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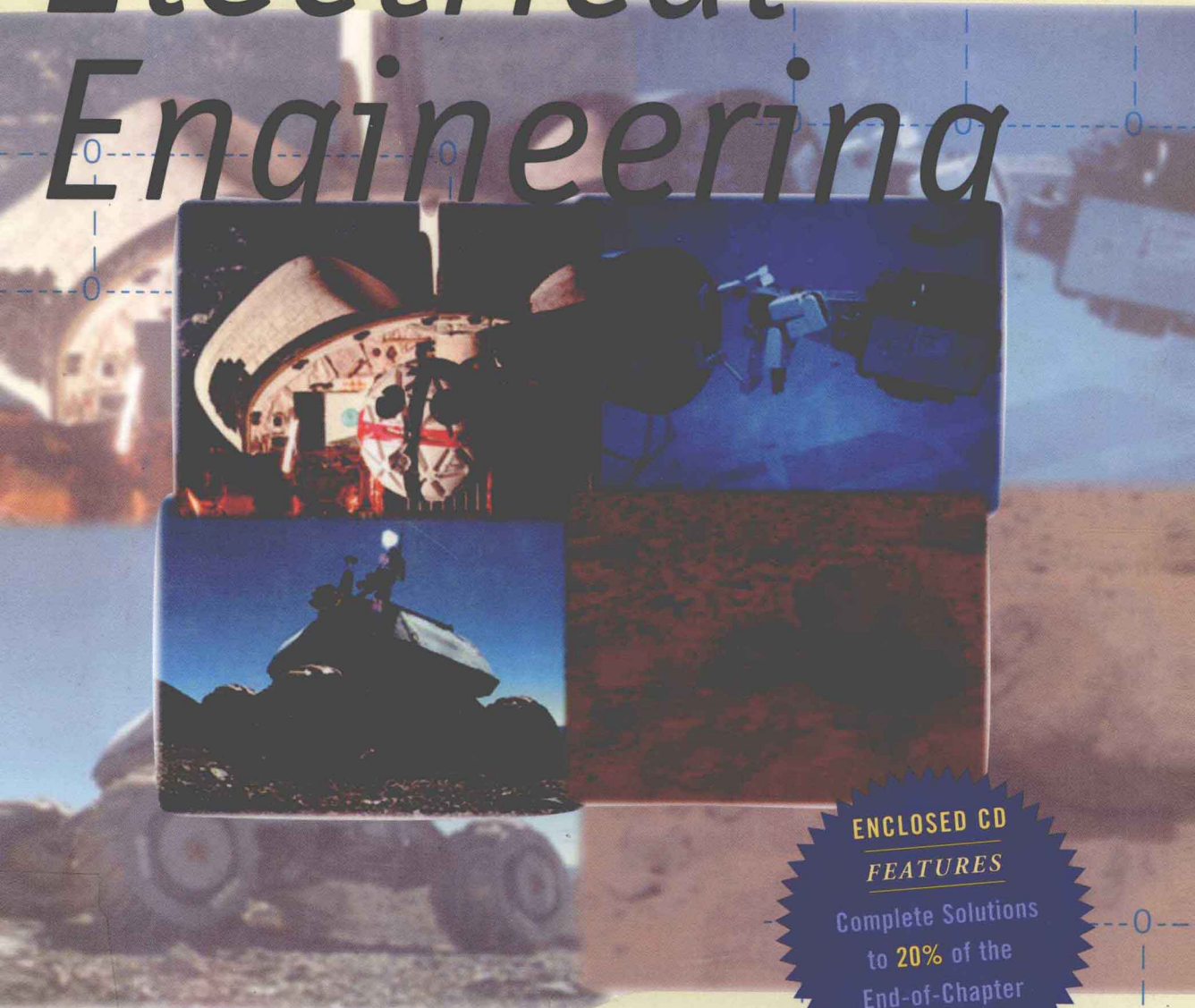

