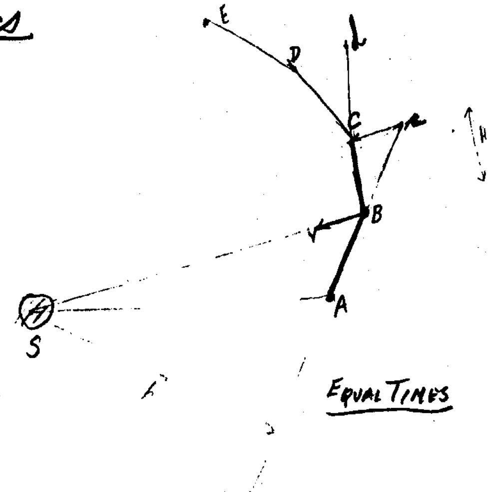
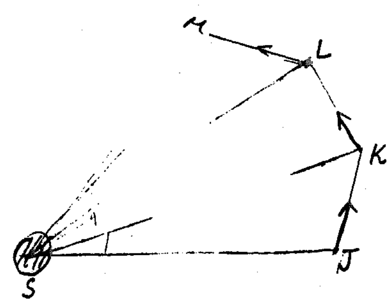
Dynamics

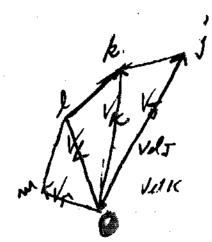


a straight line, no force
C. Force reduced to impulse at B means rotation is to C rather than c.

~~CB is in plane ABS~~
area ABS = BcS
BcS = BCS ∴ ABS = BCS

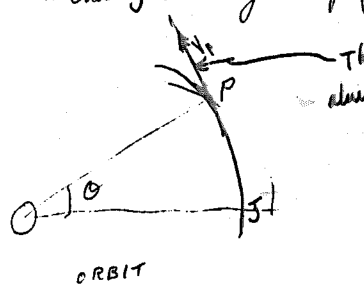
Equal areas in equal times.
~~Vel inversely~~ Vel = h = const.
Equal angles in times prop to square of distance.
also orbit in plane.

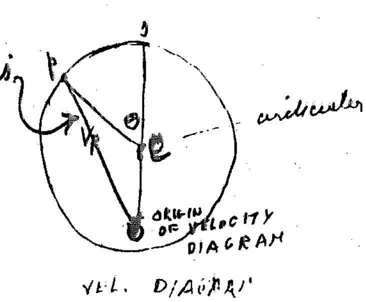




jk is ll to KS
lk is ll to LS
ml is ll to MS
lk = jk = lm

∴ Ends of Vel on regular polygon → circle.





Feynman's Lost Lecture
The Motion of Planets Around the Sun

by David L. Goodstein
and Judith R. Goodstein

This lecture is an opportunity for anyone who has mastered plane geometry to see the great Feynman at work!

For the lecture itself Feynman fans will have to read the book of the same title. Published last month, it may be found in local bookstores or ordered directly from the publisher, using the coupon on page 21. But for a little foretaste, we excerpt here Judith Goodstein's Preface, the Introduction, and a part of David Goodstein's reminiscences. (Copyright © 1996 by the California Institute of Technology. Reprinted with permission of the publisher, W. W. Norton & Company, Inc. Proceeds from the book will be used to support scientific and scholarly research at Caltech.)

All that remained of Feynman's "lost" lecture were the audiotape and a few pages of notes that Feynman jotted down for himself. Most of the lecture derives from the page at left: the figure at upper left is copied from Newton's *Principia*.

Preface

This is the story of how Feynman's lost lecture came to be lost, and how it came to be found again. In April 1992, as Caltech's archivist, I was asked by Gerry Neugebauer, the chairman of the Division of Physics, Mathematics and Astronomy, to go through the files in Robert Leighton's office. Leighton was ill and had not used his office for several years. Marge Leighton, his wife, had told Neugebauer that it was all right to clean out the office—she'd already collected her husband's books and personal effects. I could take what I wanted for the archives, and the division would dispose of the rest.

