THE *Feynman* LECTURES ON PHYSICS

The NEW MILLENNIUM *Edition*

VOLUME II: MAINLY ELECTROMAGNETISM AND MATTER

Feynman - Leighton - Sands

The Feynman

LECTURES ON PHYSICS

NEW MILLENNIUM EDITION

FEYNMAN•LEIGHTON•SANDS

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VOLUME II

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Michael A. Gottlieb, and Rudolf Pfeiffer

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About the Authors

Richard Feynman

Born in 1918 in New York City, Richard P. Feynman received his Ph.D. from Princeton in 1942. Despite his youth, he played an important part in the Manhattan Project at Los Alamos during World War II. Subsequently, he taught at Cornell and at the California Institute of Technology. In 1965 he received the Nobel Prize in Physics, along with Sin-Itiro Tomonaga and Julian Schwinger, for his work in quantum electrodynamics.

Dr. Feynman won his Nobel Prize for successfully resolving problems with the theory of quantum electrodynamics. He also created a mathematical theory that accounts for the phenomenon of superfluidity in liquid helium. Thereafter, with Murray Gell-Mann, he did fundamental work in the area of weak interactions such as beta decay. In later years Feynman played a key role in the development of quark theory by putting forward his parton model of high energy proton collision processes.

Beyond these achievements, Dr. Feynman introduced basic new computational techniques and notations into physics—above all, the ubiquitous Feynman diagrams that, perhaps more than any other formalism in recent scientific history, have changed the way in which basic physical processes are conceptualized and calculated.

Feynman was a remarkably effective educator. Of all his numerous awards, he was especially proud of the Oersted Medal for Teaching, which he won in 1972. *The Feynman Lectures on Physics*, originally published in 1963, were described by a reviewer in Scientific American as "tough, but nourishing and full of flavor. After 25 years it is *the* guide for teachers and for the best of beginning students." In order to increase the understanding of physics among the lay public, Dr. Feynman wrote *The Character of Physical Law* and *QED: The Strange Theory of Light and Matter*. He also authored a number of advanced publications that have become classic references and textbooks for researchers and students.

Richard Feynman was a constructive public man. His work on the Challenger commission is well known, especially his famous demonstration of the susceptibility of the O-rings to cold, an elegant experiment which required nothing more than a glass of ice water and a C-clamp. Less well known were Dr. Feynman's efforts on the California State Curriculum Committee in the 1960s, where he protested the mediocrity of textbooks.

A recital of Richard Feynman's myriad scientific and educational accomplishments cannot adequately capture the essence of the man. As any reader of even his most technical publications knows, Feynman's lively and multi-sided personality shines through all his work. Besides being a physicist, he was at various times a repairer of radios, a picker of locks, an artist, a dancer, a bongo player, and even a decipherer of Mayan hieroglyphics. Perpetually curious about his world, he was an exemplary empiricist.

Richard Feynman died on February 15, 1988, in Los Angeles.

Robert Leighton

Born in Detroit in 1919, Robert B. Leighton did ground-breaking work in solid state physics, cosmic ray physics, the beginnings of modern particle physics, solar physics, planetary photography, infrared astronomy, and millimeter- and submillimeter-wave astronomy over the course of his life. He was widely known for his innovative design of scientific instruments, and was deeply admired as a teacher, having authored a highly influential text, *Principles of Modern Physics*, before joining the team developing *The Feynman Lectures on Physics*.

In the early 1950s Leighton played a key role in showing the mu-meson decays into two neutrinos and an electron, and made the first measurement of the energy spectrum of the decay electron. He was the first to observe strange particle decays after their initial discovery, and elucidated many of the properties of the new strange particles.

In the mid-1950s Leighton devised Doppler-shift and Zeeman-effect solar cameras. With the Zeeman camera, Leighton and his students mapped the sun's magnetic field with excellent resolution, leading to striking discoveries of a five-minute oscillation in local solar surface velocities and of a "super-granulation pattern," thus opening a new field: solar seismology. Leighton also designed and built equipment to make clearer images of the planets, and opened another new field: adaptive optics. His were considered the best images of the planets until the era of space exploration with probes began in the 1960s.

In the early 1960s, Leighton developed a novel, inexpensive infrared telescope, producing the first survey of the sky at 2.2 microns, which revealed an unexpectedly large number of objects in our galaxy too cool to be seen with the human eye. During the mid-1960s he was Team Leader at JPL for Imaging Science Investigations on the Mariner 4, 6, and 7 missions to Mars. Leighton played a key role in the development of JPL's first deep-space digital television system, and contributed to early efforts at image processing and enhancement techniques.