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MULUKUTLA S. SARMA

INTRODUCTION TO ELECTRICAL ENGINEERING

Mulukutla S. Sarma
Northeastern University

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PREFACE

I. OBJECTIVES

The purpose of this text is to present a problem-oriented introductory survey text for the extraordinarily interesting electrical engineering discipline by arousing student enthusiasm while addressing the underlying concepts and methods behind various applications ranging from consumer gadgets and biomedical electronics to sophisticated instrumentation systems, computers, and multifarious electric machinery. The focus is on acquainting students majoring in all branches of engineering and science, especially in courses for *nonelectrical engineering majors*, with the nature of the subject and the potentialities of its techniques, while emphasizing the principles. Since principles and concepts are most effectively taught by means of a problem-oriented course, judicially selected topics are treated in sufficient depth so as to permit the assignment of adequately challenging problems, which tend to implant the relevant principles in students' minds.

In addition to an academic-year (two semesters or three quarters) introductory course traditionally offered to non-EE majors, the text is also suitable for a sophomore survey course given nowadays to electrical engineering majors in a number of universities. At a more rapid pace or through selectivity of topics, the introductory course could be offered in one semester to either electrical and computer engineering (ECE) or non-EE undergraduate majors. Although this book is written primarily for non-EE students, it is hoped that it will be of value to undergraduate ECE students (particularly for those who wish to take the Fundamentals of Engineering examination, which is a prerequisite for becoming licensed as a Professional Engineer), to graduate ECE students for their review in preparing for qualifying examinations, to meet the continuing-education needs of various professionals, and to serve as a reference text even after graduation.

II. MOTIVATION

This text is but a modest attempt to provide an exciting survey of topics inherent to the electrical and computer engineering discipline. Modern technology demands a team approach in which electrical engineers and nonelectrical engineers have to work together sharing a common technical vocabulary. Nonelectrical engineers must be introduced to the language of electrical engineers, just as the electrical engineers have to be sensitized to the relevance of nonelectrical topics.

The dilemma of whether electrical engineering and computer engineering should be separate courses of study, leading to distinctive degrees, seems to be happily resolving itself in the direction of togetherness. After all, computers are not only pervasive tools for engineers but also their product; hence there is a pressing need to weave together the fundamentals of both the electrical and the computer engineering areas into the new curricula.

An almost total lack of contact between freshmen and sophomore students and the Department of Electrical and Computer Engineering, as well as little or no exposure to electrical and computer

engineering, seems to drive even the academically gifted students away from the program. An initial spark that may have motivated them to pursue electrical and computer engineering has to be nurtured in the early stages of their university education, thereby providing an inspiration to continue.

This text is based on almost 40 years of experience teaching a wide variety of courses to electrical as well as non-EE majors and, more particularly, on the need to answer many of the questions raised by so many of my students. I have always enjoyed engineering (teaching, research, and consultation); I earnestly hope that the readers will have as much fun and excitement in using this book as I have had in developing it.

III. PREREQUISITES AND BACKGROUND

The student will be assumed to have completed the basic college-level courses in algebra, trigonometry, basic physics, and elementary calculus. A knowledge of differential equations is helpful, but not mandatory. For a quick reference, some useful topics are included in the appendixes.

IV. ORGANIZATION AND FLEXIBILITY

The text is developed to be student-oriented, comprehensive, and up to date on the subject with necessary and sufficient detailed explanation at the level for which it is intended. The key word in the organization of the text is flexibility.

The book is divided into five parts in order to provide flexibility in meeting different circumstances, needs, and desires. A glance at the Table of Contents will show that Part 1 concerns itself with basic electric circuits, in which circuit concepts, analysis techniques, time-dependent analysis including transients, as well as three-phase circuits are covered. Part 2 deals with electronic analog and digital systems, in which analog and digital building blocks are considered along with operational amplifiers, semiconductor devices, integrated circuits, and digital circuits.

Part 3 is devoted to energy systems, in which ac power systems, magnetic circuits and transformers, principles of electromechanics, and rotating machines causing electromechanical energy conversion are presented. Part 4 deals with information systems, including the underlying principles of signal processing and communication systems. Finally, Part 5 presents control systems, which include the concepts of feedback control, digital control, and power semiconductor-controlled drives.

