understand the area covered. A quick chapter-by-chapter guide to the concepts and topics discussed in this richly detailed book appears below. For readers, Morrie's approach and the guide mean quick and easy access to specific material when they first seek it. Once downloaded, it can remain readily available, retrievable by a mouse click or finger swipe. To all those who look to the evolving field of informatics for tools and approaches to providing healthcare that is efficient, effective, evidence-based, and of the highest quality possible, this is Morrie's gift.

Marion J. Ball

A Brief Overview of Concepts and Topics

The short summaries below provide an overview of the material covered in this lengthy and comprehensive volume:

Chapter 1 The Development of Digital Computers

A multi-decade perspective on the evolution of computers, operating systems, and programming languages; workstations and other interface devices; communication technologies, networks, and databases in society and specifically in healthcare.

Chapter 2 The Creation of a New Discipline

Medical informatics as a distinct field, the origin of the term itself, and the various nuances of the discipline as it has taken shape over the past six decades, with attention to roles played by publications, professional organizations, industry, academia, and government.

Chapter 3 Development of Medical Information Systems (MISs)

Medical information systems, their scope, different architectural and developmental approaches, the role of textual and non-textual data, the databases they require, the role of standards, and the use of natural language processing for textual data.

Chapter 4 Medical Databases and Patient Record Systems

Data for medical information systems; electronic patient records and the expanded electronic health record; the evolution from separate databases to more integrated models; and their role in capturing information for care, making it available in a timely fashion and affecting the care process.

Chapter 5 Outpatient Information Systems (OISs) for Ambulatory Care

Information system capabilities for patients outside of the hospital; priorities, requirements, and design implications, with emphasis on patient identification and record linkage, on capturing patient history and physician examination data; also telemedicine and mobile healthcare.

Chapter 6 The Early History of Hospital Information Systems

Early hospital information systems and the external factors influencing their development, with descriptions of early systems; admission, discharge, and transfer systems and the evolution of concept sharing during development; and functional requirements and technical designs.

Chapter 7 Nursing Informatics: Past, Present, and Future

Evolution from terminals and workstations at nursing stations to point of care devices; order entry, staffing, and scheduling functions; systems for patient classification, quality assurance, care planning, decision support, nursing education and research; nursing informatics as a specialty.

Chapter 8 Specialized High-Intensity Clinical Settings: A Brief Review

Early development of specialized systems for intensive care units and emergency departments; current status and interoperability challenges arising from incompatible equipment for intensive care and the exchange of patient information between emergency department and other settings.

Chapter 9 Information Systems for Clinical Subspecialties

Functional and technical requirements for various medical subspecialties and the development of systems to support their differing needs, focusing primarily on internal medicine, surgery, obstetrics/gynecology, pediatrics, and mental health subspecialties.

Chapter 10 Multi-Hospital Information Systems (MHISs)

Added requirements as healthcare organizations formed alliances and acquired hospitals and practices; the need for translation among databases; evolution of multi-hospital information systems in the Federal sector (Veterans Administration, Department of Defense), mental health, and commercial sector.

Chapter 11 Clinical Support Information Systems (CSISs)

Development of systems to address internal scheduling, workflow processing, and material handling of the clinical laboratory, pathology department, pharmacy, and imaging; their function to produce results available to the physician and integrated into the electronic medical record.

Chapter 12 Clinical Laboratory (LAB) Information Systems

Requirements for specimen processing and analysis, their early evolution and evaluation; special characteristics of lab subsystems for chemistry, hematology, microbiology, and other specialized analyses; developments in result and interpretive analysis reporting.

Chapter 13 Anatomic Pathology Information Laboratory Information Systems and Natural Language Processing: Early History

Development of systems for specimen management and interpretation in anatomic pathology and its subareas, of coding systems and systematized nomenclature, and of natural language processing (NLP) for extraction of findings from narrative reports; later work on image processing and telepathology.

