Physics Today

Richard P. Feynman, Teacher

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Citation: Physics Today **42**(2), 70 (1989); doi: 10.1063/1.881195
View online: http://dx.doi.org/10.1063/1.881195
View Table of Contents:
http://scitation.aip.org/content/aip/magazine/physicstoday/42/2?ver=pdfcov
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RICHARD P. FEYNMAN, TEACHER

His achievement as a teacher—and as an inspiration and model for other teachers—was based on nothing less than seeing all of physics with fresh new eyes.

David L. Goodstein

One of the principal purposes of this article is to consider Dick Feynman in his role as teacher. Let me not keep you in suspense about my conclusion. I think Dick was a truly great teacher, perhaps the greatest of his era and ours. That's not to say he was always completely successful, as he himself emphasized in his preface to *The Feynman Lectures on Physics*.[1] I would contend that these lectures often failed at the level of their superficial intent: If his purpose in giving them was to prepare classes of adolescent boys to solve examination problems in physics, he may not have succeeded particularly well; if his purpose in creating those three red volumes was to provide effective introductory college textbooks, he may not have succeeded, either. If, however, his purpose was to illustrate, by example, how to think and reason about physics, then, by all indications, he was brilliantly successful. Perhaps this is why the books are genuine and lasting classics of the scientific literature and why his lectures left an enduring trace on those fortunate enough to have heard or read them.

Feynman's role as a teacher was somewhat unconventional, like almost everything else about the man. He loved puzzles and games. In fact, he saw all the world as a sort of game, whose progress, or "behavior," follows certain rules, some known, some unknown. Given the "known" rules, find the behavior; given the behavior, find the rules. Find places or circumstances where the rules don't work, and invent new rules that do. This attitude was a central theme in all of his teaching.

Perhaps I can shed some light on Dick's personality and approach to teaching by recounting a few personal anecdotes, incidents that haven't yet made it into the "Feynman story" literature because they're not the kinds of stories he liked to tell about himself and I was the only other witness.

The joy of immersion

The first story goes back to the week that I learned from his secretary, Helen Tuck, that Dick had cancer. She told me he was to go into the hospital for surgery the

