THE CAMBRIDGE HISTORY OF SCIENCE

VOLUME 5

The Modern Physical and Mathematical Sciences

Edited by
MARY JO NYE

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK
40 West 20th Street, New York, NY 10011-4211, USA
477 Williamstown Road, Port Melbourne, VIC 3207, Australia
Ruiz de Alarcón 13, 28014 Madrid, Spain
Dock House, The Waterfront, Cape Town 8001, South Africa

http://www.cambridge.org

First published 2002

Printed in the United States of America

Typeface Adobe Garamond 10.75/12.5 pt. *System* LaTeX 2ε [TB]

A catalog record for this book is available from the British Library.

Library of Congress Cataloging in Publication Data
(Revised for volume 5)
The Cambridge history of science
p. cm.
Includes bibliographical references and indexes.
Contents: – v. 4. Eighteenth-century science / edited by Roy Porter
v. 5. The modern physical and mathematical sciences / edited by Mary Jo Nye
ISBN 0-521-57243-6 (v. 4)
ISBN 0-521-57199-5 (v. 5)
1. Science – History. I. Lindberg, David C. II. Numbers, Ronald L.
Q125 C32 2001
509 – dc21
2001025311

ISBN 0 521 57199 5 hardback

CONTENTS

PART I. THE PUBLIC CULTURES OF THE PHYSICAL SCIENCES AFTER 1800

PART II. DISCIPLINE BUILDING IN THE SCIENCES: PLACES, INSTRUMENTS, COMMUNICATION

PART III. CHEMISTRY AND PHYSICS: PROBLEMS THROUGH THE EARLY 1900s

PART IV. ATOMIC AND MOLECULAR SCIENCES IN THE TWENTIETH CENTURY

PART V. MATHEMATICS, ASTRONOMY, AND COSMOLOGY SINCE THE EIGHTEENTH CENTURY

PART VI. PROBLEMS AND PROMISES AT THE END OF THE TWENTIETH CENTURY

ILLUSTRATIONS

INTRODUCTION

The Modern Physical and Mathematical Sciences

Mary Jo Nye

The modern historical period from the Enlightenment to the mid-twentieth century has often been called an age of science, an age of progress or, using Auguste Comte's term, an age of positivism.[1]

Volume 5 in *The Cambridge History of Science* is largely a history of the nineteenth- and twentieth-century period in which mathematicians and scientists optimistically aimed to establish conceptual foundations and empirical knowledge for a rational, rigorous scientific understanding that is accurate, dependable, and universal. These scientists criticized, enlarged, and transformed what they already knew, and they expected their successors to do the same. Most mathematicians and scientists still adhere to these traditional aims and expectations and to the optimism identified with modern science.[2]

By way of contrast, some writers and critics in the late twentieth century characterized the waning years of the twentieth century as a postmodern and postpositivist age. By this they meant, in part, that there is no acceptable master narrative for history as a story of progress and improvement grounded on scientific methods and values. They also meant, in part, that subjectivity and relativism are to be taken seriously both cognitively and culturally, thereby undermining claims for scientific knowledge as dependable and privileged knowledge.[3]

---

[1] See, e.g., David M. Knight, *The Age of Science: The Scientific World View in the Nineteenth Century* (New York: Basil Blackwell, 1986). Comte's six-volume *Cours de philosophie positive* was published during 1830–42; for an abridged version, Auguste Comte, *The Positive Philosophy of Auguste Comte,* trans. Harriet Martineau (London: G. Bell & Sons, 1896).

[2] For the optimistic vision of unification and completeness, see Steven Weinberg, *Dreams of a Final Theory* (New York: Pantheon, 1992), and Roger Penrose, *The Emperor's New Mind* (New York: Oxford University Press, 1994). Against the possibility of completeness, see Nancy Cartwright, *The Dappled World: Essays on the Perimeter of Science* (Cambridge: Cambridge University Press, 1999).

[3] For a general discussion, Stephen Toulmin, *Cosmopolis: The Hidden Agenda of Modernity* (New York: Free Press, 1990). On "postmodernity" the classic text is Jean François Lyotard, *The Post-Modern Condition,* trans. Geoff Bennington and Brian Massumi (Minneapolis: University of Minnesota Press, 1984).

