



LIQUID CRYSTAL DISPLAYS

Fundamental Physics and Technology

Robert H. Chen

 WILEY

 SID

Series in Display Technology

Liquid Crystal Displays

Wiley-SID Series in Display Technology

Series Editor:

Anthony C. Lowe

Consultant Editor:

Michael A. Kriss

Display Systems: Design and Applications

Lindsay W. MacDonald and Anthony C. Lowe (Eds.)

Electronic Display Measurement: Concepts, Techniques, and Instrumentation

Peter A. Keller

Reflective Liquid Crystal Displays

Shin-Tson Wu and Deng-Ke Yang

Colour Engineering: Achieving Device Independent Colour

Phil Green and Lindsay MacDonald (Eds.)

Display Interfaces: Fundamentals and Standards

Robert L. Myers

Digital Image Display: Algorithms and Implementation

Gheorghe Berbecel

Flexible Flat Panel Displays

Gregory Crawford (Ed.)

Polarization Engineering for LCD Projection

Michael G. Robinson, Jianmin Chen, and Gary D. Sharp

Fundamentals of Liquid Crystal Devices

Deng-Ke Yang and Shin-Tson Wu

Introduction to Microdisplays

David Armitage, Ian Underwood, and Shin-Tson Wu

Mobile Displays: Technology and Applications

Achintya K. Bhowmik, Zili Li, and Philip Bos (Eds.)

Photoalignment of Liquid Crystalline Materials: Physics and Applications

Vladimir G. Chigrinov, Vladimir M. Kozenkov and Hoi-Sing Kwok

Projection Displays, Second Edition

Matthew S. Brennesholtz and Edward H. Stupp

Introduction to Flat Panel Displays

Jiun-Haw Lee, David N. Liu and Shin-Tson Wu

LCD Backlights

Shunsuke Kobayashi, shigeo Mikoshiba and Sungkyoo Lim (Eds.)

Liquid Crystal Displays: Addressing Schemes and Electro-Optical Effects, Second Edition

Ernst Lueder

Transflective Liquid Crystal Displays

Zhibing Ge and Shin-Tson Wu

Liquid Crystal Displays: Fundamental Physics and Technology

Robert H. Chen

Liquid Crystal Displays

Fundamental Physics and Technology

Robert H. Chen

National Taiwan University

 **WILEY**

A John Wiley & Sons, Inc., Publication

Copyright © 2011 by John Wiley & Sons, Inc. All rights reserved

Published by John Wiley & Sons, Inc., Hoboken, New Jersey
Published simultaneously in Canada

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permissions>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Chen, Robert H., 1947-

Liquid crystal displays : fundamental physics & technology / Robert H. Chen.
p. cm.

Includes index.

ISBN 978-0-470-93087-8 (cloth)

1. Liquid crystal displays. 2. Liquid crystal devices. I. Title.

TK7872.L56C44 2011

621.3815'422-dc22

2010045220

Printed in the United States of America

Obook ISBN 978-1-118-08435-9

ePDF ISBN 978-1-118-08433-5

ePub ISBN 978-1-118-08434-2

10 9 8 7 6 5 4 3 2 1

Contents

Series Editor's Foreword <i>by Anthony C. Lowe</i>	xiii
Preface	xv
Acknowledgments	xvii
About the Author	xix
1 Double Refraction	1
Reference	4
2 Electromagnetism	5
Faraday's Intuitive Field	7
Maxwell's Equations	9
The Derivation of $\nabla \circ E = \frac{\rho}{\epsilon}$	12
The Derivation of $\nabla \circ B = 0$	14
The Derivation of $\nabla \times E = -\frac{\partial B}{\partial t}$	15
The Derivation of $\nabla \times B = \epsilon\mu \frac{\partial E}{\partial t} + \mu J$	19
Vector Analysis	22
Light Is an Electromagnetic Wave	25
The Light Wave	30
References	34