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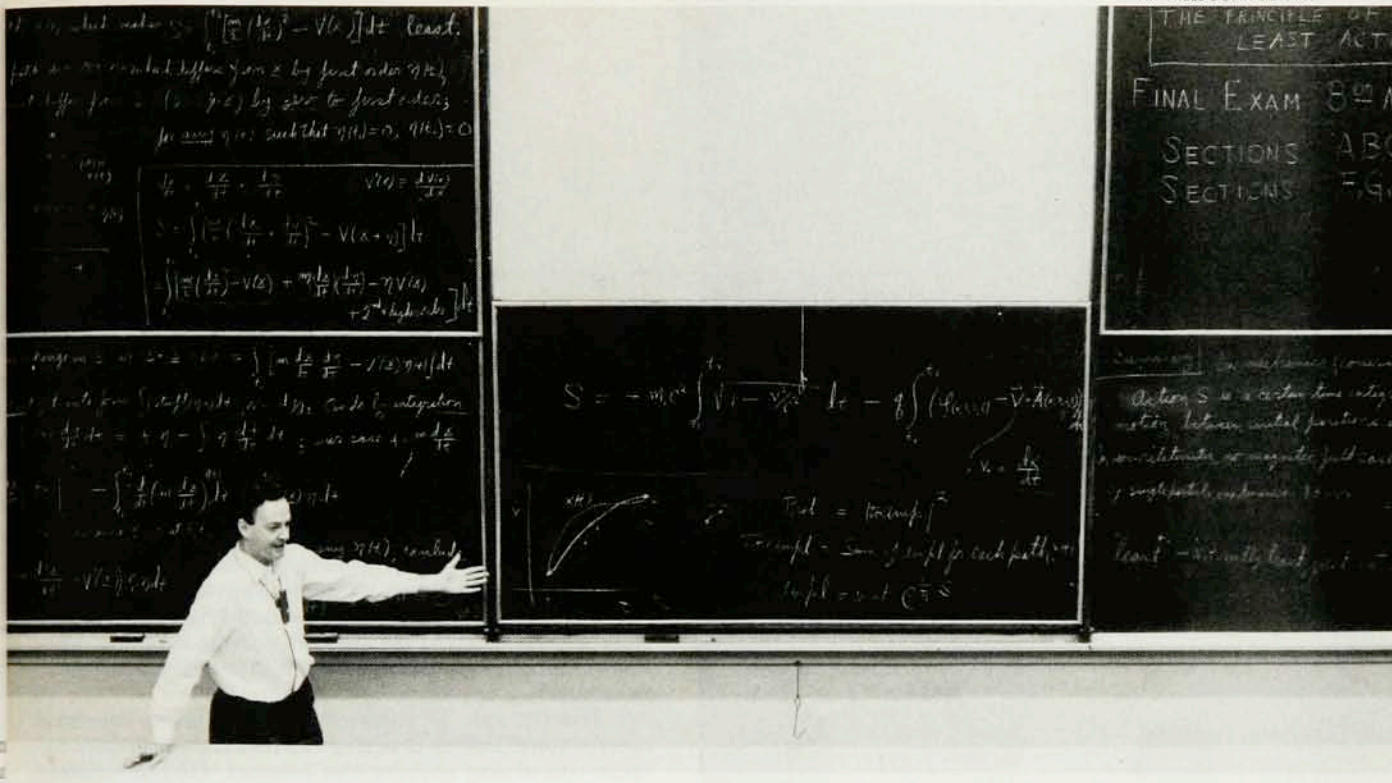

Lecturing to undergraduates on the principle of least action in the early 1960s.

following week. He might not survive. This was, I think, in June 1979.

I saw him that Friday morning, while we were "robing up" for graduation (yes, Feynman put on silly academic robes and marched in the commencement procession the week before his first cancer operation). Someone had told me there was something wrong with a calculation that Dick and I had worked on together, but I couldn't find the source of the mistake. Would Dick like to talk about it? We made an appointment for the following Monday morning.

On Monday morning we got to work. Or rather, he did. I mostly watched and commented, and marveled to myself about this man, facing the abyss but working with unflagging patience and energy on an arcane problem in two-dimensional elastic theory. Of course, he didn't know that I knew his terrible secret.

The problem proved intractable—at six o'clock that evening, we hadn't succeeded. He declared the situation hopeless and went home.

Two hours later, Feynman called me at home with the solution to the problem. He was very excited. He had not been able to stop working on it and had finally solved it. This man, who was now four days away from a major operation, was in a *very* good mood.

Giving credit

The second story goes back to the beginnings of the same collaboration in which we made the mistake I have just described. Feynman and I had been discussing some experiments that one of my students had done. One morning he marched into my office, walked to the blackboard and said, "Look, it's obvious that . . . ," and proceeded in a few minutes to sketch out an idea that might explain our results. I was dumbstruck. It was simple, intuitive, beautiful. I got to work immediately putting the data in a form that could be compared with his model. It worked pretty well, so I wrote the first draft of a paper.[2] Just as I was finishing it, I got a preprint in the mail from two English physicists, J. Michael Kosterlitz and David Thouless. It presented exactly the same theory Feynman had sketched out on my blackboard.

In my experience, beneath the surface of every scientist there lurks a wounded person who believes his work has not been fully appreciated. Feynman was a rare, perhaps even unique exception. In fact, many times I saw him go to some length to make sure that he didn't take credit away from some younger theorist who needed it much more. When the Kosterlitz–Thouless paper arrived, I went directly to Feynman to tell him what had happened. For just an instant I saw the smallest shadow of disappointment flicker across his face. Then he brightened and said (apparently thinking that Kosterlitz and Thouless were one person), "Look, if two guys in different parts of the world, thinking about different problems, get the same idea, it must be right!" The Kosterlitz–Thouless theory went on to become one of the most important theories in statistical mechanics.