Historians of science have addressed these late-twentieth-century issues by greatly expanding their tools of study in terms of subjects, methods, themes, and interpretations. Most historians of science have come to believe that there can be no unified history of science predicated upon the assumption of a "logic" or "method" of science. Some historians have concluded that there is no longer any place for a grand narrative of science ("the history of science") or even of a single scientific discipline ("the history of chemistry"). As a result, much recent work in the history of science has focused on histories of scientific practices, scientific controversies, and scientific disciplines in very local times and spaces.[4]

Still, larger narratives persist, as demonstrated, for example, in the very successful series of single-authored Norton histories of science published in the 1990s, including *The Norton History of Chemistry* and *The Norton History of Environmental Sciences*.[5] Other examples of comprehensive histories include studies of twentieth-century physics, such as Helge Kragh's history of physics in the twentieth century and Joseph S. Fruton's history of biochemistry and molecular biology as the interplay of chemistry and biology.[6]

The chapters in Volume 5 of *The Cambridge History of Science* represent a variety of investigative and interpretive strategies, which together demonstrate the fertile complementarity in history of science and science studies of insights and explanations from intellectual history, social history, and cultural studies.

It should be noted that the biographical genre of history is explicitly excluded as a focus for any one chapter in the volume, although individual figures, not surprisingly, often loom large. Among these are William Whewell, Hermann von Helmholtz, William Thomson (Lord Kelvin), and Albert Einstein. In addition, none of the chapters has a specifically national focus, since Volume 8 in the *Cambridge History of Science* series concentrates precisely on the modern sciences in national and international contexts.[7]

---

[4] For an overview of assumptions and methodologies in the history of science and science studies, see Jan Golinski, *Making Natural Knowledge: Constructivism and the History of Science* (Cambridge: Cambridge University Press, 1998).

[5] William H. Brock, *The Norton History of Chemistry* (New York: W. W. Norton, 1992); Peter J. Bowler, *The Norton History of Environmental Sciences* (New York: W. W. Norton, 1993); Donald Cardwell, *The Norton History of Technology* (New York: W. W. Norton, 1995); John North, *The Norton History of Astronomy and Cosmology* (New York: W. W. Norton, 1995); Ivor Grattan-Guinness, *The Norton History of the Mathematical Sciences* (New York: W. W. Norton, 1998); Roy Porter, *The Greatest Benefit to Mankind: Medical History of Humanity* (New York: W. W. Norton, 1998); and Lewis Pyenson and Susan Sheets-Pyenson, *Servants of Nature: A History of Scientific Institutions, Enterprises, and Sensibilities* (New York: W. W. Norton, 1999).

[6] Helge Kragh, *Quantum Generations: A History of Physics in the Twentieth Century* (Princeton, N.J.: Princeton University Press, 1999), and Joseph S. Fruton, *Proteins, Enzymes, Genes: The Interplay of Chemistry and Biology* (New Haven, Conn.: Yale University Press, 1999).

[7] Ronald L. Numbers and David Livingstone, eds., *Modern Science in National and International Contexts,* vol. 8, *The Cambridge History of Science* (Cambridge: Cambridge University Press, forthcoming).

Most authors in this volume have provided a largely Western narrative of their subjects, suggesting to the reader that historians of science in the twenty-first century still have much to write about modern scientists and scientific work in non-Western cultures.[8]

Some common themes and interpretive frameworks run through the volume, as detailed in the following discussion. Perhaps most striking among leitmotifs is historians' continuing preoccupation with Thomas S. Kuhn's characterizations of everyday science and scientific revolutions. Historians' decisions to explain scientific traditions and scientific change in terms of gradual evolution or abrupt revolution remain at the core of interpretive frameworks in the history of science.[9]

PART I. THE PUBLIC CULTURE OF THE PHYSICAL SCIENCES AFTER 1800

The first section of the volume focuses on the public culture of the modern physical and mathematical sciences, with emphasis on the Western European and North American countries in which these physical sciences were largely institutionalized until the early twentieth century.

Nancy Cartwright, Stathis Psillos, and Hasok Chang lay out various expectations of modern philosophical writers and scientific practitioners about what they hoped to achieve by defining and employing "scientific method," whether inductive or deductive, empiricist or rationalist, realist or conventionalist, theory laden or measurement dependent in normative and operative outlines. Like Frederick Gregory in his discussion of the intersections of religion and science, the coauthors note the importance for many scientists (for example, Albert Einstein around 1900 or Steven Weinberg around 2000) of a Pythagorean-like belief in the mathematical structure of the world, or what Weinberg has called the kinds of law that correspond "to something as real as anything else we know."[10]

Gregory, like David M. Knight in his essay on scientists and their publics, describes a nineteenth-century European world in which religion and science

---

[8] However, see, e.g., Lewis Pyenson, *Civilizing Missions: Exact Sciences and French Overseas Expansion, 1830–1940* (Baltimore: Johns Hopkins University Press, 1993), and Zaheer Baber, *The Science of Empire: Scientific Knowledge, Civilization, and Colonial Rule in India* (Albany: State University of New York Press, 1996).