The text material is organized for optimum flexibility, so that certain topics may be omitted without loss of continuity when lack of time or interest dictates.

V. FEATURES

1. The readability of the text and the level of presentation, from the student's viewpoint, are given utmost priority. The quantity of subject matter, range of difficulty, coverage of topics, numerous illustrations, a large number of comprehensive worked-out examples, and a variety of end-of-chapter problems are given due consideration, to ensure that engineering is not a "plug-in" or "cookbook" profession, but one in which reasoning and creativity are of the highest importance.

2. Fundamental physical concepts, which underlie creative engineering and become the most valuable and permanent part of a student's background, have been highlighted while giving due attention to mathematical techniques. So as to accomplish this in a relatively short time, much thought has gone into rationalizing the theory and conveying in a concise manner the essential details concerning the nature of electrical and computer engineering. With a good grounding

in basic concepts, a very wide range of engineering systems can be understood, analyzed, and devised.

3. The theory has been developed from simple beginnings in such a manner that it can readily be extended to new and more complicated situations. The art of reducing a practical device to an appropriate mathematical model and recognizing its limitations has been adequately presented. Sufficient motivation is provided for the student to develop interest in the analytical procedures to be applied and to realize that all models, being approximate representations of reality, should be no more complicated than necessary for the application at hand.

4. Since the essence of engineering is the design of products useful to society, the end objective of each phase of preparatory study should be to increase the student's capability to design practical devices and systems to meet the needs of society. Toward that end, the student will be motivated to go through the sequence of understanding physical principles, processes, modeling, using analytical techniques, and, finally, designing.

5. Engineers habitually break systems up into their component blocks for ease of understanding. The building-block approach has been emphasized, particularly in Part II concerning analog and digital systems. For a designer using IC blocks in assembling the desired systems, the primary concern lies with their terminal characteristics while the internal construction of the blocks is of only secondary importance.

6. Considering the world of electronics today, both analog and digital technologies are given appropriate coverage. Since students are naturally interested in such things as op amps, integrated circuits, and microprocessors, modern topics that can be of great use in their career are emphasized in this text, thereby motivating the students further.

7. The electrical engineering profession focuses on information and energy, which are the two critical commodities of any modern society. In order to bring the message to the forefront for the students' attention, Parts III, IV, and V are dedicated to energy systems, information systems, and control systems, respectively. However, some of the material in Parts I and II is critical to the understanding of the latter.

An understanding of the principles of energy conversion, electric machines, and energy systems is important for all in order to solve the problems of energy, pollution, and poverty that face humanity today. It can be well argued that today's non-EEs are more likely to encounter electromechanical machines than some of the ECEs. Thus, it becomes essential to have sufficient breadth and depth in the study of electric machines by the non-ECEs.

Information systems have been responsible for the spectacular achievements in communication in recent decades. Concepts of control systems, which are not limited to any particular branch of engineering, are very useful to every engineer involved in the understanding of the dynamics of various types of systems.

8. Consistent with modern practice, the international (SI) system of units has been used throughout the text. In addition, a review of units, constants and conversion factors for the SI system can be found in Appendix C.

9. While solid-state electronics, automatic control, IC technology, and digital systems have become commonplace in the modern EE profession, some of the older, more traditional topics, such as electric machinery, power, and instrumentation, continue to form an integral part of the curriculum, as well as of the profession in real life. Due attention is accorded in this text to such topics as three-phase circuits and energy systems.

10. Appendixes provide useful information for quick reference on selected bibliography for supplementary reading, the SI system, mathematical relations, as well as a brief review of the Fundamentals of Engineering (FE) examination.

11. Engineers who acquire a basic knowledge of electric circuits, electronic analog and digital circuits, energy systems, information systems, and control systems will have a well-rounded background and be better prepared to join a team effort in analyzing and designing systems. Therein lies the justification for the Table of Contents and the organization of this text.