Chapter 14 Pharmacy Information (PHARM) Systems

Requirements for pharmacy information management; the development of systems to support it, including identification and surveillance of adverse drug events and polypharmacy; and the development of systems for pharmacotherapy.

Chapter 15 Imaging Information Systems

Early emphasis on scheduling, workflow, etc.; advances in digital imaging, including Picture Archiving and Communication Systems (PACS), and digital image interpretation workstations; coding, structured input methods, the incorporation of voice dictation, and distribution of image-enhanced reports.

Chapter 16 Public and Personal Health Testing Systems

Systems for public and personal health testing; public health monitoring; multiphasic health testing and systems to automate it and the integration of those functions into the electronic patient record; development of advanced biosurveillance systems and public health informatics.

Chapter 17 Decision Support Systems

Evolution of tools and knowledge bases for decision support, administrative and quality management, and clinical decision making; the National Library of Medicine as a major resource provider; development of methods for data mining, data analytics, and knowledge discovery.

Chapter 18 Medical Informatics: Past and Future

Analysis of the past six decades; projections for the next decade, including transforming trends: an aging population with multiple diseases and polypharmacy; mHealth and personal biosensors; patient genotyping; cloud computing and big data; patient data security; public health in disaster scenarios.

Robert A. Greenes
Judith V. Douglas
Marion J. Ball

Acknowledgments

Let me open by thanking the most important person of all, Morris F. Collen, who would first thank his late wife Bobbie, who persuaded him to enter the field of medicine. This was and is his book, even after so many others have helped to complete it. Honored for his pioneering work in medical informatics, Morrie is remembered as well for his generosity of spirit and would join with me in thanking all those I mention below for help in bringing this volume to publication.

Kaiser Permanente, Morrie's professional home throughout his career and his long and productive retirement, continued their support for his work even after his death. Their unwavering commitment to seeing his new *History* into print never wavered and kept me on course. My heartfelt thanks go to Lincoln Cushing, Archivist, Kaiser Permanente Heritage Resources; Bryan Culp, Archivist Emeritus; Tracy Lieu, Director, and Joe Selby, Gary Friedman, and Ted Van Brunt, former Directors of the Kaiser Permanente Division of Research; Joe Terdiman and Jamila Gul, who worked with Morrie in Research; Brenda Cooke and Marlene Rozofsky Rogers, the Research librarians upon whom Morrie relied; and Morrie's many colleagues and friends in the Division of Research. I am also deeply grateful to Robert Pearl, Executive Director and CEO; Francis J. Crosson, Sharon Levine, Phil Madvig, and Holly Ruehlin, of The Permanente Medical Group, for their unflagging support of Morrie's work; and to the Board of Directors and Executive Staff of The Permanente Medical Group for their consistent and ongoing support of the Morris F. Collen Research Award since 2003.

I owe a tremendous debt to all my colleagues from the world of informatics whose names appear elsewhere in this volume, alongside the chapters they completed. Several among them did still more. Bob Greenes served as my adviser throughout, looking at the overall structure of the book; preparing the short descriptions of each chapter that appear elsewhere in the front matter; recruiting two eminent colleagues, Brad Erickson and Ron Arenson, to join with him in authoring the one completely new chapter on imaging that Morrie had envisioned; and taking Morrie's vision forward in the final chapter of the book. John Silva helped recruit Mike Becich, who in turn enlisted Alexis Carter; and Harold Lehmann helped bring on Bob Miller and involve Anne Seymour in the project.

At the Johns Hopkins University, Anne Seymour, Director of the Welch Medical Library, and Associate Director Stella Seal committed valuable staff time to complete the reference work for this volume. Associate Director and Senior Reference Specialist Ivy Linwood Garner served as lead, together with Reference Specialists Christopher Henry and Vivian McCall.