[9] Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962). Among the many sources on Kuhn's work, see Nancy J. Nersessian, ed., *Thomas S. Kuhn,* special issue of *Configurations,* 6, no. 1 (Winter 1998). On "revolution," I. Bernard Cohen, *Revolution in Science* (Cambridge, Mass.: Harvard University Press, 1985). On the argument for ruptures and mutations (and against continuities and transitions), see Michel Foucault, *The Archaeology of Knowledge,* trans. A. M. Sheridan Smith (New York: Pantheon, 1972; 1st French ed., 1969).

[10] Quoted in Ian Hacking, p. 88, *The Social Construction of What?* (Cambridge, Mass.: Harvard University Press, 1999), from Steven Weinberg, "Sokal's Hoax," *New York Review of Books,* 8 August 1996, 11–15, at p. 14.

were held to be compatible in the face of increasing secularization. William Whewell stood almost alone among scientific intellectuals in opposing on religious grounds the hypothesis of the plurality of worlds. James Clerk Maxwell, the brothers William and James Thomson, Louis Pasteur, and Max Planck all found science and religion mutually supportive, once extreme statements of scientific materialism were eliminated. Gregory notes the paradox that scientists and theologians shared a belief in the existence of foundational principles for natural phenomena, while not always agreeing on how properly to characterize these first principles.

Gregory also notes a link between religion and science in a shared gender bias toward membership in the community of scientists, a theme taken up by Margaret W. Rossiter in her history of the exclusion of women from scientific education and scientific organizations. Although there have been relatively few women in the physical sciences in comparison to men, Marie Curie nonetheless is one of the best known of *all* scientists. Female physicists currently are found in much higher proportions in countries outside Japan, the United States, the United Kingdom, and Germany. Yet, this fact may not necessarily indicate greater opportunities for women so much as a gendered proletarianization of university educators in some countries.

Some of Rossiter's female scientists figure, as well, in Knight's discussion of the popularization of science, not because women were lecturing in public places like the Friday evening lectures of the Royal Institution, but because they were writing widely read and commercially successful books, such as Jane Marcet's *Conversations on Chemistry* (1807) and Mary Somerville's *Connexion of the Physical Sciences* (1834).

Knight notes, as does Pamela Gossin, the extraordinary popularity of the science of chemistry for the early-nineteenth-century imagination, a popularity that was eclipsed in the next decades by geology. Early in the nineteenth century, light, heat, electricity, magnetism, and the discovery of new elements – all parts of chemistry – excited attention. By century's end it was "auras" and table rapping that were the rage, along with x rays that could be used to see through human flesh.

We became familiar in the twentieth century with the idea of a polarization between the "two cultures" of the sciences and the humanities. Knight and Gossin remind us of the many scientists who have themselves written literature and poetry (among them Davy, Maxwell, C. P. Snow, Primo Levi, Carl Sagan, and Roald Hoffmann), as well as the novelists and poets who have studied the sciences and incorporated scientific elements into their work (Mary Shelley, Nathaniel Hawthorne, Edgar Allan Poe, Aleksandr S. Pushkin, Honoré de Balzac, Emile Zola, James Joyce, Virginia Woolf, Vladimir Nabokov). The science-educated novelist H. G. Wells appears and reappears in chapters of this volume. From Jonathan Swift and William Blake to Bertolt Brecht and Friedrich Dürrenmatt, scientists and their work have figured in the literary and artistic products of public culture.

PART II. DISCIPLINE BUILDING IN THE SCIENCES: PLACES, INSTRUMENTS, COMMUNICATION

If natural philosophy, natural theology, chemical philosophy, and natural history were the fields of inquiry for the generalist savant who flourished in the eighteenth and early nineteenth centuries, scientific specialisms were to proliferate during the nineteenth century into disciplinary boundaries that enrolled professional "scientists" (the English term invented by William Whewell in 1833) in the classroooms, societies, and bureaucracies. The intricacies of discipline building have elicited considerable attention from historians of science in the last few decades, as has the construction of research schools and research traditions.