12. At the end of each chapter, the *learning objectives* of that chapter are listed so that the student can check whether he or she has accomplished each of the goals.

13. At the very end of each chapter, *Practical Application: A Case Study* has been included so that the reader can get motivated and excited about the subject matter and its relevance to practice.

14. Basic material introduced in this book is totally independent of any software that may accompany the usage of this book, and/or the laboratory associated with the course. The common software in usage, as of writing this book, consists of *Windows, Word Perfect, PSPICE, Math CAD,* and *MATLAB*. There are also other popular specialized simulation programs such as *Signal Processing Workstation (SPW)* in the area of analog and digital communications, *Very High Level Description Language (VHDL)* in the area of digital systems, *Electromagnetic Transients Program (EMTP)* in the field of power, and *SIMULINK* in the field of control. In practice, however, any combination of software that satisfies the need for word processing, graphics, editing, mathematical analysis, and analog as well as digital circuit analysis should be satisfactory.

In order to integrate computer-aided circuit analysis, two types of programs have been introduced in this text: A circuit simulator PSpice and a math solver MATLAB. Our purpose here is not to teach students how to use specific software packages, but to help them develop an analysis style that includes the intelligent use of computer tools. After all, these tools are an intrinsic part of the engineering environment, which can significantly enhance the student's understanding of circuit phenomena.

15. The basics, to which the reader is exposed in this text, will help him or her to select consultants—experts in specific areas—either in or out of house, who will provide the knowledge to solve a confronted problem. After all, no one can be expected to be an expert in all areas discussed in this text!

VI. PEDAGOGY

A. Outline

Beyond the overview meant as an orientation, the text is basically divided into five parts.

Part 1: Electric Circuits This part provides the basic circuit-analysis concepts and techniques that will be used throughout the subsequent parts of the text. Three-phase circuits have been introduced to develop the background needed for analyzing ac power systems. Basic notions of residential circuit wiring, including grounding and safety considerations, are presented.

Part 2: Electronic Analog and Digital Systems With the background of Part I, the student is then directed to analog and digital building blocks. Operational amplifiers are discussed as an especially important special case. After introducing digital system components, computer systems, and networks to the students, semiconductor devices, integrated circuits, transistor amplifiers, as well as digital circuits are presented. The discussion of device physics is kept to the necessary minimum, while emphasis is placed on obtaining powerful results from simple tools placed in students' hands and minds.

Part 3: Energy Systems With the background built on three-phase circuits in Part I, ac power systems are considered. Magnetic circuits and transformers are then presented, before the student is introduced to the principles of electromechanics and practical rotating machines that achieve electromechanical energy conversion.

Part 4: Information Systems Signal processing and communication systems (both analog and digital) are discussed using the block diagrams of systems engineering.

Part 5: Control Systems By focusing on control aspects, this part brings together the techniques and concepts of the previous parts in the design of systems to accomplish specific tasks. A section on power semiconductor-controlled drives is included in view of their recent importance. The basic concepts of feedback control systems are introduced, and finally the flavor of digital control systems is added.

Appendices The appendices provide ready-to-use information:

Appendix A: Selected bibliography for supplementary reading
Appendix B: Brief review of fundamentals of engineering (FE) examination
Appendix C: Technical terms, units, constants, and conversion factors for the SI system
Appendix D: Mathematical relations (used in the text)
Appendix E: Solution of simultaneous equations
Appendix F: Complex numbers
Appendix G: Fourier series
Appendix H: Laplace transforms

B. Chapter Introductions

Each chapter is introduced to the student stating the objective clearly, giving a sense of what to expect, and motivating the student with enough information to look forward to reading the chapter.

C. Chapter Endings

At the end of each chapter, the *learning objectives* of that chapter are listed so that the student can check whether he or she has accomplished each of the goals.

In order to motivate and excite the student, practical applications using electrical engineering principles are included. At the very end of each chapter, a relevant *Practical Application: A Case Study* is presented.

D. Illustrations

A large number of illustrations support the subject matter with the intent to motivate the student to pursue the topics further.