Besides heading the Division of Physics, Mathematics and Astronomy from 1970 to 1975, Leighton, together with Matthew Sands, had overseen the editing and publication of Richard Feynman's two-year course of lectures in introductory physics, delivered to Caltech freshmen and sophomores. The lectures, published in the early 1960s in three volumes by Addison-Wesley, dealt with virtually every subject in physics, with a point of view that remains fresh and original to this day. I was hoping to find some tangible evidence of the Leighton-Feynman collaboration.

It took me a couple of weeks to sift through the stacks of paper, which were stashed everywhere, but Leighton didn't disappoint me. I unearthed two folders, one marked "Feynman Freshman Lectures, unfinished," another labeled "Addison-Wesley," wedged between budget sheets and purchase orders from earlier decades and reams of yellowing computer paper covered with endless columns of numbers, all thrown together in a storage closet just outside his office. Leighton's correspondence with the publisher contained details about the format, the color of the cover, comments by outside readers, adoptions at other schools, and estimates of how well the volumes would sell. That folder I put in the "Save" pile. The other folder, the one containing the unedited Feynman physics lectures, I carried back to the archives myself.

In his June 1963 preface to *The Feynman Lectures on Physics,* Feynman commented on some of the lectures not included there. He'd given three optional lectures in the first year on how to solve problems. And, indeed, three of the items in Leighton's folder turned out to be the raw transcripts for Reviews A, B, and C, offered by Feynman in December 1961. A lecture on inertial guidance, which Feynman gave the following month, didn't make the cut either—an unfortu-

***Signora e Signore Goodstein*, portrayed by artist (and Goodstein friend) Igor Bitman as contemporaries of Galileo. The signora, however, holds Feynman's notes for the 1964 lecture, and the more familiar Goodsteins can be seen as modern Roman tourists in the painting above the book (published 1996).**

But in the end, we decided that the only lecture that still had the vitality, originality, and verve we associated with Feynman's presence in the classroom was the 1964 lecture on planetary motion—the one lecture that demanded a full complement of blackboard photographs. And we didn't have them.