Charles Ball, Debbie Ball, Alex Ball, and Ryan Ball located materials for Morrie and brought them to him to use in his research. Evelyn Graetz and Rabbi Robert Graetz of Temple Isaiah helped Morrie every day, and Vicki Shambaugh of the Pacific Health Research and Education Institute urged him on. Randall Collen, Morrie's son, and John Ball, my husband, offered continued belief in this project, and Matthew Douglas, Judy Douglas's son, helped check citations and prepare the materials that appear at the back of the book.

I would like to thank Grant Weston at Springer, who unstintingly supported Morrie over the last few years, encouraging him to complete *Computer Medical Databases* in 2012 and agreeing to see this new *History of Medical Informatics* through the publication process after Morrie's death.

Finally, I want to acknowledge Judy Douglas, who has spent the last six months almost full time working with all of the contributing editors and coauthors as well as with the Johns Hopkins Welch Medical Library staff to bring this work to fruition. Years ago, Judy helped Morrie and me bring *Aspects of the Computer-Based Patient Record* (Springer, 1992) to publication. That experience and Judy's memory of reading the first edition of *The History of Medical Informatics in the United States* when it was still in manuscript form made her determined to make this new edition measure up to the first – and to the standards of excellence that characterized Morrie professionally and personally.

Marion J. Ball

Contents

Contributors

Ronald L. Arenson, M.D. Department of Radiology and Biomedical Imaging, University of California, San Francisco, CA, USA

Marion J. Ball, Ed.D. IBM Research, Baltimore, MD, USA

Johns Hopkins University, Baltimore, MD, USA

Howard L. Bleich, M.D. Harvard Medical School, Division of Clinical Informatics, Department of Medicine, Beth Israel Deaconess Medical Center, Brookline, MA, USA

Michael J. Becich, M.D., Ph.D. Department of Biomedical Informatics, University of Pittsburgh School of Medicine, Pittsburgh, PA, USA

Alexis B. Carter, M.D., F.C.A.P., F.A.S.C.P. Department of Pathology and Laboratory Medicine, Emory University, Atlanta, GA, USA

Morris F. Collen, B.E.E., M.D., D.Sc. (Hon) Author was deceased at the time of publication

Don Eugene Detmer, M.D., M.A. Department of Public Health Sciences, University of Virginia, Charlottesville, VA, USA

Bradley James Erickson, M.D., Ph.D. Department of Radiology, Mayo Clinic, Rochester, MN, USA

Robert A. Greenes, M.D., Ph.D. Arizona State University, Tempe, AZ, USA

Department of Biomedical Informatics, Mayo Clinic, Rochester, MN, USA

W. Ed Hammond Duke Center for Health Informatics, Duke University, Durham, NC, USA

Casimir A. Kulikowski, Ph.D. Department of Computer Science Hill Center, Rutgers University, Piscataway, NJ, USA

Harold P. Lehmann, M.D., Ph.D. Division of Health Sciences Informatics, Johns Hopkins School of Medicine, Baltimore, MD, USA

Nancy M. Lorenzi, Ph.D., M.A., M.S. School of Medicine, Department of Biomedical Informatics, School of Nursing, Vanderbilt University, Medical Center, Nashville, TN, USA

Alexa T. McCray Center for Biomedical Informatics, Harvard Medical School, Boston, MA, USA

Randolph A. Miller, M.D. Department of Biomedical Informatics, School of Medicine, Vanderbilt University Medical Center, Nashville, TN, USA

Robert E. Miller, M.D. Departments of Pathology and Biomedical Engineering, Division of Health Sciences Informatics, Johns Hopkins University School of Medicine, Baltimore, MD, USA

Department of Health Policy and Management, Bloomberg School of Public Health, Johns Hopkins University, Baltimore, MD, USA

Stuart J. Nelson, M.D., F.A.C.P., F.A.C.M.I. Health Sciences Library and Informatics Center, University of New Mexico, Albuquerque, AZ, USA

John S. Silva, M.D., F.A.C.M.I. Silva Consulting Services, LLC, Eldersburg, MD, USA