E. Examples

Numerous comprehensive examples are worked out in detail in the text, covering most of the theoretical points raised. An appropriate difficulty is chosen and sufficient stimulation is built in to go on to more challenging situations.

F. End-of-Chapter Problems

A good number of problems (identified with each section of every chapter), with properly graded levels of difficulty, are included at the end of each chapter, thereby allowing the instructor considerable flexibility. There are nearly a thousand problems in the book.

G. Preparation for the FE Exam

A brief review of the Fundamentals of Engineering (FE) examination is presented in Appendix B in order to aid the student who is preparing to take the FE examination in view of becoming a registered Professional Engineer (PE).

VII. SUPPLEMENTS

A **Solutions Manual to Accompany Introduction to Electrical Engineering**, by M.S. Sarma (ISBN 019-514260-8), with complete detailed solutions (provided by the author) for all problems in the book is available to adopters.

MicroSoft PowerPoint Overheads to Accompany *Introduction to Electrical Engineering* (ISBN 019-514472-1) are free to adopters. Over 300 text figures and captions are available for classroom projection use.

A **web-site, MSSARMA.org**, will include interesting web links and enhancement materials, errata, a forum to communicate with the author, and more.

A **CD-ROM Disk is packaged with each new book**. The CD contains:

- **Complete Solutions for Students to 20% of the problems.** These solutions have been prepared by the author and are resident on the disk in Adobe Acrobat (.pdf) format. The problems with solutions on disk are marked with an asterisk next to the problem in the text.
- **The demonstration version of Electronics Workbench Multisim Version 6**, an innovative teaching and learning software product that is used to build circuits and to simulate and analyze their electrical behavior. This demonstration version includes **20 demo circuit files** built from circuit examples from this textbook. The CD also includes another **80 circuits** from the text that can be opened with the full student or educational versions of Multisim. These full versions can be obtained from Electronics Workbench at www.electronicsworkbench.com.

To extend the introduction to selected topics and provide additional practice, we recommend the following additional items:

- Circuits: *Allan's Circuits Problems* by Allan Kraus (ISBN 019-514248-9), which includes over 400 circuit analysis problems with complete solutions, many in MATLAB and SPICE form.
- Electronics: *KC's Problems and Solutions to Accompany Microelectronic Circuits* by K.C. Smith (019–511771-9), which includes over 400 electronics problems and their complete solutions.
- SPICE: *SPICE* by Gordon Roberts and Adel Sedra (ISBN 019-510842-6) features over 100 examples and numerous exercises for computer-aided analysis of microelectronic circuits.
- MATLAB: *Getting Started with MATLAB* by Rudra Pratap (ISBN 019-512947-4) provides a quick introduction to using this powerful software tool.

For more information or to order an examination copy of the above mentioned supplements contact Oxford University Press at *college@oup-usa.org*.

VIII. ACKNOWLEDGMENTS

The author would like to thank the many people who helped bring this project to fruition. A number of reviewers greatly improved this text through their thoughtful comments and useful suggestions.

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I would also like to thank my wife, Savitri, for her continued encouragement and support, without which this project could not have been completed. It is with great pleasure and joy that I dedicate this work to my grandchildren.

Mulukutla S. Sarma
Northeastern University

OVERVIEW

What is electrical engineering? What is the scope of electrical engineering?

To answer the first question in a simple way, electrical engineering deals mainly with information systems and with power and energy systems. In the former, electrical means are used to transmit, store, and process information; while in the latter, bulk energy is transmitted from one place to another and power is converted from one form to another.

The second question is best answered by taking a look at the variety of periodicals published by the *Institute of Electrical and Electronics Engineers (IEEE)*, which is the largest technical society in the world with over 320,000 members in more than 140 countries worldwide. Table I lists 75 IEEE Society/Council periodicals along with three broad-scope publications.

The transactions and journals of the IEEE may be classified into broad categories of devices, circuits, electronics, computers, systems, and interdisciplinary areas. All areas of electrical engineering require a working knowledge of physics and mathematics, as well as engineering methodologies and supporting skills in communications and human relations. A closely related field is that of computer science.