The performer

Let me tell just one more personal story, a small one, but one that hints, I think, at an essential element of Dick's motivation to teach. In 1968 my wife and I returned to Caltech from a postdoctoral year in Italy. I was now an assistant professor, but we were in debt, owned almost nothing and had moved into an apartment near campus

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Talking to students in a coffee room at Caltech, June 1964.

that had virtually no furniture at all. In fact, we had only two possessions to speak of, both acquired in Italy. One was a 2700-year-old Etruscan pottery drinking cup, and the other was a great big electric espresso machine. One day I invited Feynman and others over to the apartment for a cup of expresso.

The instant he entered the apartment, Feynman spotted the Etruscan drinking cup (not hard to do because there was almost nothing else around). He immediately picked it up and started playing with it, turning it over, tapping the surface and boasting that he would explain how you could tell it wasn't genuine. I saw my wife go absolutely white in stark terror when he bounced the cup in his hand, proceeding to tell us stories about amazing things that had been discovered in Etruscan tombs. In fact, he didn't damage the cup, and he didn't prove it was a fraud. What he did do was just what Feynman always did. He absolutely riveted the attention of everyone in the room for the entire time he was there. His need to do that helps explain some of the racy stories he liked to tell about himself, but it also lies close to the core of what made him a great teacher. For Feynman, the lecture hall was a theater, and the lecturer a performer, responsible for providing drama and fireworks as well as facts and figures. This was true regardless of his audience, whether he was talking to undergraduates or graduate students, to his colleagues or the general public.

I can remember many moments of high drama in Feynman lectures. Once, for example, several years ago, he taught a course in advanced quantum mechanics in a large lecture hall, to a class consisting of a few registered graduate students and most of the Caltech physics faculty. At one point he started explaining how to represent certain complicated integrals diagrammatically: time on this axis, space on that axis, wiggly line for this, straight line for that and . . . turning around suddenly to face the class with a wicked grin he said, "and this is called *the diagram*!" The class ignited with spontaneous applause.

A more recent memorable moment comes from the last lecture I heard Feynman give, a guest lecture at Caltech's freshman physics course. These appearances had to be kept secret so there would be room for the freshmen in the hall. The subject was curved space–time, and the lecture was characteristically brilliant. But the unforgettable moment came at the beginning before he really got started. The supernova of 1987 had just been discovered, and he was very excited about it. "Tycho

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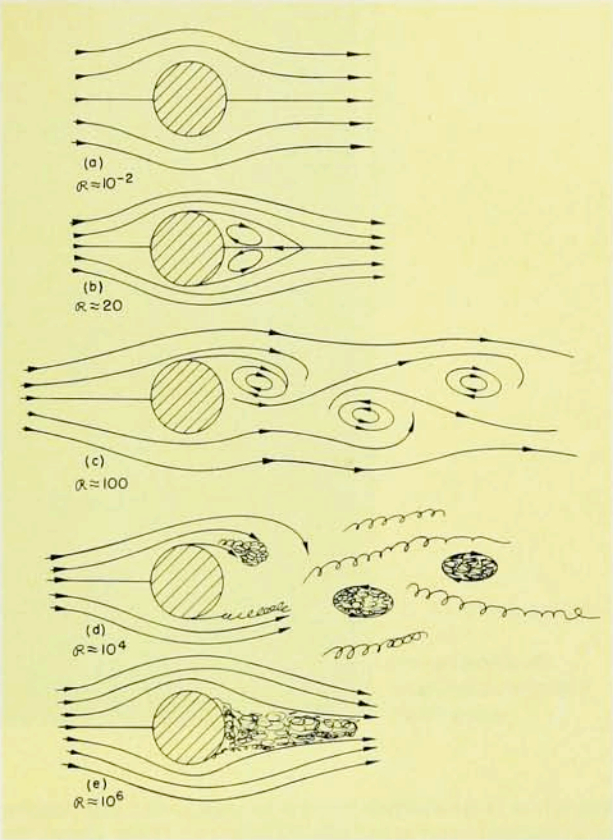

