COMPUTED TOMOGRAPHY TECHNOLOGY

EUCLID SEERAM, R.T., B.Sc.

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EUCLID SEERAM, R.T., B.Sc.

British Columbia Institute of Technology
Burnaby, British Columbia

with contributions by

THOMAS PAYNE, Ph.D.

Abbott Northwestern Hospital
Minneapolis, Minnesota

1982

W. B. SAUNDERS COMPANY

Philadelphia / London / Toronto / Mexico City
Rio de Janeiro / Sydney / Tokyo

W. B. Saunders Company: West Washington Square
Philadelphia, PA 19105

1 St. Anne's Road
Eastbourne, East Sussex BN21 3UN, England

1 Goldthorne Avenue
Toronto, Ontario M8Z 5T9, Canada

Apartado 26370 – Cedro 512
Mexico 4, D.F., Mexico

Rua Coronel Cabrita, 8
Sao Cristovao Caixa Postal 21176
Rio de Janeiro, Brazil

9 Waltham Street
Artarmon, N.S.W. 2064, Australia

Ichibancho, Central Bldg., 22-1 Ichibancho
Chiyoda-Ku, Tokyo 102, Japan

Library of Congress Cataloging in Publication Data

Seeram, Euclid.

Computed tomography technology.

1. Tomography. I. Payne, Thomas, 1944- II. Title.
[DNLM: 1. Tomography, X-ray computed – Methods.
WN 160 S453c]

RC78.7.T6S37 616.07'572 81-48093

ISBN 0-7216-8059-3 AACR2

Computed Tomography Technology ISBN 0-7216-8059-3

Last digit is the print number: 9 8 7 6 5 4 3 2 1

CT FOREWORD

Radiology has just emerged from a period of technological renaissance. In 1972, a new method of taking x-ray pictures was introduced by G. N. Hounsfield (physicist) and J. Ambrose (neuroradiologist). They had just completed testing of the first clinical computed tomographic (CT) scanner. For the remainder of the decade, CT was in the limelight as a rapidly developing but costly example of medical technology.

Today, CT scanning is considered to be an essential and accepted part of standard radiologic practice in most large hospitals. CT scans of the head, body, or spine are considered essential in the proper diagnosis and management of patient disorders. It is important that those of us working in radiology know the tools of our trade. This book examines CT as an important tool in diagnostic radiologic imaging. The basic principles of CT operation, including computer fundamentals, are covered. Complex aspects of CT are reduced to understandable terminology. Euclid Seeram has done a good job of condensing and extracting pertinent information from the prolific CT literature.

J. THOMAS PAYNE, Ph.D.

PREFACE

Computed tomography (CT) is now becoming recognized as one of the major branches of diagnostic radiology. It marks the beginning of a new activity for radiologists, technologists, medical physicists, and other related health professionals.

Ever since computed tomography was introduced into clinical radiology, there has been an increasing demand for textbooks on the fundamental principles of CT that present a solid foundation by introducing elementary theoretical groundwork and at the same time raise the reader's sophistication in the field as quickly and easily as possible. In considering these essentials, the purpose of this text is threefold: (1) To provide a clear and comprehensive introduction to the physical principles of CT through a discussion of the basic elements of computer technology and physico-mathematical concepts as they relate to CT. (2) To assist the reader in acquiring further understanding of the structure of CT. (3) To enable the reader to begin building a new vocabulary that will allow him to understand the literature pertaining to CT.

Having these objectives in mind, the text is intended for use in the following ways: (a) As a text for introductory courses in CT at the associate and baccalaureate degree levels, to be used either alone or with readings in the CT classics. (b) As an introductory reference text for professional radiologic personnel. (c) As a supplementary text for courses in applied fields, the purpose of which is to introduce the reader to the language of CT for use in applications to his field (e.g., biomedical technology). (d) As a guide to independent study. (e) As a rapid survey and review of important issues presented in introductory courses.

I have purposely written the book in a brief and concise manner to ensure that the reader's interest and attention are maintained, since the language of CT is relatively new. The text differs from others in that it is perhaps one of the first attempts to bring together the complex theory of CT and its clinical components at a rather elementary level, while still maintaining a certain degree of structure that promotes abstract thinking. Equally important, it contains summaries of key elements, review questions, and a small, selected bibliography, the purpose of which is to provide motivation and help the reader in the learning process.

Chapter 1 presents a general overview of the computer with respect to the basic components and operating principles. Computer applications in radiology are discussed briefly.