Among scientific disciplines, mathematics has been regarded as the foundational science since at least the time of Comte. Many mathematicians and historians of mathematics, as David E. Rowe points out, have never doubted the cumulative nature of mathematical knowledge and its reflection of a Platonic realm of permanent truths. Yet mathematics, too, is an intellectual and social activity that produces knowledge, sometimes by apparent revolutionary breakthroughs, as in the case of Georg Cantor's set theory, but also in the ongoing work of the normal production of university lecture notes, paradigmatic textbooks, and research journals. The result has been, as Rowe puts it, "vast quantities of obsolete materials," as well as revolutions, rediscoveries, and transformations of methods and insights long discarded.

Rowe insists particularly on the importance in the history of modern mathematics of the research seminars and of oral knowledge transmissions that took root in small German university towns in the early nineteenth century. These resulted in informal groups with intellectual orientation and loyalty to a particular mentor. National differences existed, for example, in the distinctive tradition of mixed mathematics in England.

National differences are at the heart of Terry Shinn's investigation of the relationships among science and engineering education, research capacity, and industrial performance in Germany, France, England, and the United States. Shinn takes the not-uncontroversial position that there *has been* a difference in economic achievement among these nations and that it *might be correlated* with the aims and structures of scientific education. Whereas Rowe emphasizes that neohumanist scholarship developed in Germany specifically in opposition to what post-Napoleonic Germans called the "school learning" of the French, Shinn emphasizes the successful linking of German scientific education and research with the needs of German industry, particularly in mechanics, chemistry, and electricity by the end of the nineteenth century.

At the heart of discipline building are not only the sites and spaces for the disciplines but also the array of instruments and the means of communication that define and mark off one intellectual field from another. Robert W. Smith's analysis of astronomical instrumentation notes striking changes in kind and scale that marked the history of astronomy from Giovanni Piazzi's 1801 discovery of an asteroid, using an altazimuth circle, to the 1990 launching of the Hubble Space Telescope. As Smith makes clear, the improvement of telescopes, both optical and radio, often was a goal in itself, rather than a means of addressing theoretical questions. Astronomy contributed its fair share in the nineteenth century to what historians have characterized as obsession with precision measurement.

As in other scientific disciplines in the twentieth century, the expense and the patronage of astronomy became ever greater after the Second World War. Like nuclear physicists, astronomers found themselves working in new kinds of organization, for example, the international university consortium, in which they collaborated with engineers, machinists, physicists, and chemists. In such large enterprises, as in smaller venues, communication patterns of scientists became crucial to disciplinary identities and distinctions, as well as to the accomplishment of original work.

Bernadette Bensaude-Vincent treats communication patterns and the construction of scientific languages in modern chemistry, while Arthur I. Miller focuses on changes in imagery and representation in modern physics, showing how language and image are instruments or tools for expressing theories and making predictions and discoveries, as well as for establishing group identity.

While some languages and images changed dramatically in intent and content over time, others remained remarkably stable. A small group of French chemists in 1787 famously created an artificial and theory-laden language for a new, antiphlogistonist chemistry, in which, as Bensaude puts it, the binomial name was to be a mirror image of the operations of chemical decomposition. This formalist and operationalist project succeeded quickly, despite objections to the French language from foreign chemists and opposition to theoretical names from pharmacists and artisans, who commonsensically preferred historical and descriptive names. Later projects for chemical nomenclature proved more conventional and pragmatic in design, perhaps because they were truly international and more consensual.

Miller's history of visual imagery in physics is similarly one of controversy and compromise among scientists. In this history, Miller distinguishes between visual images rooted in intuition (*Anschauung*) and visual images seated in perception (*Anschaulichkeit*). Hinting at parallels with the artistic forms developed by Pablo Picasso, Georges Braque, and, later, Mark Rothko, Miller details the increasingly abstract visualization adopted by Einstein, Werner Heisenberg and, later, Richard Feynmann. Yet, Miller argues, there is ontological realist content to Feynmann's diagrams. "All modern scientists," says Miller, "are scientific realists."

PART III. CHEMISTRY AND PHYSICS: PROBLEMS THROUGH THE EARLY 1900S

In turning to specific disciplinary areas of scientific study in the nineteenth and twentieth centuries, Parts III, IV, and V of this volume loosely employ the overlapping categories of chemistry and physics, atomic and molecular sciences, mathematics, astronomy, and cosmology, noting that these categories sometimes can be identified with professional disciplines and experts (chemistry, chemist) and sometimes not. Very different historical approaches are taken by the authors: intellectual history or social history, national traditions or local practices, gradual transitions or radical breaks.