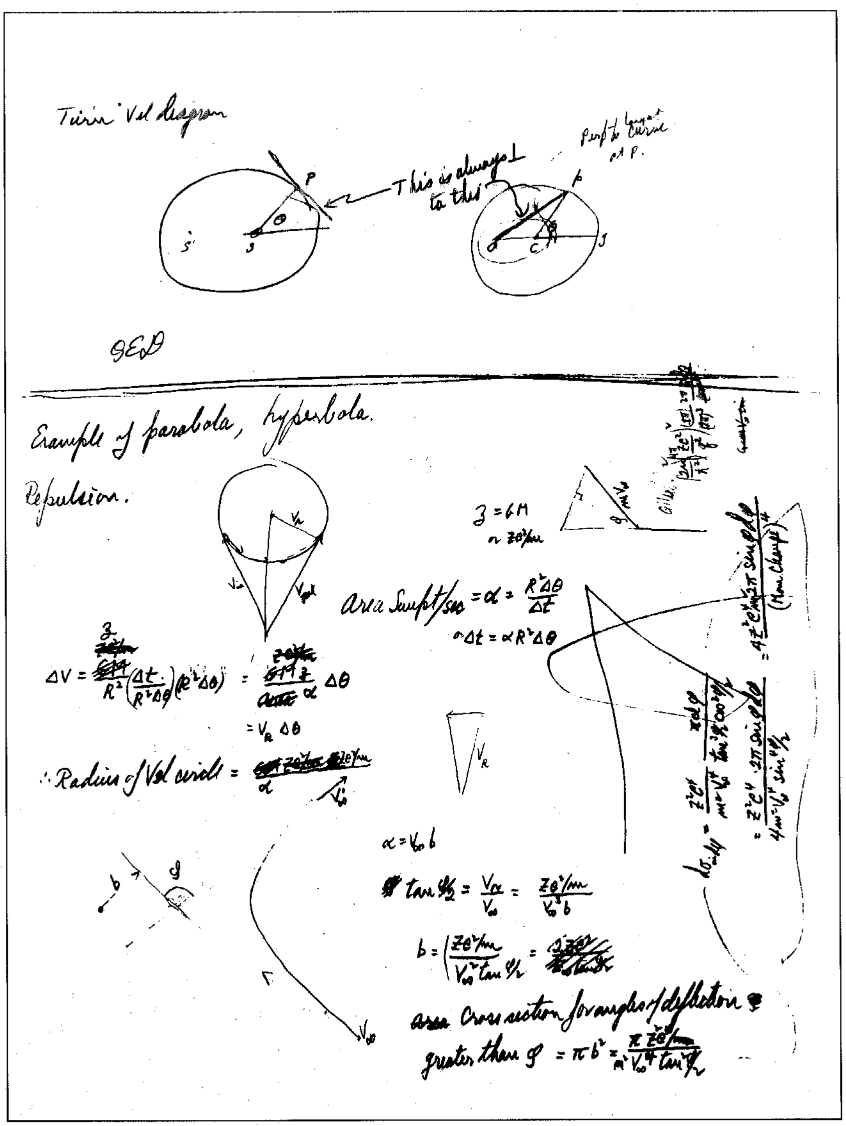
nate decision, according to Feynman—and I found a partial transcript of this lecture in Leighton's folder. The folder also contained the unedited partial transcript of a later lecture, dated March 13, 1964, along with a sheaf of notes in Feynman's handwriting. Entitled "The Motion of Planets Around the Sun," it was an unorthodox approach to Isaac Newton's geometric demonstration of the law of ellipses in the *Principia Mathematica*.

In September 1993, I had occasion to draw up a list of the original audiotapes of the Feynman lectures, which had also been contributed to the archives. They included five lectures that were not to be found in the Addison-Wesley books. Then I remembered the five unpublished lectures in Leighton's file; sure enough, the unedited transcripts matched the tapes. The archives also had photographs of the blackboard diagrams and equations for four of these lectures—the four mentioned by Feynman in his preface—but I could find none for the March 1964 lecture on planetary motion. (In the course of selecting illustrations for this book, I did stumble upon one photograph of Feynman taken during this special lecture. It is reproduced here [on page 18].) Although Feynman had given Leighton his notes on the 1964 lecture, which included sketches of his blackboard drawings, Leighton apparently decided not to include it in the last (1965) volume of *The Feynman Lectures on Physics*, which dealt primarily with quantum mechanics. In time, this lecture was forgotten. For all practical purposes, it was lost.

The idea of rescuing all five unpublished lectures from oblivion appealed to David and me. So the following December, when we went, as we often do, to the Italian hill town of Frascati, we took along copies of the tapes, the transcripts, the blackboard photographs, and Feynman's notes. In the course of the next two weeks, we listened to the tapes, took notes, laughed at the jokes, strained to hear the students' questions and Feynman's answers after each lecture was over, took more notes. But in the end, we decided that the only lecture that still had the vitality, originality, and verve we associated with Feynman's presence in the classroom was the 1964 lecture on planetary motion—the one lecture that demanded a full complement of blackboard photographs. And we didn't have them. Reluctantly, we abandoned the project.

Or so I thought. As it turned out, bits and pieces of the lecture haunted David, especially when he came to teach the same material in freshman physics the following year. He had the tape. But could he reconstruct the blackboard demonstrations from the few tantalizing sketches in Feynman's notes and the few words Feynman had jotted down more for himself than for the students? "Let's try again," he announced, early in December 1994, as we were packing for a trip through the Panama Canal. This time, we would take along only the transcript of the 1964 lecture, the lecture notes, and selected pages from Kepler's *The New Astronomy* and Newton's *Principia* for good measure.