The principles of CT are introduced in Chapter 2 in terms of historical background, physical basis, and technology. Chapter 3 deals with a number of important features of the detection system in CT, x-ray sources, and collimation.

Chapter 4 lends itself to an introduction to mathematical techniques used in image reconstruction from projections without the use of rigorous mathematics.

A description of CT not only involves a discussion of physical principles but definitely warrants a description and identification of the equipment and components. Such treatment is given in Chapter 5.

In Chapter 6, several concepts relating to image quality are introduced and several factors influencing resolution are discussed.

Since dose in CT is of great concern to the physician and radiologic personnel, it is discussed in Chapter 7.

Although the text is physically oriented, I have included in Chapter 8 a discussion of some clinical aspects of CT for the purpose of completeness. Such aspects relate to efficacy, indications, patient preparation and positioning, and so on.

Finally, Chapter 9 presents an examination of future trends in CT, including essential economic considerations.

Throughout the text, I present the results of selected research findings under separate subsections. In presenting these findings, a number of direct quotations will be used so as not to detract from the original meaning. The results of these studies are important, since they lead to the establishment of standards, the implementation of safety procedures, and other related matters. It is my belief that the inclusion of these studies will serve to provide the student with information on some current areas of research, to open up new horizons for further discussion and perhaps investigation, and to enhance the general scope of the text.

In organizing and writing this text, I have assumed that the student has had a knowledge of basic radiologic physics; however, certain concepts (e.g., radiation attenuation) can be explained at a satisfactory depth by the instructor.

It is also my growing conviction that you will enjoy the pages that follow. Good luck in your pursuit of a new technology.

Euclid Seeram
British Columbia, Canada

ACKNOWLEDGMENTS

The material in this book represents what I believe to be a fairly comprehensive review of the literature on computed tomography. The real authors are those scientists, engineers, radiologists, and many others who have done the original research. In this regard I should like to express my sincere appreciation to Dr. G. N. Hounsfield, Nobel Prize winner, who made the technique clinically feasible. I should also like to thank him for his biographic data and portrait and for his permission to use them in this text.

The book had its inception at the Ottawa General Hospital School of Radiography with a series of notes given to student radiologic technologists, who elicited a few rather important concerns that resulted in a number of additions to the text material.
further at the British Columbia Institute of Technology and resulted in a formal 12-week course for graduate technologists. I am grateful to these students, who elicited a few rather important concerns that resulted in a number of additions to the text material.

Two teachers have influenced my early years in radiography and my further educational development, and I owe them my special thanks. They are Sr. M. York, S.C.O., R.T., a warm and caring individual who provided my first experience in teaching computed tomography, and C. Hebert, Ph.D., to whom I owe my understanding of radiologic physics. One other teacher to whom I am also grateful is Professor M. B. Fenton, Ph.D., of Carleton University in Ottawa, whose course on biology taught me the rudiments of technical writing and reporting and the elements of archival research.

The book would not have been possible without the efforts of a great number of people. I therefore express thanks to all the authors, publishers, and CT equipment manufacturers who not only furnished information but gave their willing permission to reproduce data and illustrations in the text. I would especially like to acknowledge the help of General Electric Company, Medical Systems Division; EMI Medical, Inc.; Ohio Nuclear; Pfizer, Inc.; and Picker International. One other company that deserves mention here is I.B.M., which supplied a good deal of information on computers and provided the photographs used in Chapter 1.

It is my pleasure to mention the individuals whose efforts contributed to this project. The works on computed tomography by E. C. McCullough, Ph.D., of the Mayo Clinic, and J. T. Payne, Ph.D., Abbott Northwestern Hospital, provided the basic framework used in planning this text. Their research publications have been cited a number of times in this book. I should like especially to extend my sincere thanks and appreciation to Dr. J. Thomas Payne, medical physicist, for his contribution of the chapter on Radiation Dose and for his excellent review of the entire manuscript. His comments, suggestions, and corrections have been invaluable. Others include R. A. Brooks, Ph.D., National Institutes of Health; R. K. Cacak, Ph.D., University of Colorado Health Sciences Center; G. Cohen, Ph.D., University of Texas Health Sciences Center at Houston; S. J. Riederer, physicist, University of Wisconsin, Medical Physics Division; E. Ritman, M.D., Ph.D., Head, Biodynamics Research Unit, Mayo Clinic; C. M. Strother, M.D., University of Wisconsin Clinical Sciences Center; D. P. Boyd, Ph.D., University of California; G. A. Hay, Department of Medical Physics, University of Leeds; and Susan Weber, supervisor of CT scanning, Cleveland Clinic.

