教育部高等教育司推荐
国外优秀信息科学与技术系列教学用书

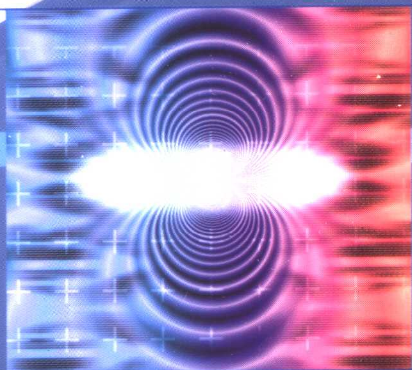
麦克斯韦方程

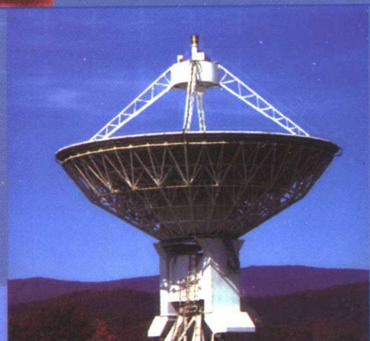
影印版

MAXWELL EQUATIONS

• JIN AU KONG

EMW





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前　　言

20 世纪末，以计算机和通信技术为代表的信息科学和技术对世界经济、科技、军事、教育和文化等产生了深刻影响。信息科学技术的迅速普及和应用，带动了世界范围信息产业的蓬勃发展，为许多国家带来了丰厚的回报。

进入 21 世纪，尤其随着我国加入 WTO，信息产业的国际竞争将更加激烈。我国信息产业虽然在 20 世纪末取得了迅猛发展，但与发达国家相比，甚至与印度、爱尔兰等国家相比，还有很大差距。国家信息化的发展速度和信息产业的国际竞争能力，最终都将取决于信息科学技术人才的质量和数量。引进国外信息科学和技术优秀教材，在有条件的学校推动开展英语授课或双语教学，是教育部为加快培养大批高质量的信息技术人才采取的一项重要举措。

为此，教育部要求由高等教育出版社首先开展信息科学和技术教材的引进试点工作。同时提出了两点要求，一是要高水平，二是要低价格。在高等教育出版社和信息科学技术引进教材专家组的努力下，经过比较短的时间，第一批引进的 20 多种教材已经陆续出版。这套教材出版后受到了广泛的好评，其中有不少是世界信息科学技术领域著名专家、教授的经典之作和反映信息科学技术最新进展的优秀作品，代表了目前世界信息科学技术教育的一流水平，而且价格也是最优惠的，与国内同类自编教材相当。

这项教材引进工作是在教育部高等教育司和高教社的共同组织下，由国内信息科学技术领域的专家、教授广泛参与，在对大量国外教材进行多次遴选的基础上，参考了国内和国外著名大学相关专业的课程设置进行系统引进的。其中，John Wiley 公司出版的贝尔实验室信息科学研究中心副总裁 Silberschatz 教授的经典著作《操作系统概念》，是我们经过反复谈判，做了很多努力才得以引进的。William Stallings 先生曾编写了在美国深受欢迎的信息科学技术系列教材，其中有多种教材获得过美国教材和学术著作者协会颁发的计算机科学与工程教材奖，这批引进教材中就有他的两本著作。留美中国学者 Jiawei Han 先生的《数据挖掘》是该领域中具有里程碑意义的著作。由达特茅斯学院的 Thomas Cormen 和麻省理工学院、哥伦比亚大学几位学者共同编著的经典著作《算法导论》，在经历了 11 年的锤炼之后于 2001 年

出版了第二版。目前任教于美国 Massachusetts 大学的 James Kurose 教授，曾在美国三所高校先后 10 次获得杰出教师或杰出教学奖，由他主编的《计算机网络》出版后，以其体系新颖、内容先进而倍受欢迎。在努力降低引进教材售价方面，高等教育出版社做了大量和细致的工作。这套引进的教材体现了权威性、系统性、先进性和经济性等特点。