It took the S.S. *Rotterdam* 11 days to sail from Acapulco to Fort Lauderdale. For two or three hours each day, David would hole up in our cabin and work on deciphering Feynman's lost lecture. He began, as Feynman had, with Newton's geometrical proofs. The initial break came when he was able to match up Feynman's first sketch [here on page 14] with one of Newton's diagrams, on page 40 of the Cajori edition of the *Principia*. We'd been at sea for three, maybe four days, Costa Rica's shoreline plainly visible, when David announced that he, too, could follow Newton's line of reasoning up to a point. By the time we'd exchanged the Pacific Ocean for the Atlantic, he was completely absorbed in Feynman's sparse, neatly labeled pencil drawings of curves and angles and intersecting lines. He stayed in the cabin, ignoring the scenery in favor of geometric figures—Newton's, Feynman's, and his own—longer and longer each morning and in the evening as well. When we arrived in Fort Lauderdale, on December 21, he knew and understood Feynman's entire argument. On the plane home, the book took shape. . . .



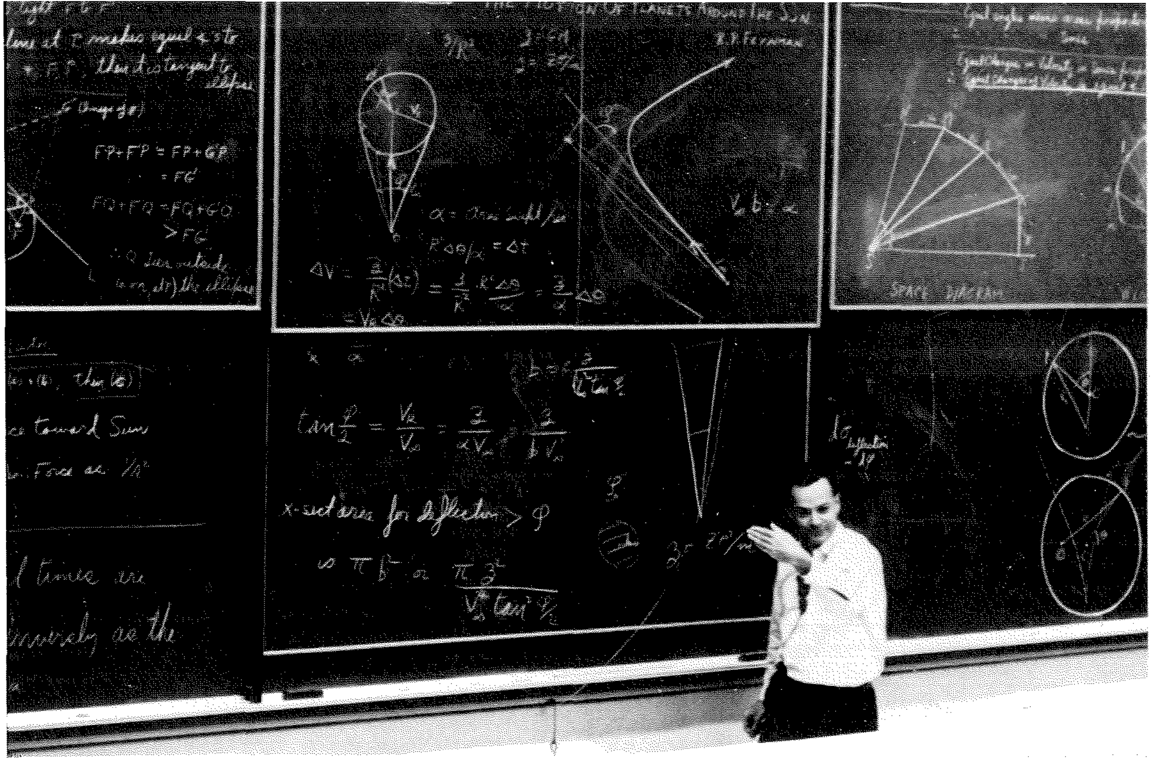
Another page of Feynman's lecture notes shows the final steps of his proof of the law of ellipses (above the line) and Rutherford's law of scattering (below the line).