Frederic L. Holmes disputes the long-standing claim, originated by scientists themselves, that nineteenth-century experimentalists, such as Helmholtz and Emile Dubois-Reymond, broke in the 1840s with vitalist presuppositions, providing a "turning point" for the reductionist application of the laws of physics and chemistry to living processes. On the contrary, Holmes argues that nineteenth-century scientists simply had more powerful concepts and methods available than had their predecessors for the exploration and characterization of digestion, respiration, nervous sensation, and other "vital" processes. Earlier investigators pursued similar aims, but with less satisfactory means at their disposal.

While historians and scientists often speak of a chemical revolution associated with the atomism of John Dalton, Hans-Werner Schütt notes the ongoing and unresolved discussions throughout the nineteenth century about the relationship between what chemists called "chemical atoms" (corresponding to chemical elements) and what natural philosophers and physicists treated as "physical atoms" (corresponding to indivisible corpuscles). Calculating relative atomic weights, defining the standard of comparison for atomic weights, classifying simple and complex substances and their behaviors by means of chemical symbols and systematic tables: All of these tasks were continuing challenges for chemists throughout the century.

What constituted a chemical fact or conclusive evidence for a formula, a classification, or a theory? Schütt relates Justus Liebig's conviction that "theories are expressions of contemporary views . . . only the facts are true." Alan J. Rocke notes August Kekulé's remark that it is an "actual fact," not a "convention," that sulfur and oxygen are each equivalent to two atoms of hydrogen. J. J. Berzelius distinguished between "empirical" and "rational" formulas for chemical molecules, one based in laboratory analysis and the second based in theory. These chemists were savvy about scientific epistemology. Yet they were not quick to adopt a new theory. Rocke has found that nearly all active organic chemists who were more than forty years old in 1858 ignored Kekulé's structure theory, while the younger generation took it on.[11] However, by the 1870s the structure theory provided a framework not only for academic chemistry but also for an expanding German chemical industry.

The reciprocal relationship between scientific innovation and industrial development is more fully developed in Crosbie Smith's study of energy and Bruce J. Hunt's analysis of electrical science. Sungook Hong also discusses the interplay among theoretical concept, laboratory effect, and technological artifact.

Hong challenges the usual history of nineteenth-century theories of light and radiation as a story of revolution. Many accounts of the wave versus particle theories of light attribute Fresnel's winning of the 1819 Academy of Sciences prize to his memoir's good fit with experimental data, in combination with the declining political and social fortunes of Laplacian physicists. Drawing upon an analysis by Jed Z. Buchwald, Hong concedes that Fresnel's mathematics fit the data, but adds that the prize-awarding jury at the time saw no significant physical hypothesis in Fresnel's work that would inhibit them from continuing to employ a ray (emission) analysis for studying light. In this case, as in the history of theories and experiments on the spectra of heat, light, and chemical (ultraviolet) radiations, Hong sees a process of "prolonged confusion" and gradual consensus, without crucial experiments, in the service of precise measurement.

Crosbie Smith addresses the question of simultaneous discovery, disputing Kuhn's presumption that energy was something in nature to be discovered. At the same time, Smith shows some of Kuhn's preoccupation with the means by which a paradigm is constituted. For Smith, it was North British (Scottish) cultures of engineering and Presbyterianism that made James Thomson and William Thomson determined to study the problem of the waste of useful work and to effect a reform of physical science, as they replaced the language and assumptions of action-at-a-distance and mechanical reversibility with a natural philosophy of energy and its transformations. In this aim, in Smith's analysis, the Thomson brothers were joined by Maxwell, most notably in his *Treatise on Electricity and Magnetism* (1873).

Hunt is less concerned with Presbyterianism than with technology, narrating, consistently with Crosbie Smith's account, the triumph of William Thomson's scientific approach to electrical engineering in the completion of Cyrus Field's venture for laying trans-Atlantic telegraphic cables during 1865–6. Hunt explains the influential reformulation of Maxwell's electromagnetic theory by Oliver Heaviside and by Heinrich Hertz in the 1880s, noting the gap between the continental action-at-a-distance approach to electromagnetism and Maxwell's field concept. An important linkage between the two was made in H. A. Lorentz's theory of tiny charges that are able

---

[11] See Max Planck's comment about generations in *Scientific Autobiography and Other Papers,* trans. F. Gaynor (New York: Philosophical Library, 1949), p. 33.