教育部也希望国内和国外的出版商积极参与此项工作，共同促进中国信息技术教育和信息产业的发展。我们在与外商的谈判工作中，不仅要坚定不移地引进国外最优秀的教材，而且还要千方百计地将版权转让费降下来，要让引进教材的价格与国内自编教材相当，让广大教师和学生负担得起。中国的教育市场巨大，外国出版公司和国内出版社要通过扩大发行数量取得效益。

在引进教材的同时，我们还应做好消化吸收，注意学习国外先进的教学思想和教学方法，提高自编教材的水平，使我们的教学和教材在内容体系上，在理论与实践的结合上，在培养学生的动手能力上能有较大的突破和创新。

目前，教育部正在全国 35 所高校推动示范性软件学院的建设和实施，这也是加快培养信息科学技术人才的重要举措之一。示范性软件学院要立足于培养具有国际竞争力的实用性软件人才，与国外知名高校或著名企业合作办学，以国内外著名 IT 企业为实践教学基地，聘请国内外知名教授和软件专家授课，还要率先使用引进教材开展教学。

我们希望通过这些举措，能在较短的时间，为我国培养一大批高质量的信息技术人才，提高我国软件人才的国际竞争力，促进我国信息产业的快速发展，加快推动国家信息化进程，进而带动整个国民经济的跨越式发展。

教育部高等教育司

二〇〇二年三月

PREFACE

My original book *Electromagnetic Wave Theory* was published in 1975 by Wiley Interscience, New York, entitled *Theory of Electromagnetic Waves,* which was based on my 1968 Ph.D. thesis, where the concept of bianisotropic media was introduced. The book was expanded and published by the same Publisher in 1986 with the title *Electromagnetic Wave Theory*, and its second edition appeared in 1990. It was subsequently published by EMW Publishing Company, Massachusetts. This textbook on *Maxwell Equations* is distilled from the introductory part of *Electromagnetic Wave Theory.*

Starting with James Clerk Maxwell's life and his theory, the Maxwell Equations and their implications and applications are studied in detail. Chapter 1 presents Maxwell Equations in the familiar mathematical form. Chapter 2 studies the various fundamental concepts of Maxwell Equations. A fundamental unit $K_o = 2\pi$ meter^{-1} for spatial frequency is introduced. Chapter 3 illustrates the fundamental importance of the wave vector $\overline{k}$. Chapter 4 examines transmission lines and circuit theory in time domain. Chapter 5 introduces complex notation for continuous waves and employs the transmission line theory to demonstrate some useful concepts. At the end of each section, exercises and problems are designed to provide useful examples for practice and applications.

During the writing and preparation of this and the previous books, many of my teaching and research assistants provided useful suggestions and proof-reading, notably Leung Tsang, Michael Zuniga, Weng Cho Chew, Tarek Habashy, Robert Shin, Shun-Lien Chuang, Jay Kyoon Lee, Apo Sezginer, Soon Yun Poh, Eric Yang, Michael Tsuk, Hsiu Chi Han, Yan Zhang, Henning Braunisch, Chi On Ao, and Bae-Ian Wu. I would like to express my gratitude to them and to the many students whose enthusiastic response and feedback continuously give me joy and satisfaction in teaching.

J. A. Kong
Cambridge, Massachusetts
March 2002

CONTENTS

1

MAXWELL'S THEORY

What is done by what is called myself is, I feel, done by something greater than myself in me.

– Maxwell, 1879

1.1 Maxwell's Equations

Maxwell's equations are mathematical expressions of the laws of nature in a precise and accurate form. There are different ways using different symbols and notations to display the same mathematical formulation, similar to using different languages and dialogues to express the same idea or concept. This book is devoted to the exposition and explanation of Maxwell's equations in the following mathematical form:

$$\nabla \times \overline{H} = \frac{\partial}{\partial t} \overline{D} + \overline{J} \tag{1.1.1}$$

$$\nabla \times \overline{E} = -\frac{\partial}{\partial t} \overline{B} \tag{1.1.2}$$

$$\nabla \cdot \overline{D} = \rho \tag{1.1.3}$$

$$\nabla \cdot \overline{B} = 0 \tag{1.1.4}$$

where $\overline{E}$, $\overline{B}$, $\overline{H}$, $\overline{D}$, $\overline{J}$, and ρ are all functions of space $\overline{r}$ and time t.

