

ELECTROMAGNETICS

JOHN D. KRAUS

Fourth Edition

ELECTROMAGNETICS

Fourth Edition

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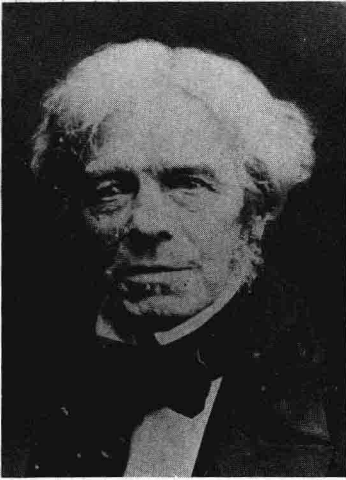
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*To **Michael Faraday**, who performed the pioneering experiments, . . .*



*To **James Clerk Maxwell**, who used them to formulate the all-encompassing theory of electromagnetics, . . . and*



*To **Heinrich Hertz**, whose experiments validated the theory and gave us radio.*

ABOUT THE AUTHOR

John D. Kraus was born in Ann Arbor, Michigan, in 1910 and received his Ph.D. degree in physics from the University of Michigan in 1933. He then did research in nuclear physics with Michigan's newly completed 100-ton cyclotron until World War II when he worked on the degaussing of ships for the U.S. Navy and on radar countermeasures at Harvard University. After the war he came to the Ohio State University where he is now Director of the Radio Observatory and McDougal Professor (Emeritus) of Electrical Engineering and Astronomy.

Dr. Kraus is the inventor of the helical antenna, the workhorse of space communication, the corner reflector, used by the millions for television reception, and many other types of antennas. He designed and built the giant Ohio radio telescope known as "Big Ear." He is the holder of many patents and has published hundreds of scientific and technical articles. He is also the author of the widely used classic textbooks *Antennas* (McGraw-Hill, 1950, second edition 1988), considered to be the "Antenna Bible"; *Electromagnetics* (McGraw-Hill, 1953, second edition 1973, third edition, 1984, and this, the fourth edition, 1992); and *Radio Astronomy* (McGraw-Hill, 1966, second edition, Cygnus-Quasar, 1986). In addition he has written two popular books *Big Ear* (1976) and *Our Cosmic Universe* (1980).

Dr. Kraus received the U.S. Navy Meritorious Civilian Service Award in 1946. He was made a Fellow of the Institute of Electrical and Electronic Engineers (IEEE) in 1954 and was elected to the National Academy of Engineering in 1972. He received the Sullivant Medal, Ohio State University's top award, in 1970; the Outstanding Achievement Award of the University of Michigan in 1981; the Distinguished Achievement Award of the IEEE Antennas and Propagation Society in 1985; and three IEEE medals: Centennial in 1984, Edison in 1985, and Heinrich Hertz in 1990.

Currently, Dr. Kraus is teaching while serving as consultant to government and industry.

This new edition is an extensive revision, presenting the basic elements of electromagnetics for the 1990s. Topics are developed in easy steps from the simplest cases to more general ones with the theory applied to numerous practical situations.

A brief history of electromagnetics sets the stage in *Chapter 1* followed by sections on dimensions and units. Chapter 1 also includes a new, concise treatment of vector analysis, vector point relations, and coordinate systems which can introduce a student to these topics or serve as a review. *Chapter 2* presents the static electric field through atomic energy levels, line integrals, gradient and Gauss's law. It also includes new sections on the moment method (MM), the earth capacitor, and the automatic electrostatic autopilot. Gauss's law is the first of the four Maxwell equations, which we develop as we go through the book. These equations are the unifying theme of electromagnetics and are all brought together in *Chapter 11*.

Chapter 3 covers charged particles moving in electric fields with a focus on applications: the cathode-ray tube, an ink-jet printer, electrostatic precipitators and separators, electrostatic painting, static eliminators, and the xerographic copier. *Chapter 4* explains electric field in dielectrics and introduces us to dipoles, dipole moments, polarization, boundary relations, transmission lines, divergence, Maxwell's equation from Gauss, and the Laplace operator. Advancing from electric fields to electric currents, we learn in *Chapter 5* about Ohm's law, Kirchhoff's law, semiconductors, superconductors, lightning, grounding, and shielding. The magnetic fields of currents and their effects are covered in *Chapter 6* with sections on forces, torques, moments, inductance, and Ampère's law. Many practical applications of magnetic fields are described in *Chapter 7*. These include cyclotron, particle separators, magnetic mirrors, motors (both rotary and linear), magnetic levitation, Hall effect, and the magnetic brake.

The phenomenon of ferromagnetism is treated in *Chapter 8* with sections on hysteresis, permanent magnets, lifting magnets, magnetic energy, and the universality of a field map to electric magnetic and current cases. Dipoles, loops, and solenoids are also compared.

Chapter 9 presents Laplace's equation and its application to boundary value problems using analytical, numerical, computer, and analog techniques, with many examples, including a semiconductor junction.