3	Light in Matter	35
	The Electric Dipole Moment	38
	The Lorentz–Lorenz Equation	41
	References	47
4	The Polarization of an Electromagnetic Wave	49
	Unpolarized Light	49
	Elliptical, Linear, and Circular Polarization	50
	Elliptic Polarization	55
	Linear Polarization	56
	Circular Polarization	57
	Birefringence	61
	Ordinary and Extraordinary Waves	64
	Quantum Mechanical Polarization	66
	References	73
5	Liquid Crystals	75
	Carrots	76
	Liquid Crystal Genealogy	78
	The Chiral Nematic	82
	The Ferroelectric Chiral Smectic-C	86
	The Blue Flash	88
	Lyotropic Liquid Crystals	90
	The Director and the Order Parameter	91
	Stiff But Flexible	97
	Liquid Crystal Character	99
	Viscosity	100
	Elasticity	101
	The Induced Dipole Moment	103
	References	108
6	Thermodynamics for Liquid Crystals	111
	The Three Laws of Thermodynamics	113
	Phase Transitions	114
	Entropy	115
	The Boltzmann Distribution	119
	The Minimization of Free Energy	122
	References	123

7	The Calculus of Variations	125
	The Brachistochrone Problem	126
	Catenary and Suspension	131
	The Euler–Lagrange Equation	132
	Deeper Meanings of the Euler–Lagrange Equation	136
	References	138
8	The Mean Field	139
	Ideal Gas in Crystal Lattice	139
	Long Rod Models	140
	The Composite Electric Field and Average Index of Refraction	141
	The Dipole Mean Field Is Born	144
	References	145
9	Maier–Saupe Theory	147
	The Nematic to Isotropic Phase Transition Calculation	148
	Dielectric Anisotropy Calculation	152
	Near Neighbor Correlation	156
	References	159
10	Phenomenological Theory	161
	The Nematic to Isotropic Phase Transition Calculation	162
	Birefringence Calculation	165
	References	169
11	Static Continuum Theory	171
	Basic Principles	171
	Static Continuum Theory Examples	176
	The Twisted Only	176
	The Twist and Tilt	179
	The Tilt Only	180
	The Freedericksz Cell	181
	The Splay Tilt	182
	In-Plane Switching	185
	The Bend Perpendicular	187
	The Twisted Nematic	188
	In Memoriam	192
	References	192

12	Dynamic Continuum Theory	193
	Conservation Principles	196
	The Leslie Work Hypothesis	198
	Turn-On Example	202
	Hydrodynamic Instability	207
	Conclusion	208
	References	209
13	The First Liquid Crystal Display	211
	Dynamic Scattering	213
	The Liquid Crystal Display Calculator	214
	References	219
14	Liquid Crystal Display Chemistry	221
	The Aromatic Compounds	222
	The Search for a Robust Display Liquid Crystal	224
	References	230
15	The Twisted Nematic	231
	A Twist of Fate	234
	The Gathering Patent Storm	235
	Watches and Calculators	237
	References	238
16	Engineering the Liquid Crystal	239
	Poincaré Sphere	240
	Refractive Index Ellipsoid	240
	Jones Vector	240
	The Phase Retardation Parameter	241
	The Mauguin Condition	243
	The Gooch–Tarry Condition	244
	Twisted Nematic Waveguiding	245
	The Twisted Nematic Cell	246
	References	248
17	The Active Matrix	249
	Matrix Addressing	250
	The Super Twisted Nematic	254
	Active Matrix Addressing	256
	References	260