Pedagogical simplicity of the diagrams in *The Feynman Lectures on Physics* is exemplified by this schematic figure (Figure 41–6, Volume II) showing fluid flow past a cylinder for various Reynolds numbers.

Brahe had his supernova," Dick said, "and Kepler had his. Then, there weren't any for 400 years. But now, I have mine." Then he went on to defuse the awed silence he had created. "There are 10^{11} stars in the galaxy," he said. "That used to be a *huge* number. But it's only a hundred billion. It's less than the national deficit! We used to call them astronomical numbers. Now we should call them economical numbers." The class dissolved in laughter, and Dick went on with his lecture.

In his public lectures Dick never hesitated to say exactly what was on his mind. When he went to speak at another university—I personally saw this happen on two separate occasions—he would express his views on psychology, and the psychology department could absolutely be depended on to rise and depart on cue, and *en masse*. Then he would do the same for philosophy. You can imagine the fiendish delight Dick took from these demonstrations. But he also knew how to illuminate a subtle point with a brilliant example that anyone could understand. I remember one time he was trying to explain why you must not verify an idea by using the same data that suggested the idea in the first place. This is a point even many scientists don't appear to understand. Seeming to change the subject, Feynman said: "You know, the most *amazing* thing happened to me tonight. I was coming here, on the way to the lecture, and I came in through the parking lot. And you won't believe what happened. I saw a car with the license plate ARW 357! Can you imagine? Of all the millions of license plates in the state, what was the chance that I would see that particular one tonight? Amazing!"

The official record

I felt I should do some real research to prepare to write here about Feynman's teaching, so I decided to find out what he had actually taught during his career. I don't have any information on what courses he gave in his early days at Cornell, but I do have the record of what he taught at Caltech.

In 35 years, from 1952 to 1987, he was listed as teacher of record for 34 courses. Most of these, in fact 25 of them, were advanced graduate courses; in typical Caltech fashion these were strictly limited to graduate students, unless undergraduates asked permission to take them. (They often did and it was nearly always granted.) These courses included advanced quantum mechanics, the course he taught more than any other course (nine times), and second most often (or five times) a course called Topics in Theoretical Physics—in other words, whatever he felt like talking about. He also taught Elementary-Particle Theory and High-Energy Physics, which were separate courses during the 1960s, the heyday of these subjects at Caltech. He taught other graduate courses such as relativity, and a couple of times he taught introductory graduate courses, including mathematical methods of physics and quantum mechanics.

In 1981, toward the end of his career, Feynman joined with John Hopfield and Carver Mead to offer an interdisciplinary course called The Physics of Computation. Two years later Hopfield and Mead were still teaching The Physics of Computation, but Dick had split off a separate course called Potentialities and Limitations of Computing Machines. I have not determined whether this represented a broadening of our offerings in this area or a schism in the high church of computing. In any case, in all those years, only twice did he teach courses purely for undergraduates. Those were the celebrated occasions in the academic years of 1961–62 and 1962–63 when he lectured, first to the freshmen, and then again to the same set of students when they were sophomores, on the materials that were to become *The Feynman Lectures on Physics*.