Introduction

I would rather discover a single fact, even a small one, than debate the great issues at length without discovering anything at all.
—Galileo Galilei

This book is about a single fact, although certainly not a small one. When a planet, or a comet, or any other body arcs through space under the influence of gravity, it traces out one of a very special set of mathematical curves—either a circle or an ellipse or a parabola or a hyperbola. These curves are known collectively as the conic sections. Why in the world does nature choose to trace out in the sky those, and only those, elegant geometrical constructions? The problem turns out to be not only of profound scientific and philosophical significance but of immense historical importance as well.

In August of 1684, Edmund Halley (after whom the comet would be named) journeyed to Cambridge to speak to the celebrated but somewhat strange mathematician Isaac Newton about celestial mechanics. The idea was abroad in scientific circles that the motions of the planets might be a consequence of a force from the Sun that diminished as the inverse square of the distance between the Sun and the planets, but no one had yet been able to produce a satisfactory demonstration. Yes, Newton let on, he had been able to demonstrate that such a force would give rise to elliptical orbits—exactly what Johannes



Although blackboard photographs of all the rest of Feynman's lectures survive, none were ever found for his 1964 lecture on the motion of the planets around the sun. Only this one shot surfaced of Feynman actually giving the lecture—with part of the blackboard behind him.

Feynman tried to follow Newton's proof, but he couldn't get past a certain point, because Newton made use of arcane properties of conic sections. . . that Feynman didn't know. So, as he says in his lecture, Feynman cooked up a proof of his own.

Kepler had deduced some 70 years earlier from observations of the heavens. Halley urged Newton to let him see the demonstration. Newton apparently begged off, saying he had misplaced it, but promised to work it out again and send it to Halley. In fact, a few months later, in November 1684, Newton did send Halley a nine-page treatise in which he demonstrated that an inverse-square law of gravity, together with some basic principles of dynamics, would account for not only elliptical orbits but Kepler's other laws of planetary motion as well, and more besides. Halley knew that he held in his hands nothing less than the key to understanding the universe as it was then conceived.

He urged Newton to let him arrange for its publication. But Newton was not entirely satisfied with this work and delayed, wanting to make revisions. The delay lasted almost three years, during which Newton, now thoroughly hooked on the problem, seems to have done nothing else but work on it. What emerged at the end, in 1687, was *Philosophiae Naturalis Principia Mathematica*, Newton's masterpiece and the book that created modern science.

Nearly 300 years later, the physicist Richard Feynman, apparently for his own amusement, undertook to prove Kepler's law of ellipses himself, using no mathematics more advanced than elementary plane geometry. When he was asked to give a guest lecture to the Caltech freshman class in March 1964, he decided to base it on that geometric proof. . . .

The discovery of Feynman's lost lecture notes affords us an extraordinary opportunity. For most people, Feynman's fame rests on the picaresque exploits, recounted in two anecdotal books (*"Surely You're Joking, Mr. Feynman!"* and *"What Do You Care What Other People Think?"*) which he produced late in life in collaboration with Leighton's son, Ralph. The stories in these books are amusing enough, but they take on a special resonance because the protagonist was also a theoretical physicist of historic proportions. Yet for the nonscientist reader there is no way to peer into Feynman's mind and see that other side of him—the powerful intellect that left an indelible imprint on scientific thought. In this lecture, however, Feynman uses all his ingenuity, insight, and intuition, and his argument is not obscured by the layers of mathematical sophistication that made most of his accomplishments in physics impenetrable to the uninitiated. This lecture is an opportunity for anyone who has mastered plane geometry to see the great Feynman at work!