18	New Screens	261
	Twisted Nematic Television	262
	Notebook Computer Screens	263
	References	270
19	The Transistor and Integrated Circuit	271
	The Bohr Atom	271
	The Point Contact Transistor	278
	The Junction Transistor	281
	The Tyranny of Numbers	285
	Monolithic Component Integration	287
	Monolithic Circuit Integration	289
	References	294
20	A Transistor for the Active Matrix	295
	Hydrogenated Amorphous Silicon	298
	The Field Effect Transistor	299
	The a-Si:H Field Effect Thin-Film Transistor	303
	References	305
21	Semiconductor Fabrication	307
	Growing Crystals	308
	The Planar Process	308
	Photolithography	309
	Etch	312
	Deposition	314
	The Four-Mask Bottom Gate	315
	References	320
22	Enhancing the Image	321
	The Grayscale	323
	The On/Off Ratio	326
	The Production of Color	328
	The CCFL Backlight and Color Filter	333
	Field Sequential Color	336
	The LED Backlight	338
	Signal Processing	343
	References	347

23	The Wider View	349
	<i>c</i> -axis a-plate <i>c</i> -plate	352
	Mid-Layer Tilt	354
	Twisted Nematic Display Oblique Viewing	355
	Negative and Positive Compensation	356
	The Discotic Solution	357
	Grayscale Inversion	360
	Compensation Overview	364
	References	367
24	Liquid Crystal Television	369
	Vertical Alignment	369
	Multiple-Domain Vertical Alignment	372
	In-Plane Switching	376
	Fringing Field Switching	380
	Response Time	383
	VA Response Time Is Good	384
	IPS Response Time in Slow	386
	TN Is In-Between	387
	Blue Flash Is Fastest	388
	Overdrive	388
	Flicker	389
	References	395
25	Glass, Panels, and Modules	397
	Glass Generations	397
	The TFT Array Plate	400
	The Color Filter Plate	401
	Side Injection and One Drop Fill	403
	Side Injection	403
	One Drop Fill	404
	Spacers	405
	Sealing, Cutting, and Inspection	406
	Electrostatic Damage Protection	407
	Laser Repair	410
	Yield	410
	LCD Module Assembly	413
	References	414

26	The Global LCD Business	415
	RCA's Legacy	416
	Optical Imaging Systems	417
	The Electronics Manufacturing Paradigm	421
	Korea, the Emerging Economy Model	424
	The Crystal Cycle and Korea	425
	Crisis and Fortune in the LCD Industry	426
	Samsung Is the Lucky Goldstar	427
	Taiwan's Twin Stars	432
	Chimei Jumps into the Liquid Crystal Sea	434
	Two Tigers, Three Cats, and a Monkey	436
	Japan's Closed Shop	438
	The Worldwide Financial Tsunami	441
	Is China a Rising Liquid Crystal Star?	443
	The Solar Cell	446
	References	448
27	New Technologies and Products	449
	Light Scattering	450
	Liquid Crystal Polymer Composites	452
	Cholesteric Bistable Reflective Displays	454
	Ferroelectric Chiral Smectic-C Bistable Displays	455
	Electrophoretic Paper	456
	The Organic Light-Emitting Diode Display	457
	The Blue Phase Display	458
	Reflective Displays	458
	Transflective Displays	459
	Projection Displays	462
	Brightness Enhancement Film	467
	Touch Screens	468
	Resistive	468
	Strain Gauge	469
	Capacitive	469
	Inductive	470
	Surface Acoustic Wave	470
	Infrared	470
	Optical Imaging	470
	Dispersive Signal	471

3D	471
LCD Products	473
References	475
Index	477

Series Editor's Foreword

For once, I found it difficult to know how to begin. Writing forewords for the Wiley-SID series (this is my twentieth) is a demanding but extremely pleasurable task. In a qualitative sense this foreword is no different; it is the book that is different. Let me explain.

On reading two sample chapters of Robert Chen's manuscript, I realized that this would be like no other book in the series. Not only was its intended scope to cover the entirety of liquid crystal display (LCD) science and technology from the fundamentals of mathematics and physics to the production of products, but it was written by an author who has not only the academic background but also the experience as an executive in several major companies to provide first-hand insight and understanding of the global development of what is now a predominantly Asia-based industry.