$\overline{H}(\overline{r}, t)$ = magnetic field strength (amperes/m)

$\overline{E}(\overline{r}, t)$ = electric field strength (volts/m)

$\overline{B}(\overline{r}, t)$ = magnetic flux density (webers/m^2)

$\overline{D}(\overline{r}, t)$ = electric displacement (coulombs/m^2)

$\rho(\overline{r}, t)$ = electric charge density (coulombs/m^3)

$\overline{J}(\overline{r}, t)$ = electric current density (amperes/m^2)

Equation (1.1.1) is Ampère's law or the generalized Ampère circuit law. Equation (1.1.2) is Faraday's law or Faraday's magnetic induction law. Equation (1.1.3) is Coulomb's law or Gauss' law for electric fields. Equation (1.1.4) is Gauss' law or Gauss' law for magnetic fields. We generally refer to $\overline{E}$ and $\overline{D}$ as electric fields, and $\overline{H}$ and $\overline{B}$ as magnetic fields.

Maxwell's contribution to the laws of electricity and magnetism is the term $\partial\overline{D}/\partial t$, which is called the displacement current. The addition of the displacement current to the electric current density $\overline{J}(\overline{r},t)$ in the original Ampère's law has at least three major consequences. First, in a capacitor which is an open circuit for direct current, the displacement current insures the continuity of alternating currents in electric circuits. Secondly, the continuity law follows from taking divergence of (1.1.1) and making use of (1.1.3)

$$\nabla\cdot\overline{J}(\overline{r},t)=-\frac{\partial}{\partial t}\rho(\overline{r},t) \tag{1.1.5}$$

which states that the electric current and charge densities at $\overline{r}$ are conserved for all time t. The divergence of current $\overline{J}$ from an infinitesimal volume surrounding $\overline{r}$ is equal to the decreasing of electric charge density ρ with time t. Thirdly, Faraday's law in (1.1.2) states that surrounding a time-varying magnetic field, electric fields are produced, and are also time-varying. With the displacement term in (1.1.1), Ampère's law states that around time-varying electric fields, time-varying magnetic fields are produced. This interrelationship between the time-varying electric and magnetic fields constitutes the foundation of electromagnetic wave theory and led Maxwell to the prediction of electromagnetic waves.

At the conceptual level, the development of the *field* concept to account for action of bodies at a distance is of paramount importance. Inspired by Faraday's concept of *lines of force*, Maxwell published his papers 'On Faraday's Lines of Forces' in 1855, 'On Physical Lines of Force' in 1861, and 'A Dynamical Theory of the Electromagnetic Field' in December 1864. In 1865, at age 33, he retired to his country home estate and spent six years to write his monumental book 'A Treatise of Electricity and Magnetism', which was published in 1873. The field concept established by him has fundamental and profound impact on scientific and philosophical developments.

In 1888, Heinrich Rudolf Hertz (1857–1894) demonstrated the generation of radio waves and experimentally verified Maxwell's theory. Since then, electromagnetic theory has played a central role in the development of radio, television, wireless communications, radar, microwave heating, remote sensing, and numerous other practical applications. The special theory of relativity developed by Albert Einstein (1879–1955) in 1905 further asserted the rigorousness and elegance of Maxwell's theory. As a well-established scientific discipline, this sophisticated theoretical structure embodies many principles and concepts which serve as fundamental rules of nature and vital links for all scientific disciplines.