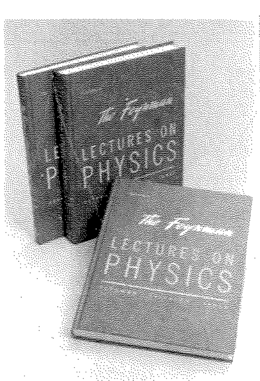
Why did Feynman undertake to prove Kepler's law of ellipses using only plane geometry? The job is more easily done using the powerful techniques of more advanced mathematics. Feynman was evidently intrigued by the fact that Isaac Newton, who had invented some of those more advanced techniques himself, nevertheless presented his own proof of Kepler's law in the *Principia* using only plane geometry. Feynman tried to follow Newton's proof, but he couldn't get past a certain point, because Newton made use of arcane properties of conic sections (a hot topic in Newton's time) that Feynman didn't know. So, as he says in his lec-

"I couldn't do it. I couldn't reduce it to the freshman level. That means we don't really understand it."

ture, Feynman cooked up a proof of his own.

Moreover, this is not just an interesting intellectual puzzle that Feynman has doodled with. Newton's demonstration of the law of ellipses is a watershed that separates the ancient world from the modern world—the culmination of the Scientific Revolution. It is one of the crowning achievements of the human mind, comparable to Beethoven's symphonies, or Shakespeare's plays, or Michelangelo's Sistine Chapel. Aside from its immense importance in the history of physics, it is a conclusive demonstration of the astonishing fact that has mystified and intrigued all deep thinkers since Newton's time: nature obeys mathematics. . . .

Feynman: A Reminiscence . . .



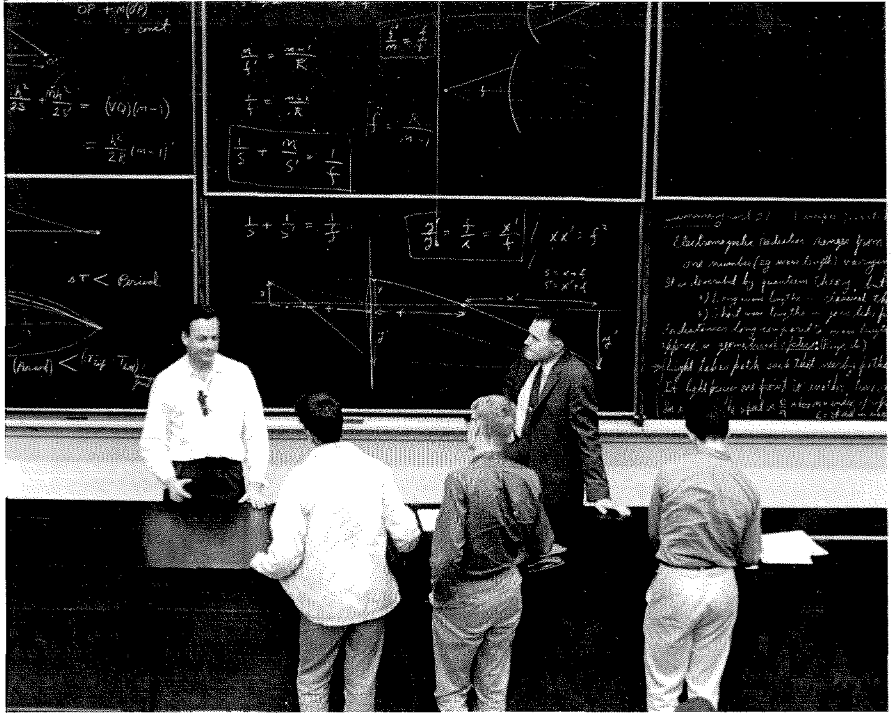
In 1961, Feynman undertook a project that would have far-reaching impact on the entire scientific community. He agreed to teach the two-year sequence of introductory physics courses that were required of all incoming Caltech students. His lectures were recorded and transcribed, and all the blackboards he filled with equations and sketches were photographed. From this material, his colleagues Robert Leighton and Matthew Sands, with help from Rochus Vogt, Gerry Neugebauer, and others, produced a series of books called *The Feynman Lectures on Physics*, which have become genuine, enduring classics of the scientific literature.