The author has covered his subject matter with great proficiency and style. But there is more: the book is filled with interesting footnotes, often witty, of technical or historical relevance or a combination of all three. The most significant references are cited, but this is not a book where the reader will find a comprehensive list of all relevant publications. Other books in the series which address specific aspects of the technology provide that.

The unique feature of this book is that when discussing the global industrial development of the LCD industry, the author provides an account which is unprecedented—certainly in this series—in its level of detail, its understanding of cultural influences, and its degree of frankness. I believe

that few will disagree with his arguments, but some will find it uncomfortable reading.

So, as the author aspires, this book may be read at several different levels. Anyone who reads it will find it rewarding as a technical introduction to the field replete with a sense of history. They will realize that this industry, which has made most of its growth in the last two decades, is built on the shoulders of scientific progress going back two centuries. Last, but certainly not least, I hope that they will find it a first-rate literary experience.

Anthony C. Lowe
Series Editor

Braishfield, UK

Preface

The liquid crystal display (LCD) has become the principal modern medium for visual information and image appreciation. It is now a pervasive and increasingly indispensable part of our everyday lives. Apart from its utility, this marvelous device relies on a science and technology that I believe makes the device all the more attractive and interesting.

This book is organized to highlight the basic physics, chemistry, and technology behind this intriguing product, and while describing the LCD, I attempt to provide some insight into that physics, chemistry, and technology. I believe that the history of the development of the LCD is equally intriguing, and thus I make excursions into tales of the principal contributors and their achievements and thinking in their research. Finally, the allure of liquid crystal television has made it a coveted symbol of modern life worldwide, and so apart from the technical descriptions, I also describe how the LCD business has become a global enterprise.

I attempt to describe the physics and technology in a clear and simple manner understandable to an educated reader. Further, I have endeavored to pay attention to literary exposition as far as I am able, in the hope that, in addition to describing the technology, the book may also provide some literary enjoyment. Of course whether I have succeeded here depends on the reader's assessment.

This book is written at an introductory level suitable for advanced undergraduates and first-year graduate students in physics and engineering, and

as a reference for basic concepts for researchers. I also have tried to make the scientific and technical descriptions intuitively clear so that any educated person who has studied calculus can easily understand the exposition and thereby understand and appreciate liquid crystal displays and the science behind them.

Readers new to the field should read this book in chapter sequence to understand the gradual development of the LCD and the science and engineering involved; advanced researchers and practitioners can select the chapters and sections to find descriptions of the background of those selected topics.

Robert H. Chen

Taipei, Taiwan
June 2011

Acknowledgments

I would like to thank Professor Paul Nahin, for his books on mathematics and engineering from which I learned a great deal and borrowed liberally, and for his kind encouragement; Simone Taylor, Editorial Director at Wiley, who saw the potential of the manuscript and undertook the task of getting this book published while guiding me along the way; and most gratefully Dr. Anthony C. Lowe, the Editor of the Wiley-SID Series, who corrected mistakes and blocked metaphors (I am of course solely responsible for any that have gotten through). Further thanks are due to my wife Fonda, for her patient understanding; my daughter Chelsea, for cheerful enthusiasm; and my cat Amao, for accompanying me all the while. For my technical education, I would like to thank Dr. Hsu Chenjung, whose intelligence inspired me; Professor Andrew Nagy of Michigan and Professor Von Eshleman of Stanford, who supported me; and Chimei Optoelectronics Corporation where I learned about LCDs. Many of the drawings were done by Ingrid Hung at Chimei and Tsai Hsin-Huei of the National Taiwan University of Art.

