course, the Fourier technique is a very powerful mathematical tool, as chapter 6 illustrates by its extensive use of two-dimensional Fourier transforms to treat diffraction and the properties of images. Probability theory is the other major area of mathematics used extensively in the book. The level of presentation throughout is above what most undergraduates can handle without considerable prior preparation.

Léna's book is clearly not designed to give the reader much practical information about observational techniques. The discussions of CCD detectors (less than two pages, and a bit out of date), spectrographs and several other areas of great concern to modern observers are very brief overviews. However, each chapter is followed by a number of good exercises, and the reader with the diligence to work through them will learn a considerable amount about applications. Aside from a scattering of minor typographical errors and an occasionally awkward grammatical structure, the book reads very clearly in A. R. King's translation.

Daniel Schroeder's *Astronomical Optics* takes a very different approach from the two books already discussed. The book is clearly focused on its title subject, and the results are superb. In 17 lucid chapters Schroeder takes us through the general theory of astronomical optics, relying heavily on Fermat's principle, and then to applications in the design and performance of a variety of optical instruments—reflecting telescopes, Schmidt cameras, auxiliary optics and spectrographs. After working out the basic theory of the performance characteristics of these devices, he illustrates each case with a practical application. Chapter 11, for example, contains a detailed discussion of the optical performance of the Hubble Space Telescope. The discussion of spectrographs is especially good. The considerations that go into the design of simple grating and echelle grating spectrographs are very complex, but Schroeder's exposition is clear. Following each chapter are a few key references, which are very well chosen. The only thing I might like to see added to the book is a discussion of fiberoptics and their coupling to other optical instruments. Of course the incorporation of optical fibers into astronomical instruments is a very recent and rapidly evolving development.

Each of the three books discussed in this review has its place. Walker's could be used in an undergraduate or a graduate course on astronomical instrumentation, where it would be of value for rather brief overviews of a variety of topics. Léna's book could be of real value to the theoretical astrophysicist or physicist who wants a concise introduction to the theory of a wide diversity of astronomical techniques. It could be used in a graduate class, but its practical value to the observational astronomer engaged in instrument design would be limited. Schroeder's book should be mandatory reading for all graduate students interested in observational astronomy; it would make an excellent textbook for a course on astronomical optics. Its practical value is considerable. I am sure I will consult it for many years to come.

How Experiments End

Peter Galison
U. of Chicago P.,
Chicago, 1987. 330 pp.
$14.95 pb ISBN 0-226-27915-4

In this thought-provoking and stimulating book, Peter Galison examines the process that leads to the closure of experiments. Historians and philosophers of science for years have cast experiments in a secondary role, subservient to theory, while the apparatus of science has been largely ignored. Galison's book comes on the crest of a wave of the more recently sophisticated appraisals of the relationship among these three elements of the scientific process: theory, experiments and instruments. He has very much reinforced Ian Hacking's protest against the conventional parody of experimental work: "Noting and reporting readings of dials—Oxford philosophy's picture of experiments—is nothing. Another kind of observation is what counts: the uncanny ability to pick out what is odd, wrong, instructive or distorted in the antics of one's equipment."

Galison observes with feeling that the twisting of wire, the shielding of chambers, the hoisting of thousand-pound steel plates and the arguments over computer simulations are the stuff experiments in modern physics are made of. Actually, this is essentially (albeit on a larger scale) the experimental method first advocated by the new breed of 17th-century natural philosophers. Their introduction of the craftsman's techniques into the study of nature caused the showdown with the Roman Catholic Church, which had embraced Aristotelian science. The church authorities recognized that experimental demonstrations could never have the surety (in modern jargon, the closed form) of a deductive argument. As Pierre Duhem has pointed out, "experimental contradiction does not have the power to transform a physical hypothesis into an indisputable truth." There is no strictly logical point at which an experiment terminates.

When and how do experiments end? This question has recently been addressed by those who stress the sociological processes in science, and by others who write sensationally about "scientific frauds." Both groups usually betray their ignorance of what goes on at the laboratory bench. What is so fruitful about this book is the author's intimate acquaintance with the practical and the theoretical aspects of the subject under discussion.

Galison compares three periods of 20th-century microphysical experimentation. His first epoch relied on tabletop experiments with classical 19th-century physics apparatus designed to investigate macroscopic forces and effects, as defined by Maxwell in 1876. These were the tools used by Einstein, Wander Johannes de Haas, Samuel Jackson Barnett and others to determine the gyromagnetic ratio to confirm the electron-orbit hypothesis. It became increasingly clear in the 1920s, when these difficult experiments were repeated with other apparatus, that the gyromagnetic ratio was different from what these early workers claimed to have found.