A. Maxwell's Aether

In developing his theory for the electromagnetic fields in space and time, Maxwell conceived of a substance filling the whole space called aether. In the aether, the electric fields $\overline{D}$ and $\overline{E}$ are related by a dielectric permittivity ϵ_o, and the magnetic fields $\overline{B}$ and $\overline{H}$ are related by a magnetic permeability μ_o.

$$\overline{D} = \epsilon_o \overline{E} \qquad \epsilon_o \approx 8.85 \times 10^{-12} \text{ farad/meter} \qquad (1.1.6a)$$

$$\overline{B} = \mu_o \overline{H} \qquad \mu_o = 4\pi \times 10^{-7} \text{ henry/meter} \qquad (1.1.6b)$$

where the numerical values for ϵ_o and μ_o are expressed in MKS units. We now call (1.1.6) the constitutive relations for free space.

Maxwell had modelled the aether hydrodynamically, mechanically, and molecularly as a luminiferous medium. He nevertheless avoided the hypothesis of a detailed model for the aether although the various models at different stages of developing his theory were indispensable in shaping his thoughts. Thus, I believe whether we call this medium aether or vacuum or free space or something else, or argue that there is no medium at all, is immaterial, for they are all described by the same constitutive relations.

In his paper 'A Dynamical Theory of the Electromagnetic Fields,' Maxwell stated: 'In speaking of the Energy of the field, however, I wish to be understood literally. ..... On our theory it resides in the electromagnetic field, in the space surrounding the electrified and magnetic bodies, as well as in those bodies themselves, and is in two different forms, which may be described without hypothesis as magnetic polarization and electric polarization'.

The constitutive relations (1.1.6) characterize Maxwell's aether. They can be extended to describe other media by adding an electric polarization vector and a magnetization vector. For a simple dielectric medium, for instance, ϵ_o can be simply replaced by a dielectric permittivity ϵ assuming values other than that for free space. Later, I shall generalize the constitutive relations to cover all media and in conformity with relativity.

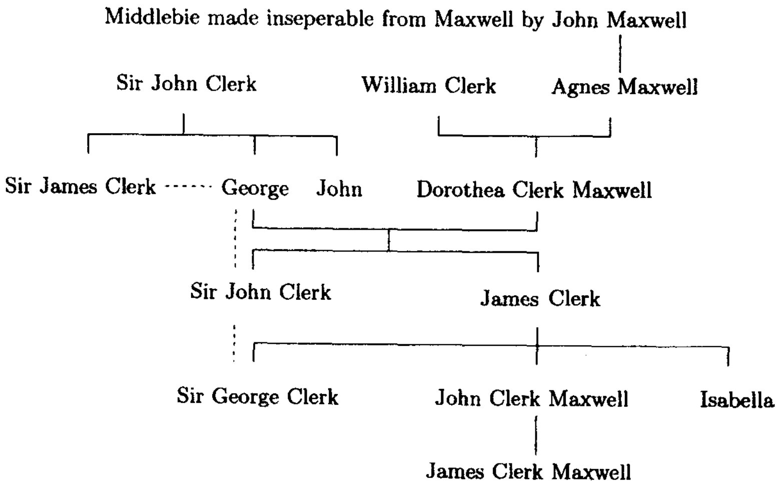
With Equations (1.1.1), (1.1.2), (1.1.3), (1.1.4) and (1.1.6), Maxwell's theory of electromagnetic fields is completely expressed. Yet Maxwell's theory was not accepted easily by the scientific community at his time, and skepticism was widespread, which included his long time friend Lord Kelvin. As Hertz remarked:

> 'What is Maxwell's theory? I cannot give any clearer or briefer answer than the following: Maxwell's theory is the system of Maxwell's equations.'

B. Maxwell's Life

James Clerk Maxwell was born on 13 June 1831 in Edinburgh, Scotland. His father was John Clerk, who at age thirty six, married Frances Cay, thirty four. They first had a daughter Elizabeth who died in infancy. At almost forty years old, Frances gave birth to James Clerk Maxwell, their only child. When Maxwell was eight years old, his mother died of abdominal cancer on 6 December 1839 at age nearly forty eight.

Maxwell's last name was originally Clerk. His grandfather was Captain James Clerk, a sea captain in the service of the Honourable East India Company, which was responsible for Britain's trade and authority in India. In order for his son John Clerk to inherit the country estate of Middlebie from the Maxwell family, the surname of Maxwell was added and he became John Clerk Maxwell.