Based on these data, should Dick be remembered as relatively untried in the teaching of undergraduates? Not really: In spite of the formal, written record, the real story—that of informal contact with undergraduates—is a little different. For many years—at least 17,

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Performing at a Caltech talent show, spring 1966.

but there is no written record to check—he also taught an informal course called Physics X. This class, for which no credit was offered, met weekly, on Monday or Tuesday afternoons at 5 pm, which was the most convenient time for the students. The curriculum consisted of whatever the students felt like discussing. There was, in fact, just one unbreakable rule: No faculty were permitted to attend. As a result, I can't tell you anything else about what went on in Physics X. There is one more thing I can tell you, though. Tuck, who was Feynman's secretary for 17 years, had the job of deflecting visitors, avoiding appointments and generally protecting Feynman's privacy. There was one standing exception to this rule: The door was always, unconditionally, open to any student who wanted to see him.

The undergraduate lectures

Dick once told me that in the long run, his most important contribution to physics would be not QED or the theory of superfluid helium or polarons or partons. His real monument would be his *Feynman Lectures*. I think we can all agree at least that it was his most important contribution to physics education. I didn't arrive at Caltech until a few years after it was completed, so in an attempt to find out how it was all done and how it went, I've talked to a number of people who where there. Here's a bit of what I've gleaned.

It was apparently Matthew Sands who had the idea of asking Dick to give the lectures. There was a feeling that the Caltech students, who were among the best in the country, were getting turned off rather than turned on by their two years of compulsory physics, and something had to be done. When Dick agreed to do the job, it was immediately decided to transcribe the lectures and publish them. That job turned out to be far more difficult than anyone had imagined. Turning out publishable books required a tremendous amount of work on the part of Sands, Robert Leighton, Gerry Neugebauer, Rochus Vogt and many others, as well as Feynman himself.

Meanwhile, there was the matter of how to take care of the nuts and bolts of running a course for nearly 200 students. This task was greatly complicated by the fact that Feynman used only a minimal outline of what he wanted to cover, so that no one but he knew what he was going to say until he said it. A single sheet, $8\frac{1}{2}$ by 11, with cue words and diagrams was the norm.

This scheme was particularly hard on Neugebauer, a young assistant professor at the time, who had the job of turning out homework assignments for the students on the afternoon after each lecture. The problem, he says, is that he sometimes didn't capture all of the lecture. To help out with this problem, Feynman, Leighton, Sands and Neugebauer would have lunch together after each lecture at the campus cafeteria, known affectionately to generations of Caltech students as "the Greasy." At these sessions, Leighton, Sands and Feynman would rehash the finer points of the lecture while Neugebauer (as he tells the story) would try desperately to pick up enough additional comprehension to be able to make up homework problems.

Incidentally, when I arrived at Caltech as a postdoc five years later, Neugebauer, who was by then well launched on his distinguished career, was the lecturer in Physics 1, and I was pressed into service as a teaching assistant, teaching a recitation section. Feynman still came to lunch after each lecture, and it was at those lunches at the Greasy that I first really got to know him.

Many of the students, Gerry says, feared the course when Feynman taught it. I've spoken to some of those students in recent times, and in the gentle glow of dim memory, each has told me that having two years of physics from Feynman himself was the experience of a lifetime. But that's not the way Gerry remembers it. As the course wore on, attendance by the kids at the lectures started dropping alarmingly, but at the same time, more and more faculty and graduate students started attending, so the room stayed full, and Feynman may never have known he was losing his intended audience.