I owe thanks to A. Burgess, Ph.D., physicist in diagnostic radiology, University of British Columbia, who provided answers to several of my questions on computed tomography, and to Mark Dumont, M.Sc., computer specialist, who reviewed Chapter 1 and provided useful comments that helped to bring the chapter to its present form.

I must also express my gratitude to Bev Brown and Shirley Matkowski, CT technologists, who assisted me with some clinical details for Chapter 8.

My friend and colleague Norma Smith, R.T., B.A., Program Head, Radiography Section, British Columbia Institute of Technology, deserves special mention here. Her fitting disposition and concern helped me to maintain the impetus necessary to complete this task. In this regard also, I should like to thank L. Timko, M.D., radiologist, whose thoughtfulness and attitude gave me encouragement.

To all the people at Saunders who were involved in the making of this text, I owe a good deal of thanks. I would like to identify particularly Marie Low, former editor, Allied Health Sciences, whose enthusiasm and dynamic professionalism set the proposed manuscript into motion. Her comments and guidance were extremely helpful and encouraging. Wendy Phillips, former assistant editor, Allied Health Sciences, also provided encouragement and assistance in reshaping the manuscript to bring it to its present form. Baxter Venable, Medical Editor, supervised the completion of this project and provided constant feedback on various aspects of its development. I would also like to acknowledge the Editorial/Design/Production Team at Saunders for their meticulous work on the general layout of the manuscript.

Finally, my family's encouragement and help is what really brought the text to its present form. My wife, Trish, a very special person, provided the motivation throughout the research and writing stages of this book. She influenced and also contributed to my professional and educational development, particularly my university studies, and I am most appreciative of all her support in this undertaking, and for her help in the galley and page proof stages of publication. To my son David, a very perceptive and special lad, who gave me the "good feelings" about the project throughout all aspects of its development — thanks, pal.

Last, but not least, I thank my barber-stylist, Lyle Folkett, a well-read gentleman who wanted to know more about computed tomography.

A NOTE TO THE STUDENT

To assist you in the study of this text, each chapter is preceded by an outline and concludes with a summary of the main points. Such an outline is to guide you into the material, while the summary will indicate to you whether you have grasped the concepts.

The following suggestions are offered to enable you to achieve the general objectives of the text:

a. Consider Chapter 1 a very important chapter. It must not be skipped over, since the computer is now a key element in diagnostic radiology.

b. Consider Chapter 2 a pivotal chapter, since it is the basis of this text. It should be referred to as often as necessary to ensure understanding of further concepts.

c. Read the appropriate chapter before each lecture. This initial reading is intended to provide you with the content and language of the course.

d. After studying each chapter, read through the summary section to review the important points in the chapter.

e. To ensure that the main points have been assimilated, complete the review questions.

f. It is highly recommended that you read through the selected reading material as a basis for further discussion and insight into CT.

CONTENTS

CT INTRODUCTION

Innovations are quite commonplace in twentieth-century society. More specifically, innovations are becoming commonplace in the radiology department. New methods, ideas, and techniques, and hence new equipment, are constantly being generated so that improved patient care and optimum diagnostic information can be acquired.

As an important technological development, the rate of growth of the computer industry is increasing because of the numerous new possibilities for analysis and information processing. The computer has arrived in the radiology department, and its applications are receiving widespread attention.

The introduction of the computer in radiology goes back two decades. In 1955, K. C. Tsien used the computer to provide rapid and accurate calculations of radiation dose distributions in cancer patients. As his problem was a mathematical one, the use of the computer proved fruitful. This created a stimulus for other workers, and hence a series of applications was generated.

Today, computer applications in radiology range from the automated handling of patient records and radiologic reporting to difficult problems in imaging. Imaging applications include computer aided diagnosis, automated image analysis, and computed tomography. Computed tomography (CT) is a new imaging modality that was developed in 1969 by Godfrey N. Hounsfield of Electric and Musical Industries (EMI), Limited, a British-based international group of companies.

In CT, special detectors are used to measure x-rays passing through an object. This information is then sent to a computer, which reconstructs an image of the object by using complex mathematical techniques. The image is displayed on a television screen for viewing and photographic recording. It can also be obtained as a numerical print-out in which the numbers are the relative absorption values of the internal structures of the object.