Obviously, one cannot deal with all aspects of all of these areas. Instead, the general concepts and techniques will be emphasized in order to provide the reader with the necessary background needed to pursue specific topics in more detail. The purpose of this text is to present the basic theory and practice of electrical engineering to students with varied backgrounds and interests. After all, electrical engineering rests upon a few major principles and subprinciples.

Some of the areas of major concern and activity in the present society, as of writing this book, are:

- Protecting the environment
- Energy conservation
- Alternative energy sources
- Development of new materials
- Biotechnology
- Improved communications
- Computer codes and networking
- Expert systems

This text is but a modest introduction to the exciting field of electrical engineering. However, it is the ardent hope and fervent desire of the author that the book will help inspire the reader to apply the basic principles presented here to many of the interdisciplinary challenges, some of which are mentioned above.

TABLE I IEEE Publications

Publication	Pub ID
IEEE Society/Council Periodicals	
Aerospace & Electronic Systems Magazine	3161
Aerospace & Electronic Systems, Transactions on	1111
Annals of the History of Computing	3211
Antennas & Propagation, Transactions on	1041
Applied Superconductivity, Transactions on	1521
Automatic Control, Transactions on	1231
Biomedical Engineering, Transactions on	1191
Broadcasting, Transactions on	1011
Circuits and Devices Magazine	3131
Circuits & Systems, Part I, Transactions on	1561
Circuits & Systems, Part II, Transactions on	1571
Circuits & Systems for Video Technology, Transactions on	1531
Communications, Transactions on	1201
Communications Magazine	3021
Components, Hybrids, & Manufacturing Technology, Transactions on	1221
Computer Graphics & Applications Magazine	3061
Computer Magazine	3001
Computers, Transactions on	1161
Computer-Aided Design of Integrated Circuits and Systems, Transactions on	1391
Consumer Electronics, Transactions on	1021
Design & Test of Computers Magazine	3111
Education, Transactions on	1241
Electrical Insulation, Transactions on	1301
Electrical Insulation Magazine	3141
Electromagnetic Compatibility, Transactions on	1261
Electron Device Letters	3041
Electron Devices, Transactions on	1151
Electronic Materials, Journal of	4601
Energy Conversion, Transactions on	1421
Engineering in Medicine & Biology Magazine	3091
Engineering Management, Transactions on	1141
Engineering Management Review	3011
Expert Magazine	3151
Geoscience & Remote Sensing, Transactions on	1281
Image Processing, Transactions on	1551
Industrial Electronics, Transactions on	1131
Industry Applications, Transactions on	1321
Information Theory, Transactions on	1121
Instrumentation & Measurement, Transactions on	1101
Knowledge & Data Engineering, Transactions on	1471
Lightwave Technology, Journal of	4301
LTS (The Magazine of Lightwave Telecommunication Systems)	3191
Magnetics, Transactions on	1311
Medical Imaging, Transactions on	1381
Micro Magazine	3071
Microelectromechanical Systems, Journal of	4701
Microwave and Guided Wave Letters	1511
Microwave Theory & Techniques, Transactions on	1181
Network Magazine	3171
Neural Networks, Transactions on	1491
Nuclear Science, Transactions on	1061
Oceanic Engineering, Journal of	4201
Parallel & Distributed Systems, Transactions on	1501
Pattern Analysis & Machine Intelligence, Transactions on	1351
Photonics Technology Letters	1481
Plasma Science, Transactions on	1071
Power Delivery, Transactions on	1431