Edward H. Shortliffe, M.D., Ph.D. Arizona State University, Phoenix, AZ, USA

Columbia University, New York, NY, USA

Weill Cornell Medical College, New York, NY, USA

New York Academy of Medicine, New York, NY, USA

Warner V. Slack, M.D. Harvard Medical School, Division of Clinical Informatics, Department of Medicine, Beth Israel Deaconess Medical Center, Brookline, MA, USA

Patricia Hinton Walker, Ph.D., RN, FAAN, DNAP, PCC Strategic Initiatives and Graduate School of Nursing, Uniformed Services University of the Health Sciences, Bethesda, MD, USA

Part I
Prologue

Chapter 1
The Development of Digital Computers

Morris F. Collen and Casimir A. Kulikowski

Abstract In the 1950s, the transistor replaced the vacuum tubes that had empowered Eniac, Colossus, and other early computers in the 1940s. In the 1960s and 1970s, computing moved from slow, expensive mainframes to faster mini- and microcomputers and multiprocessors, empowered by chip technology and integrated circuits, and leveraged by increasingly sophisticated operating systems and programming languages. By the 1980s, commercially available programs were able to perform commonly needed computational functions. With the growth of computer capabilities and computer storage capacities, database technology and database management systems gave rise to the development of distributed database systems. Efficient computer-stored databases proved essential to many medical computing applications, making vast amounts of data available to users. Over time computer applications became more numerous and complex, with software claiming a larger fraction of computing costs. Display terminals and clinical workstations offered graphic displays and supported structured data entry and reporting. Devices, such as the mouse, light pens, touch screens, and input technologies, such as speech and handwriting recognition, were developed to ease the user's tasks and foster physician acceptance. Over the same span of time, computer communications evolved as well, moving from copper wire to fiber optic cable and, most recently, to wireless systems. The Internet and the World Wide Web became the main modes used for local and global communications. By the 2010s laptops replaced desktop computers, and tablets and smart phones were commonplace in health care.

Keywords Early computers • Computer languages • Computer communication networks • Computer terminals • Data storage • Clinical records and systems • User computer interfaces • Networking and the World Wide Web

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Author was deceased at the time of publication.

M.F. Collen (deceased)

C.A. Kulikowski, Ph.D. (✉)
Department of Computer Science Hill Center, Rutgers University,
Busch Campus, Piscataway, NJ, USA
e-mail: kulikow@rutgers.edu

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In the latter part of the nineteenth century, John Shaw Billings, a physician and the director of the Army Surgeon General's Library (later to become the National Library of Medicine) initiated a series of events that led to the development of the modern digital computer in the United States [114]. Asked to assist the Census Bureau with the 1880 and with the 1890 census, Billings suggested to Hollerith, an engineer, that there should be a machine for doing the purely mechanical work of tabulating population and similar statistics. Hollerith used paper cards the size of a dollar bill, allowing him to store the cards using Treasury Department equipment and eliminate the need for new storage devices. Descriptions were printed on the edge of the cards for individual data items punched into corresponding specific locations on the card [6]. In 1882 Hollerith invented the paper punch card with 288 locations for holes, punched out by a hand-operated device, until he built a machine for electrically punching the holes; and next he built machines for reading and sorting the punched cards. The 1890 census data on 62 million people were processed in 1 month using 56 of Hollerith's machines. In 1896 Hollerith established the Tabulating Machines Company which became the Computing-Tabulating-Recording (CTR) Corporation in 1911, but soon after lost most of its business to a rival more up-to-date firm. However, when Thomas J. Watson Sr. joined the CTR Corporation and became its executive in 1918, CTR recovered, and in 1924 changed its name to the International Business Machines (IBM) Corporation. Thus, a physician, Billings, laid the foundation for the development of digital computing in the United States.