About the Author

Robert Hsin Chen

Robert Hsin Chen is an adjunct professor at National Taiwan University and also teaches at Tsinghua and Jiaotong Universities in Taiwan. He was formerly a Senior Vice-President at Chimei Optoelectronics, a Director at Taiwan Semiconductor Manufacturing Company, Vice-President at Acer Corporation, and Of Counsel at the law firm Baker & McKenzie. Dr. Chen has a PhD from the University of Michigan (Space Physics Research Lab), a postdoctorate from Stanford University (Center for Radar Astronomy), and a JD from the University of California at Berkeley. He is a member of many scientific organizations, as well as the California Bar, and is a registered patent attorney; he has written many articles for international scientific and intellectual property journals, and is the author of *Made in Taiwan* (1997) and *Crystals, Physics, and Law* (in Chinese, 2010).

1

Double Refraction

The operation of liquid crystal displays is founded on the phenomenon of the double refraction of light as first recorded in Denmark by Erasmus Bartholinus in 1670. A piece of translucent calcite apparently divides incident light into two streams, producing a double image. This is depicted in Figure 1.1, as shown by the offset of the word “calcite.” At about the same time in the Netherlands, Christian Huygens discovered that the light rays through the calcite could be extinguished by passing them through a second piece of calcite if that piece were rotated about the direction of the ray; this is depicted in Figure 1.2. This may be observed by taking two pairs of polarizing sunglasses and rotating them relative to each other.

One hundred and thirty-eight years later, in 1808, a protégé of the famous French mathematician Fourier, Etienne Louis Malus, observed that light reflected from a window, when passing through a piece of calcite also would change intensity as the calcite was rotated, apparently showing that reflected light was also altered in some way. The intensity of the light changed in both cases because the molecules of calcite have a crystal order that affects the light in an intricate but very understandable way called *polarization*.



Figure 1.1 Double refraction in calcite. From <http://www.physics.gatech.edu/gcuo/lectures>.



Figure 1.2 Two pieces of calcite at an angle. From <http://www.physics.gatech.edu/gcuo/lectures>.

It would be another 80 years later in Austria that double refraction, also called *birefringence*, and light polarization would be observed, not in crystalline rocks, but in a viscous liquid, later to be called a “liquid crystal.” Although no doubt intriguing to natural scientists, intensive investigation of liquid crystals had to wait for yet another 80 years, when commercial interests provided the impetus for further study.

Briefly, a liquid crystal display can reproduce an image of a scene through the use of a video camera that, upon receiving the light reflected from the scene through its lens, in accord with the photoelectric effect first explained by Einstein, an electric current is generated in a metal when struck by light of sufficient energy, the current being proportional to the intensity of that light. That current is then transmitted to transistors that control an analog voltage that is applied to a pair of transparent electrode plates. Those plates enclose a thin layer of liquid crystal between them, and the voltage on the plates generates an electric field that is used to control the orientation of the electric dipole moment of the liquid crystal molecules, causing them to turn. Then light from a light source placed behind the liquid crystal layer, after being linearly polarized by a polarizer, will have its polarization states altered by the different orientations of the liquid crystal molecules, in accord with the liquid crystal’s degree of birefringence. The beauty of the liquid crystal display is that the birefringence effected by a liquid crystal is precisely controllable by that electric field. The different polarization states of the light in conjunction with a second polarizer changes the brightness of the light emanating from the backlight source, and that modulated brightness can represent the light intensity of the original scene; the millions of picture elements so produced then combine to form an image that replicates the original scene.

Liquid crystal displays thus are based on an optical phenomena of electrically controlled birefringence and polarization, which can only be understood through knowledge of the interaction of light and matter.

However, light may be familiar to everybody, but Samuel Johnson succinctly observed that [1]*

We all know what light is, but it is not easy to tell what it is.

* Samuel Johnson (1709–1784), English lexicographer, critic, poet, and moralist who completed the *Dictionary of the English Language* in 1755; Johnson is one of the preeminent authorities on the English language.

The understanding of light can gainfully begin at the outset with an appreciation of light as described by the Maxwell equations.

Reference

- [1] Johnson, S. 1755. *Boswell's Life; Dictionary of the English Language*; quoted in Clegg, B. 2001. *Light Years*. Piatkus, London.