Galison's second epoch started around the time of the First World War. Attention was now focused on small-scale scattering experiments with cosmic rays and radioactive materials. The new generation of instruments was sensitive not to the macroscopic effects of heat, light, mechanics and electricity, but to *individual* rays and particles. Geiger counters and cloud chambers marked the transition from classical to quantum mechanical physics. Galison compares the attitudes and related experiments of the two main groups active in this field. The one centered on Robert Millikan did not accept the quantum mechanical approach for several years; the other group did. This difference influenced both groups' research strategies, yet they arrived almost simultaneously at the conclusion that what was required was not a radical reformulation of quantum mechanics to explain the effects, but a new particle—the positron.

What characterizes his third epoch are the giant accelerator-based experiments that require the collaborative effort of large teams of physicists. Galison analyzes the research of the

Gargamelle heavy-liquid bubble-chamber group at CERN and of the E1A spark-chamber and calorimeter collaboration at the National Accelerator Laboratory, which is now called Fermilab. The experiments these groups performed to test the existence of neutral currents in the early 1970s helped to generate present-day interest in gauge physics.

Galison's detailed case studies provide much insight into the multifaceted processes that transform scientific data into evidence. These include the styles of argumentation developed by the various research teams, heuristic demonstrations, computer simulations and model-making, and the threefold interaction of experimental practices, theory and instrumentation. Science is a creative activity, and in some respects the laboratory is not that different from the artist's studio. Michelangelo is supposed to have remarked ironically that nothing could have been simpler than carving his *David*; all he had to do was to remove everything that was not his masterpiece. In physics, too, removing the effect from its background is a complex process. Quite sensibly, Galison has remained within the bounds of the modern physics about which he knows most. His analysis can be read with profit by physicists, historians and philosophers of science, and should be extended to other branches of science.

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Gauge Fields and Strings

A. M. Polyakov
Harwood Academic
(Gordon and Breach),
New York, 1987. 301 pp.
$48.00 hc ISBN 3-7186-0393-4;
$18.00 pb ISBN 3-7186-0392-6

Twenty years ago, quantum field theory was considered by many a mathematical concoction of dubious consistency, good for the calculation of amplitudes in electrodynamics but clearly inapplicable to strong interactions. Today, we generally consider quantum field theory to be the most important theoretical tool not only in elementary-particle physics but also in statistical physics and other areas—that deal with the interactions of many degrees of freedom. A major part of the development of this theory has come through its intertwining with the study of phase transitions; this relationship has brought the ideas of spontaneous symmetry breaking and the renormalization group to their present central position in the subject. Alexander Polyakov has been one of the major figures in this development, from his early use of conformal invariance in the study of phase transitions, to his introduction of topologically nontrivial field configurations and explication of their physical implications, and to his most productive reformulation of the theory of strings. In this volume he attempts to set out the main currents of his thought on this broad subject, emphasizing especially the problems that remain unsolved.

Polyakov's book is intended for students, but he does presume a certain level of sophistication. Each argument that he gives is self-contained, though sometimes new mathematical tools appear out of the blue just when needed. The treatment of quantum field theory anomalies, both the axial-vector anomaly and the conformal anomaly, which plays a central role in string theory, are exceptionally nicely done. But other topics, such as the strong-coupling expansion and the loop equations for QCD, go by very quickly. References to the literature are either useless or nonexistent. More advanced students should be able to follow all of the developments; beginners in field theory will find this book something of a wild ride.

And the ride is wild indeed. Polyakov's imagination is wide ranging, and one of his goals is to tie together bits of intuition from disparate physical situations, using gauge invariance as a unifying principle. He begins with the statement "The garbage of the past often becomes the treasure of the present (and vice versa)." The flow of his ideas at times becomes a jumble, but it does contain an ample supply of gems. The first half of the book is devoted to the applications of gauge invariance and topology in field theory. As one example of Polyakov's approach, he characterizes a superfluid by its superconducting properties (that is, the response of the medium to an externally applied gauge field), and this discussion turns out to be a warm-up for the characterization of the quark-confining state of gauge theories in terms of its response to an antisymmetric tensor gauge field. Instantons are introduced in the setting of the two-dimensional Heisenberg ferromagnet, where Polyakov can derive not only the general solution for these topologically twisted field configurations but also the dipole–dipole character of their interactions. This last piece of information leads to some fascinating (albeit inconclusive) sta-