1.1 Electro-Mechanical Digital Computers

The earliest digital data computers were mechanical calculators Pascal invented in France in the mid-1600s. In the 1830s Babbage, a British mathematician, built an automated mechanical computing machine with gears and linkages that he called a Difference Engine. Babbage then conceived a more advanced Analytical Engine that would have become the first mechanical digital computer. During the 1840s, Ada Byron, the Countess of Lovelace and daughter of Lord Byron, collaborated with Babbage to develop programs for his Analytical Engine, which he never actually completed; she is credited by some as the first programmer of a digital computer [264].

In 1940 Stibitz and his colleagues at Bell Laboratories developed a partially automated digital computer that used electrically controlled, mechanical magnetic switches as relay switches. The "on" and "off" positions of the relay switches represented the numbers 0 and 1 as the binary-bits in the base-2 system [47]. Stibitz exploited the relative simplicity of using the binary system for a digital computer since every number, letter, symbol, and punctuation could be represented by a unique combination of bits. Previous calculators and computers had processed numbers using the base-10 decimal system, which required multiples of ten-gear teeth to turn switches on and off in order to count. Later the American Standard Code for Information Exchange (ASCII) assigned an eight-digit binary code to each letter, so that 01000001 was the letter A, 01000010 was letter B, 01000011 was letter C, and so forth in the ASCII code.

In 1941 Zuse built the world's first fully functional, program-controlled, general-purpose, electro-mechanical digital computer in Germany. This machine used relay switches and was based on the binary system; thus, when a switch was turned "on" it represented the number "1", and when turned "off" it represented "0". Due to World War II, Zuse's invention received little recognition in the United States.

In 1943 the Mark I computer was designed by Aiken at the Harvard Computation Laboratory. Built by the International Business Machine (IBM) Company as the Automatic Sequence Controlled Calculator (ASCC), in 1944 it was installed at Harvard University, where it was called Mark I. Run by an electric motor, it was a program-controlled computer based on the decimal system; all machine operations were performed electro-mechanically by its wheel counters and relay switches [6, 80].

1.2 Early Electronic Digital Computers

With the advent of modern electronics, the flow of electric current replaced mechanical moving parts of earlier computers, and vacuum tubes replaced electromechanical switches. First generation computers were "hardwired", and their circuits were their programs. As computer processors advanced, new computer system architectures were developed.

Colossus is generally credited to have been the first all-electronic digital computer in the world. Guided by the mathematicians Turing, Newman, and their colleagues at the Bletchley Park Research Establishment in England [173], the Colossus was installed and working in December 1944. Used by the British during World War II to carry out the many logical steps needed to break German coded messages, it showed that computers could be used for purposes other than just processing numbers [133]. Atanasoff's computer is considered by some to be the very first, fully electronic, digital computer built in the United States. Invented by Atanasoff, a physicist at Iowa State University and operational in 1942, it was a single-purpose computer that used the binary system [52, 173].

However, ENIAC (Electronic Numerical Integrator and Calculator) is more generally credited to be the first electronic digital computer built in the United States. Invented in 1946 by Mauchly, Eckert, and their coworkers at the Moore School of the University of Pennsylvania [221], ENIAC occupied a space 30×50 ft, weighed 30 tons, used 18,000 vacuum tubes for its active arithmetic and logic elements, and was based on a decimal numeral system. Secretly built under contract with the U.S. Army Ballistics Research Laboratory to calculate the trajectories for gunnery in World War II, ENIAC was capable of solving a wide variety of problems in science, engineering, and statistics. The computations were electronic, but the problems had to be entered manually by setting switches and plugging in cables [53]. EDVAC (Electronic Discrete Variable Automatic Computer) was also designed by Mauchly and Eckert in 1944, even before the ENIAC was completed. Delivered in

1949, EDVAC was a binary-based computer that had 6,000 vacuum tubes and covered 490 ft^2 of floor space. UNIVAC (Universal Automatic Computer) was developed in the late 1940s; it used von Neumann's computer-stored program technology. The first computer to process both numeric and alphabetic data, UNIVAC had 5,000 vacuum tubes and was still based on the decimal system.