In 1967, Hounsfield was investigating pattern recognition techniques when he deduced that if an x-ray beam were passed through a body from all directions and if measurements were made of all these x-ray transmissions, it would be possible to obtain information about the internal structure of that body. It was decided that this information should be presented to the radiologist in the form of pictures that would show three-dimensional representations of the part under examination.

The initial reconstruction of an image was simply based on multiple sampling to obtain multiple solutions. Since each part of the x-ray beam that

G. N. Hounsfield. (Courtesy of EMI Limited Central Research Laboratories, England.)

passed through the object formed a series of simultaneous equations, the use of a computer for this task was almost mandatory. Using a suitable mathematical model, the computer was programmed to reconstruct an image.

With encouragement from the British Department of Health to investigate the clinical feasibility of the technique, an apparatus was constructed, using radiation from a gamma source. Because of the low radiation output, the apparatus took about nine days to generate a picture. The computer took two and one-half hours to process the readings and had to solve 28,000 simultaneous equations. Various modifications were made and the study was then done using x-rays. The results were much more accurate, but it took about one day to produce a picture.

To evaluate the usefulness of such a machine, Dr. James Ambrose, a consultant radiologist at Atkinson-Morley's Hospital in Wimbledon, joined the study. Together, Hounsfield and Ambrose made readings from a specimen of human brain. The findings were rewarding, in that tumor tissue was differentiated from gray and white matter. Controlled experiments using "fresh bullocks' brains" showed details such as ventricles and the pineal gland. Experiments were also done using kidney sections from pigs.

In September, 1971, the first CT scanner was installed at Atkinson-Morley's Hospital, and under the direction of Dr. Ambrose clinical tests were conducted. The processing time for each picture was reduced to about 20 minutes. Some time later, with the utilization of minicomputers, the processing time for each picture was reduced even further to four and one-half minutes.

So remarkable is the CT that in many cases it generates a dramatic increase in diagnostic information over conventional x-ray techniques. In trying to describe its significance, one may be tempted to use the term "diagnostic breakthrough."

The introduction of CT in diagnostic radiology has been received with much enthusiasm. The first EMI CT scanner was restricted to brain imaging studies only, but researchers quickly adapted this technique for other parts of the body. Hence, new CT equipment has now become available to provide body scans with excellent resolution and contrast and with short scan times to minimize motion distortion. Other refinements of the first CT scanner have also been made with regard to scanning, the detection system, degrees of rotation, slice thickness, the number of readings, and so on. So rapid are these developments that already CT is in the so-called "fourth generation" of its history.

The fundamental concepts of CT can be traced back to numerous mathematical and other related developments. The history of reconstruction techniques began in 1917. A summary of other events is shown below:

1917	Radon	Laid down roots of tomography in terms of mathematics.
1956	Bracewell	Performed practical reconstructions of image of the sun.
1961–1963	Oldendorf, Kuhl, Edwards, and Cormack	Applied reconstruction technique to medical problems.
1967	Hounsfield (England)	Worked on pattern recognition reconstruction techniques.
1967–1970	Hounsfield	Developed first clinically useful CT head scanner.
1971	Atkinson-Morley Hospital (England)	First clinically useful CT head scanner installed.
1972	Hounsfield and Ambrose	First paper on CT presented to British Institute of Radiology.
1973	Mayo Clinic (U.S.), Massachusetts General Hospital (U.S.)	First CT brain scanner installed.
1974	Ledley (U.S.)	Introduced whole-body CT scanner (ACTA scanner).

The growth of the CT has been dramatic. In the United States, for example, the number of scanners purchased in 1973 was about 30, while this number increased to about 100 in 1974, and to more than 300 whole-body and head scanners in 1975. The rate of growth continues to increase with time. Numerous manufacturers and research groups are actively involved in making further improvements and developments in the technology.

Although other workers investigated the idea of CT, it was Hounsfield who independently developed the first practical CT scanner. Therefore, he will be recognized as the man who opened up a whole new area of interest for radiologists, technologists, medical physicists, and other related scientists, just as Professor Roentgen did when he discovered x-rays.

Godfrey Hounsfield was born in 1919, in Nottinghamshire, England. After an outstanding performance at Magnus Grammar, he moved on to radar school at the Royal Air Force in Cranwell. There he undertook his formal education in electronics. After his student days he was appointed a lecturer at the same school. Following this, he attended Faraday House, where he studied electrical and mechanical engineering.