Feynman was a truly great teacher. He prided himself on being able to devise ways to explain even the most profound ideas to beginning students. Once, I said to him, "Dick, explain to me, so that I can understand it, why spin one-half particles obey Fermi-Dirac statistics." Sizing up his audience perfectly, Feynman said, "I'll prepare a freshman lecture on it." But he came back a few days later to say, "I couldn't do it. I couldn't reduce it to the freshman level. That means we don't really understand it."

Feynman delivered the *Feynman Lectures* to the Caltech freshman class in the academic year 1961–62 and to the same students as sophomores in 1962–63. His taste in physics topics was perfectly eclectic; he devoted just as much creative energy to describing the flow of water as to discussing curved spacetime. Of all the subjects he covered in that introductory course, perhaps his most impressive accomplishment is the presentation of quantum mechanics (Volume III of the series); in only slightly disguised form, it is the new view of quantum mechanics that he himself had developed.

While Feynman was a riveting, dramatic performer in the classroom, the period 1961–62 was to be the only time he ever taught formal undergraduate courses. For the rest of his professional life, before and after, he taught only courses designed for graduate students. The lecture that is the subject of this book was not part of the original course but rather a "guest lecture" to the freshman class at the end of the winter quarter in 1964. Rochus Vogt had taken over the teaching of introductory physics by then, and he invited Feynman to give the talk as a treat for the students. The *Feynman Lectures* were never successful as introductory textbooks—not even at Caltech, where they originated. They would instead make their lasting contribution as a source of insight and inspiration for accomplished scientists who had learned their physics by more conventional means.

In the immediate aftermath of his Nobel Prize in 1965, Feynman suffered a brief period of dejection, during which he doubted his ability to continue to make useful, original contributions at the forefront of theoretical physics. It was during this time that I joined the Caltech faculty. The Feynman physics course was now being taught by Gerry Neugebauer. When Feynman himself had been giving the lectures, Gerry, as a young assistant professor, had had the difficult job of making up homework assignments from them for the 200 or so students—difficult in large part because no one, maybe not even Feynman himself, knew in advance exactly what he was going to say. Just as he did for the lost lecture in Chap-



"You have to worry about your own work and ignore what everyone else is doing."

1962: Feynman and Leighton in 201 East Bridge.

ter 4 in this book, Feynman would come to class with no more preparation than one or two pages of scribbled notes. Neugebauer, to make his own task somewhat easier, would join Feynman, Leighton, and Sands for lunch after each lecture, in the Caltech cafeteria, known to generations of students as "the Greasy"; Caltech's elegant faculty club, the Athenaeum, was not Feynman's style. During these lunches, the lecture would be rehashed, with Leighton and Sands competing to score points with Feynman, while Neugebauer desperately tried to figure out the essence of the lecture.

Now, in 1966, Neugebauer was giving the lectures, and I was pressed into service as a T.A. (teaching assistant), in charge of one of the small recitation sections that supplemented the main course of lectures. The by now traditional lunches at the Greasy continued, with Feynman still in attendance. It was here that I first really got to know him, mostly exchanging ideas with him on how to teach physics. That fall, he got an invitation to give a public lecture at the University of Chicago the following February. At first he was inclined to refuse (invitations to speak arrived almost daily), but then he decided to accept and to talk about our ideas on teaching, if I would agree to come with him. He said that he would pay for my travel expenses out of the absurdly large ($1,000) honorarium they were offering. I thought the matter over carefully for a microsecond or so, and agreed to go. When he told the University of Chicago that I would be joining him, they were no doubt mystified about who I was and why I was needed, but they invited me with good grace and paid my way in the bargain.