SEAC (Standard Eastern Automatic Computer) was used by Ledley, a pioneer in the use of digital computers for medical purposes in the United States, when in 1950 he conducted research in computer applications to dental projects at the National Bureau of Standards. Since at that date the UNIVAC was not yet operational, Ledley [157] claimed that SEAC was the world's first high-speed electronic digital computer in which the programs were stored digitally in the computer's memory. Demonstrated in 1951, the first real-time computer, the Whirlwind, was the source of several significant technological innovations. In addition to having the first magnetic core, random-access memory, it was the first 16-bit computer and paved the way for the development of the minicomputer in the mid-1960s [6].

When Eckert and Mauchly recognized the potential usefulness of computers in science and industry, and obtained patents for their inventions, they left the University of Pennsylvania and set up the first commercial computer company in the United States, the Eckert and Mauchly Electronic Control Company of Philadelphia. In 1950 Remington Rand, founded in 1911 to make typewriters and tabulating equipment, took control of the Eckert and Mauchly Company; a year later, in 1951, Remington Rand completed the first UNIVAC for the Census Bureau to be used in analyzing the 1950 census data.

International Business Machines (IBM) Company, which in 1939 had financed the construction of Aiken's Mark I at the Harvard Computation Laboratory, initiated work in 1945 on its first internally developed computer, the IBM 604. Marketed in 1948, the 604 was an electronic multiplier with 1,400 vacuum tubes and a plug board for wiring simple instructions. In 1952 Watson Jr. became the president of IBM; there he directed the manufacturing of the IBM 701 Defense Calculator. A binary-based computer with 4,000 vacuum tubes that was faster than the UNIVAC, the IBM 701 computer supported the U.S. Army's needs during the Korean War [30]. In 1950 IBM released its 704 scientific computer; with magnetic core memory, a cathode-ray tube (CRT) display monitor, FORTRAN programming and some graphics capability, it was among the earliest computers used for medical research [217].

Transistor-based, second generation digital computers were introduced in the late 1950s. Instead of using vacuum tubes these computers employed transistors, invented in 1947 by Shockley, Bardeen, and Brattain at AT&T's Bell Laboratories. In their work, for which they won the 1956 Nobel prize for physics, the three scientists had observed an electric signal was produced when two contacts were applied to a crystal. Their initial point-contact transistor served as an electric switch with four components: a source where the electric current entered, a drain where the current left, a channel linking the two, and a device that acted as a gate to the channel. By opening and closing the channel, the gate governed whether an electric current could flow along a thin metal film of a semiconductor, and thus defined the on-or-off state that provided a computer's binary function. In 1951 Shockley and his team also developed a junction transistor which used the internal properties of semiconductors rather than the surface effects on which point-contact devices depended. Shockley "doped" a silicon semiconductor with impurities (such as arsenic or boron) that created free electrons to produce a negative charge, or stole electrons from the semiconductor's lattice to create positively charged "holes". When joined together, the negatively charged electrons and the positively charged holes flowed toward the junction where they joined and others took their place, creating a current that flowed in one direction [105].

Computer transistor chips were invented in 1959 when Kilby at Texas Instruments and Noyce at Fairchild Semiconductor were independently able to make the crystal in a transistor serve as its own circuit board [38]. Kilby's device required putting the circuit components together by hand. Noyce's group fabricated the components of a circuit (the resistors, capacitors, transistors, and the interconnecting wireless conductive pathways) all on one surface of a flat wafer of silicon. They thereby created the first miniature integrated circuit on a chip [200]. Transistor-based computers are wired much the same way as vacuum tube-based computers; but they are much smaller, require less power, and are more reliable. In 1959 IBM began marketing its first transistorized computer, the IBM 7090, which contained 32,768 words of memory, with each word being 36-bits in length instead of the prior 16-bit word length; it employed magnetic tape for secondary storage [34]. By the end of the 1950s, IBM had three-fourths of the computer market in the United States [50]. Friedel [105] noted that within a decade transistors were used in hundreds of devices, including telephones, radios, hearing aids, pocket calculators, and digital computers. In 1961 Fairchild and Texas Instruments introduced logic chips that, in addition to the arithmetic *AND* function, performed the Boolean operations *OR* and *NOR* (not OR). By stringing logic chips as gates together in different ways, the engineers could endow computers with the power to support decision making processes [6]. The invention of the computer chip with its integrated circuits produced dramatic changes in computers, and was probably the most important event that ushered in the information age.