With *Chapter 10*, we progress from static fields to time-changing electric and magnetic fields. This chapter covers Faraday's law, induction, Maxwell's equation from Faraday, Stokes's theorem, self- and mutual inductance, eddy currents, Maxwell's equation from Ampère, displacement current, dielectric hysteresis, and boundary relations with a new section on push-pull propulsion of magnetically levitated (Maglev) vehicles. *Chapter 11* brings Maxwell's equations, as developed in earlier chapters, together and illustrates the interrelation of field and circuit theory.

Waves and transmission lines, with sections on coaxial, two-wire and field-cell lines, the terminated line, line matching, the Smith Chart, line transformers, bandwidths, S parameters, traveling and standing waves, absorbers, the axon, and shielding are discussed in *Chapter 12*. *Chapter 13* gives a concise treatment of wave polarization, reflection, refraction, and diffraction with sections on Huygen's principle, physical optics, and geometrical optics.

Waveguides and resonators, are covered in *Chapter 14* with discussions on rectangular and cylindrical hollow waveguides, open guides, fiber optics guides, and cavity resonators. This chapter includes new sections on electromagnetic compatibility chambers, microwave ovens, and dielectric resonators. *Chapter 15* gives a condensed presentation of basic antenna theory with application to the short, $\lambda/2$ and $3\lambda/2$ dipoles and includes a new section on 22 practical antennas with data sufficient to design most of them. The chapter concludes with radio links, the Friis formula, radar, antenna temperature, signal-to-noise ratio, and remote sensing. Finally, the *Appendix* has some useful tables, references, and answers to starred problems.

There are over 1000 problems ranging from drill to very practical which cover all levels of difficulty. More than 90 percent of the problems are new. The problems constitute an important extension of the text, many topics being included that are not in the main text.

With the problem sets or in *Appendix B* are 15 computer programs for running on PCs (personal computers). The programs include V-LEVEL (potentials of charge configurations); V-COLOR (potentials in full color display); REPLA (repetitive Laplace) for potentials in a conducting enclosure; POST (potentials around a post projecting into a previously uniform field); BOUNCING PULSES and TRAVELING WAVES (on a transmission line); TERMINATED LINE (impedance along a line); LOSSY LINE (voltage and phase on a lossy line); SMITH CHART; and ARRAYPATGAIN (pattern and gain of antenna arrays). Appendix B includes a directory of the computer programs. All the programs in the book are on a diskette which accompanies a solutions manual available to instructors. I hope instructors will make the diskette or copies of it available to students.

Since many students now have PCs or access to one, or to computer terminals connected to larger computers, these easy-to-run programs can provide a valuable instructional supplement to the text. Potential plots, field maps, waves on lines, and antenna patterns are so easily shown on a screen that many different variations

can be quickly tried, supplementing the book examples with dozens more over a wide range of parameters and providing insights that would be very difficult to obtain otherwise.

Although an objective of problem solving is to obtain an answer, I have endeavored to also provide insights as to how many of the problems relate to engineering situations in the real world. Thus, problems involving engineering feasibility and/or design of practical devices may have multiple or indefinite solutions. Few real-world engineering problems have a single exact answer due to the compromises and trade-offs required in practice.

There are many ways of adapting this new edition to a variety of course requirements. Many sequences for courses ranging from 10 to 30 weeks in length are listed in the solutions manual available to instructors. As prerequisites, the student is assumed to have a knowledge of introductory physics and mathematics through differential and integral calculus.

Not only is electromagnetics basic to a complete electrical engineering curriculum, but it is three-dimensional. Much of electrical engineering is one- or two-dimensional. However, we live in a three-dimensional world, and one of the great values of electromagnetics is that it makes one familiar with 3-D concepts. These are introduced early in the book.

It would not have been possible to prepare this edition without the dedicated assistance of Dr. Erich Pacht, who has been involved in all aspects of the editorial process. He also wrote one of the computer programs and checked all the others. Kristine Hall has provided unusually capable assistance on the manuscript preparation. I have also benefited from the comments and suggestions of many others who have been kind enough to read sections or entire chapters. These include Professor Jim Akers of Mississippi State University; Richard Mallozzi, Harvard University junior; Professors Steven Bibyk, Stuart Collins, Robert Garbacz, Daniel Hodge, Professors Benedikt Munk, William Peake, Jack Richmond, and Roger Rudduck of The Ohio State University; Paul Khanna of Avantek, Inc.; Maynard Hill of H-Cubed Corp.; and the following reviewers for McGraw-Hill Inc.: Robert Engelken, Arkansas State University; Ronald J. Gutmann, Rensselaer Polytechnic Institute; Herbert Hacker, Duke University; Glenn S. Smith, Georgia Institute of Technology; and James C. Rogers, Michigan Technological University. Professor Akers also supplied two computer programs. Three programs were kindly provided by Harry Shamansky of The Ohio State University Electro-Science Laboratory with the assistance of Weihung Lin. The McGraw-Hill editors, Lyn Beamesderfer and James W. Bradley were also most helpful. Thus, the book is a cooperative team effort of many persons.

Finally, I thank my wife, Alice, for her patience, encouragement, and dedication through all the years of work it has taken.

John D. Kraus

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