At Chicago, Feynman and I shared a suite in the Quadrangle Club, the university's faculty club. On the evening after his talk, we had dinner at the home of friends, Val and Lia Telegdi. The next morning, I wandered down to the faculty club dining room for breakfast a bit late. Feynman was already there, eating with someone I didn't know. I joined them, introductions were mumbled but not heard, and I sleepily drank my morning coffee. As I listened to the conversation, it dawned on me that this person was James Watson, discoverer with Francis Crick of the double-helical structure of DNA. He had with him a typed manuscript entitled *Honest Jim* (the title would later be changed by the publisher to *The Double Helix*), which he wanted Feynman to read, in the hope that Feynman might contribute something to the dust jacket. Feynman agreed to look at the manuscript.

That evening there was a cocktail party and dinner in Feynman's honor at the Quadrangle Club. At the cocktail party, the worried host asked me why Feynman wasn't there. I went up to the suite and found him immersed in Watson's manuscript. I insisted that since he was the honoree, he had to come down to the party. Reluctantly, he did, but he fled after dinner at the earliest moment permitted by civility. When the party broke up, I went back up to the suite. Feynman was waiting for me in the living room. "You've gotta read this book," he said.

"Sure," I said, "I'll look forward to it."

"No," he shot back, "I mean right now." And so, sitting in the living room of our suite, from one to five in the morning, with Feynman waiting impatiently for me to finish, I read the manuscript that would become *The Double Helix*. At a certain point, I looked up and said, "Dick, this guy must be either very smart or very lucky. He constantly claims he knew less about what was going on than anyone else in the field, but he still made the crucial discovery." Feynman virtually dove across the room to show me the notepad on which he'd been anxiously doodling while I read. There he had written one word, which he had proceeded to illuminate with drawings, as if he were working on some elaborate medieval manuscript. The word was "Disregard!"

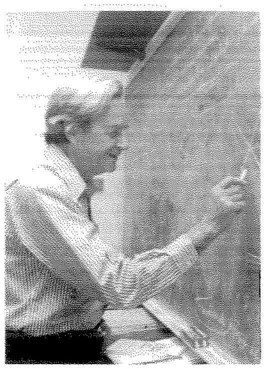
"That's what I'd forgotten!" he shouted (in the middle of the night). "You have to worry about your own work and ignore what everyone else is doing." At first light, he called his wife, Gweneth, and said, "I think I've figured it out. Now I'll be able to work again!". . .

Feynman's lost lecture on planetary motion was by no means the only ad-hoc lecture he ever gave for the benefit of the Caltech undergraduates. Over the years, he was often asked to make a guest appearance, and he nearly always complied. The last of these guest lectures took place on Friday morning, December 4, 1987. I was now teaching the freshman introductory physics course, and he agreed to my request to give the final lecture of the fall quarter.

The subject of Feynman's lecture on this occasion was to be curved spacetime (Einstein's theory of general relativity). Before starting, however, he had a few words to say on a subject that excited him greatly. That year a supernova had occurred at the edge of our galaxy. "Tycho Brahe had his supernova," Feynman told the class, "and Kepler had his. Then there weren't any for 400 years. Now I have *mine*!"

This remark was greeted with a stunned silence by the freshmen, who had reason enough to be in awe of Feynman even before he opened his mouth. Dick grinned with obvious pleasure at the effect he had created, and defused it in the next breath. "You know," he mused, "there are about a hundred billion stars in a galaxy—10 to the 11th power. That used to be considered a huge number. We used to call numbers like that 'astronomical numbers.' Today it's less than the national debt. We ought to call them 'economical numbers.'" The class dissolved in laughter, and Feynman went on with his lecture.

Richard Feynman died two months later, on February 15, 1988.



Feynman in 1985—still rarely far from a blackboard.

Caltech Registrar and Archivist Judith Goodstein and her husband, David (professor of physics and applied physics, the Frank J. Gilloon Distinguished Teaching and Service Professor, and vice provost) have been, separately, loyal contributors to Engineering & Science *(see page 40). Their last joint appearance in these pages was in October 1980, when they viewed the scientific method from different, but concurring, perspectives.*