The estate of Middlebie was made inseparable from the name of Maxwell in 1722 by John Maxwell, father of Agnes Maxwell. Agnes Maxwell married William Clerk, and had a daughter Dorothea, who was left orphan at age seven. William Clerk Maxwell was younger brother of Sir John Clerk of Penicuik, who arranged the marriage of his second son, George Clerk, at age 20, with his cousin Dorothea Maxwell, heiress of Middlebie, at age 17, thus keeping the estate of Middlebie in the family. In 1755, Sir John Clerk was succeeded by his elder son, Sir James Clerk. Sir James Clerk died in 1782 without children, and was succeeded by his next brother, George Clerk Maxwell, who had sold most of the Middlebie estate and kept the part at Glenlair.

Sir George Clerk Maxwell died in 1784 and was succeeded by his elder son, Sir John Clerk. His younger son, Captain James Clerk, who died in 1793, had two sons, George and John, and a daughter Isabella. The elder son George Clerk succeeded to Penicuik to become Sir George Clerk when his uncle Sir John Clerk died in 1798 without children. The younger son John Clerk succeeded to the property of Middlebie from his grandmother Dorothea Clerk Maxwell and added the surname of Maxwell.

In order to be near his sister Isabella Wedderburn, John Clerk Maxwell and his mother in 1820 moved to 14 India Street in Edinburgh. His mother died in 1824 and in October 1826, he married Frances Cay. Soon after James Clerk Maxwell was born, John Clerk Maxwell and his wife moved to Glenlair to raise their son. Thus if it had not been for the estate of Glenlair, Maxwell equations would have been called Clerk equations.

On the other hand, if it had not been for the estate of Glenlair, I think the birth place of Maxwell's equations would have been London or Cambridge or possibly nowhere. Glenlair is the home farm of the original estate of Middlebie. James Clerk Maxwell spent his childhood in Glenlair until he was 10 years old. During his studying and working periods, he frequently returned to the country home of Glenlair to nourish his thoughts and to renew his intellectual initiatives. Had it not been for the wealth of the Maxwell inheritance, he may not have had the means to retire to Glenlair from 1865 to 1871 to write his monumental work 'A Treatise of Electricity and Magnetism' and produce the Maxwell equations.

At age 10, in November 1841, Maxwell was sent to the Edinburgh Academy, where he had the nickname 'Dafty'. He lodged with his father's widowed sister Isabella Wedderburn at 31 Heriot Row, and sometimes at 6 Great Stuart Street, Edinburgh, with his mother's sister, Aunt Jane, who was never married. He gained friends Peter Guthrie Tait, future Professor of Natural Philosophy at Edinburgh University, and Lewis Campbell, future Professor of Classics at St Andrews University and his eventual biographer. In early 1846 at the age of 14, Maxwell published his first paper on the description of oval curves.

At age 16, in October 1847, Maxwell entered Edinburgh University. There, for three years, he would learn natural philosophy (physics) under James Forbes' lecturing. In July and early August 1850, at the meeting of the British Association for the Advancement of Science in Edinburgh, he confronted Sir David Brewster on the issue of whether attributing the observational effect of polarized lights to the retina or the cornea of the eye. Professor George Gabriel Stokes and William Thomson (later Lord Kelvin) were also presented at the meeting.

At age 19, in October 1850, Maxwell went to Peterhouse, the oldest college Cambridge University had. In December 1850, he moved to Trinity College and in October 1851 he became a pupil of William Hopkins. Maxwell obtained a scholarship in April 1852 and graduated with a degree in mathematics from Trinity College in 1854. In October 1855, he became Fellow of Trinity College after failing in his first attempt to obtain the fellowship. His paper 'On Faraday's Lines of Force' was read to the Cambridge Philosophical Society in two parts, in 1855 and 1856.