2

Electromagnetism

The scientific study of light has more than 1500 years of illustrious history. Beginning with Euclid and his geometrical study of light beams, the list of luminaries includes the great scientist/mathematicians Descartes, Galileo, Snell, Fermat, Boyle, Hooke, Newton, Euler, Fourier, Bartholinus, Huygens, Malus, Gauss, Laplace, Fresnel, Hamilton, Cauchy, Poisson, Faraday, and Maxwell. From those classical beginnings, the theories have evolved into atomic and quantum mechanical theories of light, developed by the great physicists Planck, Bohr, Heisenberg, Schrodinger, Born, Dirac, and Einstein. With such brainpower as driving force, the subsequent profound understanding of light should not have been unexpected.

The first mathematical treatments of light however quickly became mired in an ineluctable *æther*; that is, the early physical theory of *action at a distance* required the presence of an all-pervasive, elastic, and very subtle material to serve as the medium through which forces could transfer their effect. Simply put, although often not easy to apply, the interaction between two separate bodies is determined by a mechanical transfer of force acting along a line connecting the bodies, that force weakening with the distance between the bodies. The action at a distance theory could successfully describe many observations in common experience, the most cogent example being sea waves. But this “*æthereal*” view of Nature confounded even its proponents

when faced with the equally naturally observed electromagnetic phenomena, such as the effects of a magnet on a current-carrying wire and the invisible transfer of electromagnetic forces through a vacuum.

The great mathematical physicist Maxwell too was caught up in the æthereal action at a distance and a physics based on mechanics and fluid dynamics, so his initial efforts to mathematically describe the observed electromagnetic phenomena were based on such conceptualizations of electrical energy as the stored energy in a spring, and magnetic energy as the kinetic energy of a flywheel, and of course, electric current was seen as flowing water (an analogy nonetheless still used today). When Maxwell faced the *interaction* between electricity and magnetism, however, he was confounded: how would an electric current in a wire produce a concentric circulating magnetic force, and how would a moving magnet near a wire coil produce an electric current in that coil? The description of all the parts and the mutual interactions among them using purely mechanistic and fluid formulations would result in some strange machines [1].

For example, the *deus ex machina* sketched in Figure 2.1 consisting of an interconnected contraption of balls, wheels, gears, and tubes. Solidly ingenious as it was, in order to explain what the experimentalists Oersted, Ampere, and Faraday had observed in Nature and experiments, it also was clear that this mechanical beast was going to be very difficult to tame.

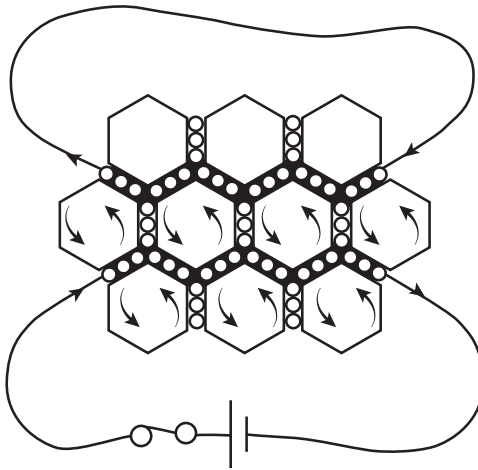


Figure 2.1 Maxwell's electromagnetic mechanical machine. From Mahon, B. 2003. *The Man Who Changed Everything, The Life and Times of James Clerk Maxwell*, Wiley, p. 100.

Indeed, the intricate *pas de deux* of electromagnetic forces at the time was clearly observed but only murkily understood. One force apparently engenders another force, but the generation clearly was not acting in the line through the distance between the bodies producing those forces. In a vain attempt to tie the forces, the construction of springs, flywheels, balls, and interconnecting water pipes, ropes, pulleys, and gears became just too complicated and contrived to attain the simplicity and elegance sought by a mathematical theoretician like Maxwell. But worst of all, the bits and pieces could not hope to operate to produce electromagnetic forces in a vacuum; the mechanical theory still relied upon the ethereal yet ubiquitous *æther* and all its attendant mystery. If Maxwell was to overcome the *æther's* dark art, he needed the power of mathematical physics to smite that *ævil* witch.