Third generation computers appeared in 1963 in the form of solid state integrated circuits that consisted of hundreds of transistors, diodes, and resistors embedded on one or more tiny silicon chips, in a process called large scale integration (LSI) [32]. Once again computers became smaller and more reliable, and required less power. The manufacture of computer circuits became more like a printing process and less like a traditional assembly process, since the chip makers worked like photoengravers with masks and light-sensitive chemicals etching the silicon layers [83]. In 1964 IBM introduced its system/360 series of computers, a family of the earliest third generation computers all using the same operating system (OS/360) that allowed data processing operations to expand from the smallest machine in the series to the largest without the need to rewrite essential programs. The IBM series/360 computer with its Systems Network Architecture (SNA) led the industry into modern commercial computing, and was the basis for IBM's spectacular growth [271].

In the early 1970s, IBM replaced its 360 series with the system/370 series that used only integrated circuit chips.

Fourth generation computers appeared in the late 1960s and exploited very large scale integration (VLSI) that contained thousands of components on very tiny silicon chips, greatly increasing performance with less cost. By the early 1980s, a silicon flake a quarter-inch on a side could hold a million electronic components, ten times more than in the 30 ton ENIAC and 30,000 times as cheap. Drawing the electric power of a bedroom nightlight instead of that of a hundred lighthouses, in some versions it could perform 200 times as many calculations per second as the ENIAC [38].

The history of the development of some of the earliest generations of electronic computers was described by Tropp [266] and Bernstein [22, 23].

1.3 Minicomputers, Microcomputers, and Multiprocessors

In the 1960s, when general purpose, higher level computers had evolved to perform a broad range of tasks, smaller special purpose minicomputers were developed to perform restricted sets of tasks with greater speed, economy, and convenience [79]. In 1962 the Laboratory Instrumentation Computer (LINC) was demonstrated by Clark and Molnar at the Lincoln Laboratory at the Massachusetts Institute of Technology (MIT), as a small, special-purpose computer that increased the individual researcher's control over the computer [65]. Waxman, then the executive secretary of the Computer Science Advisory Committee of the National Institutes of Health (NIH), arranged for a grant to construct, evaluate, and distribute 12 LINCs in 1963 to various computing research laboratories in the United States. Additional development of the LINC occurred at the University of Wisconsin by Rose, and at the University of Washington in St. Louis by Clark, Molnar, and Cox [186]. The Digital Equipment Company (DEC), founded in 1957 by Olsen, who had worked with Molnar and Clark at MIT, took over commercial production of the LINC machines [131]. The LINC was the first of a number of smaller, low-cost minicomputers to appear in the 1960s. Bell designed the first DEC Programmed Data Processor (PDP)-8; released in 1965, it helped popularize the term minicomputer [223]. In 1978 DEC introduced its VAX series of minicomputers; with more flexible and modular architecture, it was faster than the PDPs. In 1966 Hewlett-Packard introduced its Model 2116A minicomputer, more powerful than the LINC; by 1970 Hewlett-Packard was second only to DEC in the minicomputer market. Minicomputers were soon used for many medical applications because they outperformed the more expensive mainframe computers for specific input/output processing tasks, and demands at that time for processing large numerical calculations in clinical medicine were infrequent [127].

In 1970 Hyatt filed a patent application for a prototype microprocessor that used integrated circuits [159]. In 1971 Blankenbaker assembled what was considered by a panel of judges to be the first personal computer; 40 of his $750 Kenbak machines