In the 1970s, Leighton's interest shifted to the development of large, inexpensive dish antennae that could be used to pursue millimeter-wave interferometry and submillimeter-wave astronomy. Once again, his remarkable experimental abilities opened a new field of science, which continues to be vigorously pursued at the Owens Valley Radio Observatory and the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile.

Robert Leighton died on March 9, 1997, in Pasadena, California.

Matthew Sands

Born in 1919 in Oxford, Massachusetts, Matthew Sands received his BA from Clark University in 1940 and his MA from Rice University in 1941. During World War II he served on the Manhattan Project at Los Alamos, working on electronics and instrumentation. After the war Sands helped found the Los Alamos Federation of Atomic Scientists, which lobbied against the further use of nuclear weapons. During that period he earned his Ph.D. at MIT researching cosmic rays under Bruno Rossi.

In 1950 Sands was recruited by Caltech to build and operate its 1.5 GeV electron synchrotron. He was the first to show, theoretically and experimentally, the importance of quantum effects in electron accelerators.

From 1960 to 1966, Sands served on the Commission on College Physics, spearheading reforms in the Caltech undergraduate physics program that created *The Feynman Lectures on Physics*. During that time he also served as a consultant on nuclear weapons and disarmament to the President's Science Advisory Committee, the Arms Control and Disarmament Agency, and the Department of Defense.

In 1963 Sands became Deputy Director for construction and operation of the Stanford Linear Accelerator (SLAC), where he also worked on the Stanford Positron Electron Asymmetric Rings (SPEAR) 3 GeV collider.

From 1969 to 1985 Sands was a physics professor at University of California, Santa Cruz, serving as its Vice Chancellor for Science from 1969 to 1972. He received a Distinguished Service Award from the American Association of Physics Teachers in 1972. As Professor Emeritus, he continued to be active in particle accelerator research until 1994. In 1998 the American Physical Society awarded Sands the Robert R. Wilson Prize "for his many contributions to accelerator physics and the development of electron-positron and proton colliders."

In his retirement Sands mentored local elementary and high school science teachers in Santa Cruz, helping them set up computer and laboratory activities for their students. He also supervised the editing of *Feynman's Tips on Physics*, to which he contributed a memoir describing the creation of *The Feynman Lectures on Physics*.

Matthew Sands died on September 13, 2014, in Santa Cruz, California.

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Preface to the New Millennium Edition

Nearly fifty years have passed since Richard Feynman taught the introductory physics course at Caltech that gave rise to these three volumes, *The Feynman Lectures on Physics*. In those fifty years our understanding of the physical world has changed greatly, but *The Feynman Lectures on Physics* has endured. Feynman's lectures are as powerful today as when first published, thanks to Feynman's unique physics insights and pedagogy. They have been studied worldwide by novices and mature physicists alike; they have been translated into at least a dozen languages with more than 1.5 millions copies printed in the English language alone. Perhaps no other set of physics books has had such wide impact, for so long.

This *New Millennium Edition* ushers in a new era for *The Feynman Lectures on Physics (FLP)*: the twenty-first century era of electronic publishing. *FLP* has been converted to *eFLP*, with the text and equations expressed in the LaTeX electronic typesetting language, and all figures redone using modern drawing software.

The consequences for the *print* version of this edition are *not* startling; it looks almost the same as the original red books that physics students have known and loved for decades. The main differences are an expanded and improved index, the correction of 885 errata found by readers over the five years since the first printing of the previous edition, and the ease of correcting errata that future readers may find. To this I shall return below.

The *eBook Version* of this edition, and the *Enhanced Electronic Version* are electronic innovations. By contrast with most eBook versions of 20th century technical books, whose equations, figures and sometimes even text become pixellated when one tries to enlarge them, the LaTeX manuscript of the *New Millennium Edition* makes it possible to create eBooks of the highest quality, in which all features on the page (except photographs) can be enlarged without bound and retain their precise shapes and sharpness. And the *Enhanced Electronic Version*, with its audio and blackboard photos from Feynman's original lectures, and its links to other resources, is an innovation that would have given Feynman great pleasure.

Memories of Feynman's Lectures

These three volumes are a self-contained pedagogical treatise. They are also a historical record of Feynman's 1961–64 undergraduate physics lectures, a course required of all Caltech freshmen and sophomores regardless of their majors.