Faraday's Intuitive Field

The untenable complications wrought by the purely mechanistic and *æther*-laden action at a distance were unraveled by the great experimentalist Faraday. Having had little formal education, Faraday was not equipped to use mathematical physics to describe what he observed; instead he depended on his (considerable) powers of intuition.

To start off, a point charge (q) acted upon by an electric force (E) will experience a mechanical force (F) described simply by the equation $F = qE$, where the force is directly proportional to, and in the same direction as, the electric force. But Faraday observed that the effect that a magnet has on a current-carrying wire is to move it, as shown in the schematic drawing in Figure 2.2 as the dashed line. That is, when the current is turned on, the wire near the magnet will move horizontally in a direction perpendicular to the direction of the South to North poles of the magnet, so mathematically the magnetic force emanating from the magnet produces a mechanical force F that can be described by the vector equation $F = qv \times B$. The equation says that a point charge traveling in the wire at a velocity (v) will be subject to a force (F) that is proportional and perpendicular to both v and B (the *cross product* in the vector calculus). The electric and magnetic forces combined in a single equation is the well-known Lorentz force,

$$F = q(E + v \times B).$$

From the above equation, it is clear that while there is a force (E) associated directly with an electric charge (q), a magnetic force requires motion (v) to act.

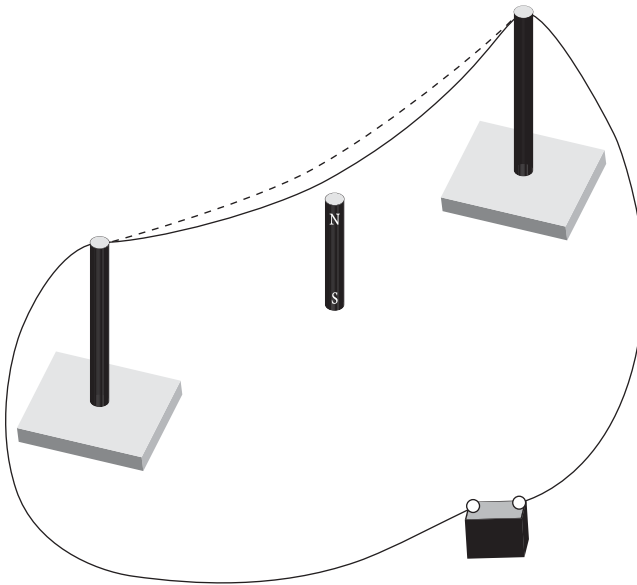


Figure 2.2 Magnetic force acting on a current in a wire moves the wire.

Other observations were not so simply describable, however; for example, the subsequent mutual interaction of the current, the generated magnetic force, and the magnet's magnetic force.

To help matters along, Faraday here visualized the force effect of the magnet as a pattern of *lines of force*, the grouping together of which constituted a *flux* of force lines, the number and closeness of the lines representing the density of the flux, and that flux density indicating the strength or intensity of the magnetic force. Faraday's own drawing of the lines of force emanating from a bar magnet is shown in Figure 2.3, where he described the flux lines as a *field*. This then was the basic idea of a field to intuitively conceptualize electromagnetism.

The idea of lines of force constituting a field to describe the electric and magnetic effects was not the only pivotal concept invented by Faraday; another critical idea was that the field lines could be superimposed to describe the cumulative effect from many different sources of electric and magnetic force. This *principle of superposition* can reduce a very complicated collection of electromagnetic sources of force into a simple addition of the different contributions from the various sources. That is, at a given point in space, no matter what the distribution of the other electric or magnetic