In 1951, he joined the staff at EMI, Limited, in London, where he began working on radar systems and later on computer technology. His research on computers led to the evolution of EMIDEC 1100, the first solid-state business computer in Britain.

In 1967, Hounsfield became interested in pattern recognition and reconstruction techniques using the computer. His research gave birth to the first clinically useful CT brain scanner. For this work, he received the equivalent of the Nobel Prize in Engineering, the McRobert Award, in 1972.

More recently (1979), Hounsfield shared the Nobel Prize in Physiology and Medicine with Allan MacLeod Cormack, a 55-year-old physics professor at Tufts University, Medford, Massachusetts, for work on CT.

Professor Cormack was born in Johannesburg, South Africa, in 1924. He attended the University of Capetown and then studied nuclear physics at Cambridge University. Later, he moved to the United States and did a sabbatical at Harvard University before joining the physics department at Tufts University. Professor Cormack developed solutions to mathematical problems involved in CT, which he has published in the *Journal of Applied Physics* in 1963 and 1964.

The clinical usefulness of CT is already well established in the diagnosis of diseases of the central nervous system. Disorders such as gliomas, metastases, intracranial lesions, aneurysms, infarctions, hemorrhage, atrophy, and so on, have been successfully detected by CT. In children, CT is useful in evaluating intracranial disorders such as hydrocephalus and neoplasms. At present, CT is more specific and more sensitive to the presence of primary and secondary neoplasms than is radionuclide scanning.

With the introduction of body scanners, CT of other parts of the body, such as the neck, thorax, abdomen, retroperitoneum, pelvis, and extremities, has, in some cases, produced definitive results. On the other hand, some controversies have arisen regarding the clinical efficacy of CT for other areas of the body. Despite these concerns, CT investigations of the body continue at a rapid rate.

CT is a noninvasive technique and does not cause discomfort to the patient or carry definite risks. It does not require hospitalization, as do cerebral angiography and pneumoencephalography. CT examinations can also reduce other problems related to patient management, such as postoperative care. For some examinations, however, the patient may receive an intravenous injection of iodine contrast medium prior to the scanning process. This enhances the contrast of certain internal structures. The contrast agent may cause some reaction in the patient, so the CT examination is not entirely hazard-free.

One of the major concerns in CT examination is the radiation dose, since x-radiation is damaging to most tissues. A fundamental objective in CT equipment design is to provide maximum information content with minimal radiation dose to the patient. Studies have indicated that the radiation dose in a CT brain scan is about equal to that received from a conventional skull x-ray examination requiring 6 to 10 films. Because the x-ray beam is well collimated, the amount of scattered radiation present during a CT scan is very small.

CT technology has already demonstrated how valuable physics, mathematics, and computer technology are to diagnostic radiology. A true understanding of CT will ultimately require at least a fundamental knowledge of computer technology and image reconstruction mathematics. At present, extensive research is being done on the physics and engineering aspects of CT; this research will ultimately be reflected in additional clinical benefits.

CT opens up a remarkable method of radiologic diagnosis. It is indeed a revolutionary evolution and a technological achievement. As time progresses, CT may become routine in most large-scale radiology departments. Therefore, every effort must be made to develop a fundamental understanding of the concepts underlying the principles of CT.

CT

CHAPTER 1

FUNDAMENTALS OF THE COMPUTER

We are still in control, but the capabilities of computers are increasing at a fantastic rate while raw human intelligence is changing slowly, if at all. . . . In the 1990s, when the sixth generation appears, the compactness and reasoning power of an intelligence built out of silicon will begin to match that of the human brain.

ROBERT JASTROW,
Director, NASA Goddard Institute for Space Studies (1978)

The use of computers in society is growing rapidly. The introduction and evolution of computers have profoundly influenced the lives of each of us. Today, the computer is used in every facet of human activity, including business administration, government, military, education, science, medicine, architecture, engineering, communications, and research, to mention only a few. The use of the computer is advantageous because of its speed, accuracy, and capacity for storing information that can be easily retrieved.

The primary purpose of this chapter is to introduce some fundamental concepts and associated terminology of computer technology. It is imperative that those who work in the field of radiology gain a basic understanding of the computer, since it is beginning to receive widespread application in radiology.

DEFINITION OF A COMPUTER

The computer is a machine for solving problems. More specifically, a modern computer is a fast electronic computational machine that receives input data, processes the information by performing arithmetic or logical operations using a program stored in its memory, and generates output data that can be displayed on suitable output devices. In common usage this machine has come to be referred to as an "electronic computer" or simply "computer."