Readers may wonder, as I have, how Feynman's lectures impacted the students who attended them. Feynman, in his Preface to these volumes, offered a somewhat negative view. "I don't think I did very well by the students," he wrote. Matthew Sands, in his memoir in *Feynman's Tips on Physics* expressed a far more positive view. Out of curiosity, in spring 2005 I emailed or talked to a quasi-random set of 17 students (out of about 150) from Feynman's 1961–63 class—some who had great difficulty with the class, and some who mastered it with ease; majors in biology, chemistry, engineering, geology, mathematics and astronomy, as well as in physics.

The intervening years might have glazed their memories with a euphoric tint, but about 80 percent recall Feynman's lectures as highlights of their college years.

"It was like going to church." The lectures were "a transformational experience," "the experience of a lifetime, probably the most important thing I got from Caltech." "I was a biology major but Feynman's lectures stand out as a high point in my undergraduate experience ... though I must admit I couldn't do the homework at the time and I hardly turned any of it in." "I was among the least promising of students in this course, and I never missed a lecture.... I remember and can still feel Feynman's joy of discovery.... His lectures had an ... emotional impact that was probably lost in the printed *Lectures*."

By contrast, several of the students have negative memories due largely to two issues: (i) "You couldn't learn to work the homework problems by attending the lectures. Feynman was too slick—he knew tricks and what approximations could be made, and had intuition based on experience and genius that a beginning student does not possess." Feynman and colleagues, aware of this flaw in the course, addressed it in part with materials that have been incorporated into *Feynman's Tips on Physics:* three problem-solving lectures by Feynman, and a set of exercises and answers assembled by Robert B. Leighton and Rochus Vogt. (ii) "The insecurity of not knowing what was likely to be discussed in the next lecture, the lack of a text book or reference with any connection to the lecture material, and consequent inability for us to read ahead, were very frustrating.... I found the lectures exciting and understandable in the hall, but they were Sanskrit outside [when I tried to reconstruct the details]." This problem, of course, was solved by these three volumes, the printed version of *The Feynman Lectures on Physics*. They became the textbook from which Caltech students studied for many years thereafter, and they live on today as one of Feynman's greatest legacies.

A History of Errata

The Feynman Lectures on Physics was produced very quickly by Feynman and his co-authors, Robert B. Leighton and Matthew Sands, working from and expanding on tape recordings and blackboard photos of Feynman's course lectures* (both of which are incorporated into the *Enhanced Electronic Version* of this *New Millennium Edition*). Given the high speed at which Feynman, Leighton and Sands worked, it was inevitable that many errors crept into the first edition. Feynman accumulated long lists of claimed errata over the subsequent years—errata found by students and faculty at Caltech and by readers around the world. In the 1960s and early '70s, Feynman made time in his intense life to check most but not all of the claimed errata for Volumes I and II, and insert corrections into subsequent printings. But Feynman's sense of duty never rose high enough above the excitement of discovering new things to make him deal with the errata in Volume III.† After his untimely death in 1988, lists of errata for all three volumes were deposited in the Caltech Archives, and there they lay forgotten.

In 2002 Ralph Leighton (son of the late Robert Leighton and compatriot of Feynman) informed me of the old errata and a new long list compiled by Ralph's friend Michael Gottlieb. Leighton proposed that Caltech produce a new edition of *The Feynman Lectures* with all errata corrected, and publish it alongside a new volume of auxiliary material, *Feynman's Tips on Physics*, which he and Gottlieb were preparing.

Feynman was my hero and a close personal friend. When I saw the lists of errata and the content of the proposed new volume, I quickly agreed to oversee this project on behalf of Caltech (Feynman's long-time academic home, to which

* For descriptions of the genesis of Feynman's lectures and of these volumes, see Feynman's Preface and the Forewords to each of the three volumes, and also Matt Sands' Memoir in *Feynman's Tips on Physics*, and the *Special Preface to the Commemorative Edition* of *FLP*, written in 1989 by David Goodstein and Gerry Neugebauer, which also appears in the 2005 *Definitive Edition*.

† In 1975, he started checking errata for Volume III but got distracted by other things and never finished the task, so no corrections were made.

he, Leighton and Sands had entrusted all rights and responsibilities for *The Feynman Lectures*). After a year and a half of meticulous work by Gottlieb, and careful scrutiny by Dr. Michael Hartl (an outstanding Caltech postdoc who vetted all errata plus the new volume), the 2005 *Definitive Edition of The Feynman Lectures on Physics* was born, with about 200 errata corrected and accompanied by *Feynman's Tips on Physics* by Feynman, Gottlieb and Leighton.