At age 24, on 3 April 1856, Maxwell's father died. In November 1856, Maxwell was appointed Professor of Natural Philosophy at Marischal College in Aberdeen. His research work at Aberdeen was dominated by Saturn's rings. He showed that stability could be achieved only if the rings consisted of numerous small solid particles, an explanation confirmed over one hundred years later by the first Voyager space probe to reach Saturn.

At age 26, on 2 June 1858, he married Katherine Mary Dewar, age 33, daughter of the principal of Marischal College. They had no children. In September 1859 he read to the British Association of Aberdee his paper 'Illustrations of the Dynamical Theory of Gases', in which he showed that the velocity distribution of molecules was "Maxwellian".

At age 28, in January 1860, Maxwell was out of job when the Marischal College and King's College merged to become the University of Aberdeen. Earlier, Maxwell declared himself a fusionist for retaining one professor per subject, instead of a unionist favoring retaining both sets of professors. However when the two colleges fused, he was declared redundant and the position of Professor on Natural Philosophy went to King's College Professor David Thomson, who was a nephew of Michael Faraday and taught William Thomson for a time at Glasgow. Maxwell fought to retain his position to no avail. He became a candidate for the Professorship of Natural Philosophy at Edinburgh University. The position was vacated by James Forbes who took the appointment of Principal of the United Colleges at St. Andrews to succeed Sir David Brewster, who had become the principal of the University of Edinburgh in 1859. Maxwell was defeated by his old friend P. G. Tait.

At age 29, in July 1860 he was appointed Professor of Natural Philosophy at King's College, London, to reside at 8 Palace Gardens Terrace, Kensington. In May 1861 he presented his lecture on 'On the Theory of Three Primary Colours' at the Royal Institution of Great British. In 1861–62, he published in *Philosophical Magazine* 'On Physical Lines of Force.' On 8 December 1864, he read to the Royal Society his paper 'A Dynamical Theory of the Electromagnetic Field'.

At age 33, in February 1865, Maxwell resigned from King's College and went into retirement. In 1866 he published his paper 'On the Dynamical Theory of Gases' in the Philosophical Transactions. In November 1868, James Forbes retired from the position of the Principal of St. Andrews. Maxwell made an effort to apply for the position but failed. In his retirement he produced the book 'A Treatise of Electricity and Magnetism', which was published in 1873.

At age 39, in March 1871, Maxwell was selected to be the first Cavendish Professor of Experimental Physics at the Cambridge University. He was urged by Stokes and John William Strutt (later Lord Rayleigh) to apply after Thomson in Glasgow, and Helmholtz in Berlin turned down the job. Maxwell directed the construction of the Cavendish Laboratory from 1872 to 1874 and was its first director. The Laboratory was formally opened on 16 June 1874.

At age 48, on 5 November 1879, Maxwell died of abdominal cancer in Cambridge, England. He was buried in the Corsock churchyard of Parton Kirkyard, north of Castle Douglas, near his beloved Glenlair. His Cavendish Laboratory directorship was succeeded by Strutt and his Glenlair ownership was passed on to his cousin Andrew Wedderburn Maxwell.

Lewis Campbell at the end of his biography of Maxwell, presented his own tributes: 'The leading note of Maxwell's character is a grand simplicity. But in attempting to analyse it we find a complex of qualities which exist separately in smaller men. Extraordinary gentleness is combined with keen penetration, wonderful activity with a no less wonderful repose, personal humility and modesty with intellectual scorn. His deep reserve in common intercourse was commensurate with the fulness of his occasional outpourings to those he loved. His tenderness for all living things was deep and instinctive; from earliest childhood he could not hurt a fly. Not less instinctive was the sense of equality amongst all human beings, which underlay the plainness of his address. But, on the other hand, his respect for the actual order of the world and for the wisdom of the past, was at least steadfast as his faith in progress. While fearless in speculation, he was strongly conservative in practice.'

In the words of Maxwell himself:

'Every great man of the first rank is unique. Each has his own office and his own place in the historic procession of the sages. That office did not exist even in the imagination, till he came to fill it, and none can succeed to his place when he has passed away.'