HISTORICAL NOTES

The history of computers and computing goes back about two hundred decades to the *abacus,* the first digital calculator, which was used for counting by sliding beads on wires (IBM, 1971).

No other counting machine found widespread use until 1642, when Blaise Pascal, the French mathematician, developed an *arithmetic machine*. Later, in 1694, Gottfried Wilhelm von Leibnitz completed a *calculating machine* for solving problems in multiplication and division. Following this, Jacquard in France developed an automatic loom in which the sequence of operations was based on coded information punched onto paper cards.

In 1822, Charles Babbage, a nineteenth-century English mathematician, developed a *difference engine,* a machine for calculating mathematical tables. Later he used the idea of punched-card coding to develop the *analytical engine,* a machine that solved mathematical problems automatically.

Around 1890, Dr. Herman Hollerith of the United States Census Office developed the first electrical tabulator (Fig. 1–1), based on a punched-card operation, which was used for the US Census of 1890 (IBM, 1971).

After this period, the development of computers progressed at a rapid rate. Since it is not the intent of this section to present a detailed account of computer history, only a summary of some important events will be listed here.

1937–1944 Howard Aiken at Harvard University developed the MARK 1 (automatic sequenced controlled calculator), a large electromechanical calculator.

1943–1946 At the University of Pennsylvania, Eckert and Mauchly developed the first electronic calculator, ENIAC (electronic numerical integrator and calculator).

1946–1952 The electronic computer EDVAC (electronic discrete variable automatic computer) was developed at the University of Pennsylvania by Eckert and Mauchly, while EDSAC was developed in England.

1951 UNIVAC (universal automatic computer) became the first commercially available computer.

1954 First computer used for business was fabricated and delivered to the General Electric Company (Davis, 1973; IBM, 1971).

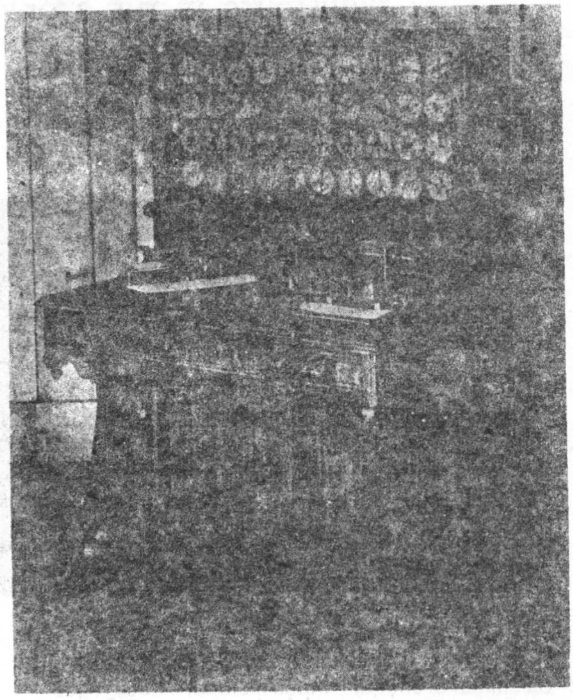

Figure 1–1. The first electrical tabulator developed by Dr. Herman Hollerith. (Courtesy of International Business Machines Corporation.)

In Figure 1–2, some other highlights in the development of the computer are shown.

Today, the computer has been developed to such a point that it is said to be in the fourth generation of its history (Couger and McFadden, 1977). The term *generation* is used to indicate that several significant changes have occurred throughout the development stages of the computer. In Table 1–1, four generations of computers and some characteristic features of each are given.

TABLE 1–1. SOME CHARACTERISTICS OF FOUR GENERATIONS OF COMPUTERS*

GENERATION	PRINCIPAL FEATURES
First	Vacuum tubes Data processing applications Expensive, relatively slow, unreliable Air-conditioned room needed
Second (introduced in 1959–1969)	Solid-state devices (transistors) Smaller, less heat production Less power requirements Reliable
Third (introduced in 1965)	Integrated circuits (including magnetic cores and semiconductors) Smaller still, greater speed and reliability
Fourth	Advanced storage system (miracle chips) Faster, smaller, less expensive than present-day computers

*After Couger, J. D., and McFadden, F. R.: A First Course in Data Processing. New York, John Wiley and Sons, Inc., 1977.