I *thought* that edition was going to be "Definitive". What I did not anticipate was the enthusiastic response of readers around the world to an appeal from Gottlieb to identify further errata, and submit them via a website that Gottlieb created and continues to maintain, *The Feynman Lectures Website*, `www.feynmanlectures.info`. In the five years since then, 965 new errata have been submitted and survived the meticulous scrutiny of Gottlieb, Hartl, and Nate Bode (an outstanding Caltech physics graduate student, who succeeded Hartl as Caltech's vetter of errata). Of these, 965 vetted errata, 80 were corrected in the fourth printing of the *Definitive Edition* (August 2006) and the remaining 885 are corrected in the first printing of this *New Millennium Edition* (332 in volume I, 263 in volume II, and 200 in volume III). For details of the errata, see `www.feynmanlectures.info`.

Clearly, making *The Feynman Lectures on Physics* error-free has become a world-wide community enterprise. On behalf of Caltech I thank the 50 readers who have contributed since 2005 and the many more who may contribute over the coming years. The names of all contributors are posted at `www.feynmanlectures.info/flp_errata.html`.

Almost all the errata have been of three types: (i) typographical errors in prose; (ii) typographical and mathematical errors in equations, tables and figures—sign errors, incorrect numbers (e.g., a 5 that should be a 4), and missing subscripts, summation signs, parentheses and terms in equations; (iii) incorrect cross references to chapters, tables and figures. These kinds of errors, though not terribly serious to a mature physicist, can be frustrating and confusing to Feynman's primary audience: students.

It is remarkable that among the 1165 errata corrected under my auspices, only several do I regard as true errors in physics. An example is Volume II, page 5-9, which now says "... no static distribution of charges inside a closed *grounded* conductor can produce any [electric] fields outside" (the word grounded was omitted in previous editions). This error was pointed out to Feynman by a number of readers, including Beulah Elizabeth Cox, a student at The College of William and Mary, who had relied on Feynman's erroneous passage in an exam. To Ms. Cox, Feynman wrote in 1975,* "Your instructor was right not to give you any points, for your answer was wrong, as he demonstrated using Gauss's law. You should, in science, believe logic and arguments, carefully drawn, and not authorities. You also read the book correctly and understood it. I made a mistake, so the book is wrong. I probably was thinking of a grounded conducting sphere, or else of the fact that moving the charges around in different places inside does not affect things on the outside. I am not sure how I did it, but I goofed. And you goofed, too, for believing me."

How this New Millennium Edition Came to Be

Between November 2005 and July 2006, 340 errata were submitted to *The Feynman Lectures Website* `www.feynmanlectures.info`. Remarkably, the bulk of these came from one person: Dr. Rudolf Pfeiffer, then a physics postdoctoral fellow at the University of Vienna, Austria. The publisher, Addison Wesley, fixed 80 errata, but balked at fixing more because of cost: the books were being printed by a photo-offset process, working from photographic images of the pages from the 1960s. Correcting an error involved re-typesetting the entire page, and to ensure no new errors crept in, the page was re-typeset twice by two different

* Pages 288–289 of *Perfectly Reasonable Deviations from the Beaten Track, The Letters of Richard P. Feynman*, ed. Michelle Feynman (Basic Books, New York, 2005).

people, then compared and proofread by several other people—a very costly process indeed, when hundreds of errata are involved.

Gottlieb, Pfeiffer and Ralph Leighton were very unhappy about this, so they formulated a plan aimed at facilitating the repair of all errata, and also aimed at producing eBook and enhanced electronic versions of *The Feynman Lectures on Physics*. They proposed their plan to me, as Caltech's representative, in 2007. I was enthusiastic but cautious. After seeing further details, including a one-chapter demonstration of the *Enhanced Electronic Version*, I recommended that Caltech cooperate with Gottlieb, Pfeiffer and Leighton in the execution of their plan. The plan was approved by three successive chairs of Caltech's Division of Physics, Mathematics and Astronomy—Tom Tombrello, Andrew Lange, and Tom Soifer—and the complex legal and contractual details were worked out by Caltech's Intellectual Property Counsel, Adam Cochran. With the publication of this *New Millennium Edition*, the plan has been executed successfully, despite its complexity. Specifically:

Pfeiffer and Gottlieb have converted into LaTeX all three volumes of *FLP* (and also more than 1000 exercises from the Feynman course for incorporation into *Feynman's Tips on Physics*). The *FLP* figures were redrawn in modern electronic form in India, under guidance of the *FLP* German translator, Henning Heinze, for use in the German edition. Gottlieb and Pfeiffer traded non-exclusive use of their LaTeX equations in the German edition (published by Oldenbourg) for non-exclusive use of Heinze's figures in this *New Millennium* English edition. Pfeiffer and Gottlieb have meticulously checked all the LaTeX text and equations and all the redrawn figures, and made corrections as needed. Nate Bode and I, on behalf of Caltech, have done spot checks of text, equations, and figures; and remarkably, we have found no errors. Pfeiffer and Gottlieb are unbelievably meticulous and accurate. Gottlieb and Pfeiffer arranged for John Sullivan at the Huntington Library to digitize the photos of Feynman's 1962–64 blackboards, and for George Blood Audio to digitize the lecture tapes—with financial support and encouragement from Caltech Professor Carver Mead, logistical support from Caltech Archivist Shelley Erwin, and legal support from Cochran.

The legal issues were serious: In the 1960s, Caltech licensed to Addison Wesley rights to publish the print edition, and in the 1990s, rights to distribute the audio of Feynman's lectures and a variant of an electronic edition. In the 2000s, through a sequence of acquisitions of those licenses, the print rights were transferred to the Pearson publishing group, while rights to the audio and the electronic version were transferred to the Perseus publishing group. Cochran, with the aid of Ike Williams, an attorney who specializes in publishing, succeeded in uniting all of these rights with Perseus (Basic Books), making possible this *New Millennium Edition*.

Acknowledgments

On behalf of Caltech, I thank the many people who have made this *New Millennium Edition* possible. Specifically, I thank the key people mentioned above: Ralph Leighton, Michael Gottlieb, Tom Tombrello, Michael Hartl, Rudolf Pfeiffer, Henning Heinze, Adam Cochran, Carver Mead, Nate Bode, Shelley Erwin, Andrew Lange, Tom Soifer, Ike Williams, and the 50 people who submitted errata (listed at `www.feynmanlectures.info`). And I also thank Michelle Feynman (daughter of Richard Feynman) for her continuing support and advice, Alan Rice for behind-the-scenes assistance and advice at Caltech, Stephan Puchegger and Calvin Jackson for assistance and advice to Pfeiffer about conversion of *FLP* to LaTeX, Michael Figl, Manfred Smolik, and Andreas Stangl for discussions about corrections of errata; and the Staff of Perseus/Basic Books, and (for previous editions) the staff of Addison Wesley.

Kip S. Thorne
The Feynman Professor of Theoretical Physics, Emeritus
California Institute of Technology *October 2010*

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The Feynman LECTURES ON PHYSICS

MAINLY ELECTROMAGNETISM AND MATTER

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Feynman's Preface

These are the lectures in physics that I gave last year and the year before to the freshman and sophomore classes at Caltech. The lectures are, of course, not verbatim—they have been edited, sometimes extensively and sometimes less so. The lectures form only part of the complete course. The whole group of 180 students gathered in a big lecture room twice a week to hear these lectures and then they broke up into small groups of 15 to 20 students in recitation sections under the guidance of a teaching assistant. In addition, there was a laboratory session once a week.

The special problem we tried to get at with these lectures was to maintain the interest of the very enthusiastic and rather smart students coming out of the high schools and into Caltech. They have heard a lot about how interesting and exciting physics is—the theory of relativity, quantum mechanics, and other modern ideas. By the end of two years of our previous course, many would be very discouraged because there were really very few grand, new, modern ideas presented to them. They were made to study inclined planes, electrostatics, and so forth, and after two years it was quite stultifying. The problem was whether or not we could make a course which would save the more advanced and excited student by maintaining his enthusiasm.

The lectures here are not in any way meant to be a survey course, but are very serious. I thought to address them to the most intelligent in the class and to make sure, if possible, that even the most intelligent student was unable to completely encompass everything that was in the lectures—by putting in suggestions of applications of the ideas and concepts in various directions outside the main line of attack. For this reason, though, I tried very hard to make all the statements as accurate as possible, to point out in every case where the equations and ideas fitted into the body of physics, and how—when they learned more—things would be modified. I also felt that for such students it is important to indicate what it is that they should—if they are sufficiently clever—be able to understand by deduction from what has been said before, and what is being put in as something new. When new ideas came in, I would try either to deduce them if they were deducible, or to explain that it *was* a new idea which hadn't any basis in terms of things they had already learned and which was not supposed to be provable—but was just added in.

At the start of these lectures, I assumed that the students knew something when they came out of high school—such things as geometrical optics, simple chemistry ideas, and so on. I also didn't see that there was any reason to make the lectures in a definite order, in the sense that I would not be allowed

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