Continued

TABLE I Continued

Publication	Pub ID
Power Electronics, Transactions on	4501
Power Engineering Review	3081
Power Systems, Transactions on	1441
Professional Communication, Transactions on	1251
Quantum Electronics, Journal of	1341
Reliability, Transactions on	1091
Robotics & Automation, Transactions on	1461
Selected Areas in Communication, Journal of	1411
Semiconductor Manufacturing, Transactions on	1451
Signal Processing, Transactions on	1001
Signal Processing Magazine	3101
Software Engineering, Transactions on	1171
Software Magazine	3121
Solid-State Circuits, Journal of	4101
Systems, Man, & Cybernetics, Transactions on	1271
Technology & Society Magazine	1401
Ultrasonics, Ferroelectrics & Frequency Control, Transactions on	1211
Vehicular Technology, Transactions on	1081
Broad Scope Publications	
IEEE Spectrum	5001
Proceedings of the IEEE	5011
IEEE Potentials	5061

A historical perspective of electrical engineering, in chronological order, is furnished in Table II. A mere glance will thrill anyone, and give an idea of the ever-changing, fast-growing field of electrical engineering.

TABLE II Chronological Historical Perspective of Electrical Engineering

1750–1850	Coulomb's law (1785) Battery discovery by Volta Mathematical theories by Fourier and Laplace Ampere's law (1825) Ohm's law (1827) Faraday's law of induction (1831)
1850–1900	Kirchhoff's circuit laws (1857) Telegraphy: first transatlantic cables laid Maxwell's equations (1864) Cathode rays: Hittorf and Crookes (1869) Telephony: first telephone exchange in New Haven, Connecticut Edison opens first electric utility in New York City (1882): dc power systems Waterwheel-driven dc generator installed in Appleton, Wisconsin (1882) First transmission lines installed in Germany (1882), 2400 V dc, 59km Dc motor by Sprague (1884) Commercially practical transformer by Stanley (1885) Steinmetz's ac circuit analysis Tesla's papers on ac motors (1888) Radio waves: Hertz (1888) First single-phase ac transmission line in United States (1889): Ac power systems, Oregon City to Portland, 4 kV, 21 km First three-phase ac transmission line in Germany (1891), 12 kV, 179 km First three-phase ac transmission line in California (1893), 2.3 kV, 12 km Generators installed at Niagara Falls, New York Heaviside's operational calculus methods

1900–1920	Marconi's wireless telegraph system: transatlantic communication (1901) Photoelectric effect: Einstein (1904) Vacuum-tube electronics: Fleming (1904), DeForest (1906) First AM broadcasting station in Pittsburgh, Pennsylvania Regenerative amplifier: Armstrong (1912)
1920–1940	Television: Farnsworth, Zworykin (1924) Cathode-ray tubes by DuMont; experimental broadcasting Negative-feedback amplifier by Black (1927) Boolean-algebra application to switching circuits by Shannon (1937)
1940–1950	Major advances in electronics (World War II) Radar and microwave systems: Watson-Watts (1940) Operational amplifiers in analog computers FM communication systems for military applications System theory papers by Bode, Shannon, and Wiener ENIAC vacuum-tube digital computer at the University of Pennsylvania (1946) Transistor electronics: Shockley, Bardeen, and Brattain of Bell Labs (1947) Long-playing microgroove records (1948)
1950–1960	Transistor radios in mass production Solar cell: Pearson (1954) Digital computers (UNIVAC I, IBM, Philco); Fortran programming language First commercial nuclear power plant at Shippingport, Pennsylvania (1957) Integrated circuits by Kilby of Texas Instruments (1958)
1960–1970	Microelectronics: Hoerni's planar transistor from Fairchild Semiconductors Laser demonstrations by Maiman (1960) First communications satellite *Telstar I* launched (1962) MOS transistor: Hofstein and Heiman (1963) Digital communications 765 kV AC power lines constructed (1969) Microprocessor: Hoff (1969)
1970–1980	Microcomputers; MOS technology; Hewlett-Packard calculator INTEL's 8080 microprocessor chip; semiconductor devices for memory Computer-aided design and manufacturing (CAD/CAM) Interactive computer graphics; software engineering Personal computers; IBM PC Artificial intelligence; robotics Fiber optics; biomedical electronic instruments; power electronics
1980–Present	Digital electronics; superconductors Neural networks; expert systems High-density memory chips; digital networks

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