Why did Feynman accept the assignment to devote all

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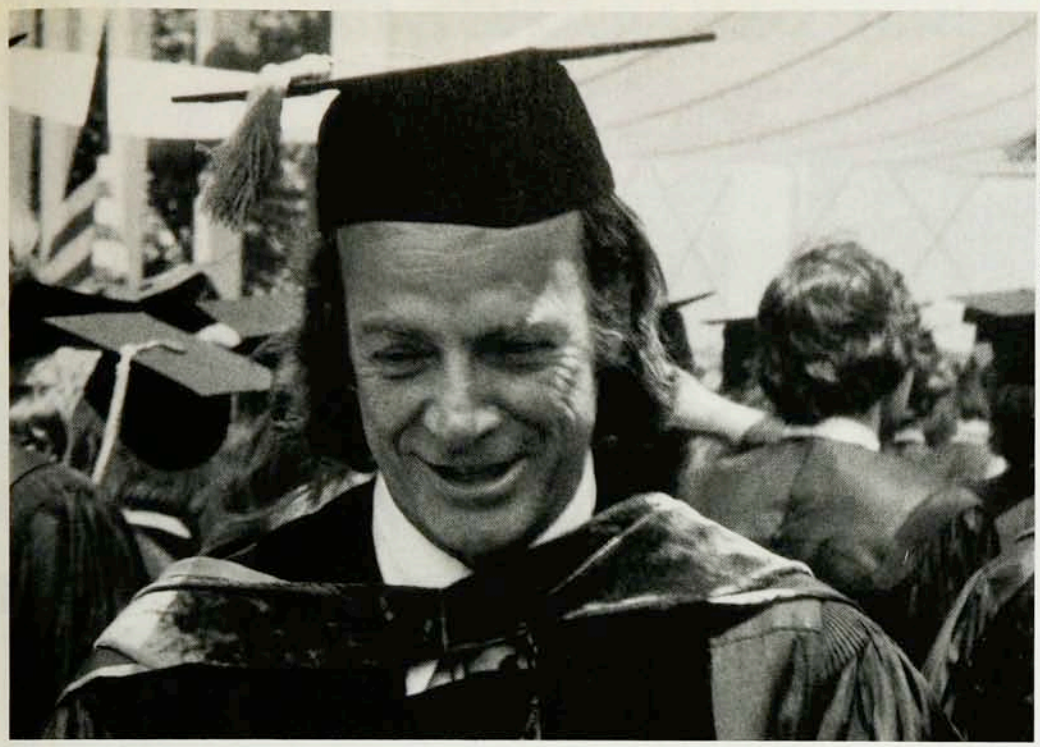

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In academic robes at Caltech's commencement ceremony, June 1974.

of his formidable energy for two years to teaching beginning physics as it had never been taught before? My guess is that there were three basic reasons. One was that, as we saw earlier, he loved to have an audience, and this gave him a bigger one than he usually had in the graduate courses he normally taught. The second was that he genuinely cared about students. He simply thought that teaching freshmen was an important thing to do, and so he couldn't turn down the invitation when it came. The third reason—and this might have been the most important of all—was the sheer challenge of reformulating physics, as he understood it, so that it could be presented to young students. This was a specialty of his. In fact, it was the standard by which he measured whether something was really understood. Once I asked him to explain to me, so that I could understand it, why spin-$\frac{1}{2}$ particles obey Fermi–Dirac statistics. Gauging his audience perfectly, he said, "I'll prepare a freshman lecture on it." But a few days later he came to me and said: "You know, I couldn't do it. I couldn't reduce it to the freshman level. That means we really don't understand it."

It's true, as we've seen earlier, that he sometimes missed the mark. The lessons in physics he prepared, the explanations of physics at the freshman level, weren't really for freshmen, but were for us, his colleagues. As I reread the red books, which I did last summer, I thought every once in a while that I caught him looking over his shoulder, not at his young audience, but directly at us, and saying: "Look at that! Look how I finessed that delicate point! Wasn't that clever?" But even when he thought he was explaining things lucidly to freshmen or sophomores, it was not always really they who benefited most from what he was doing. It was more often us, scientists, physicists, professors, who would be the main beneficiaries of his magnificent achievement, which was nothing less than to see all of physics with fresh new eyes. Feynman was more than merely a great teacher. His lasting monument is that he was a great teacher of teachers.

I will finish by quoting something directly from the source. I have my own favorite passages, of course. Probably we all do. But I'm going to choose one that he, in effect, chose himself. One day a few years ago, I ran into him on campus. He was in a state of high excitement, which for him was perfectly normal of course, but the cause of his excitement was a passage from *The Feynman Lectures*, which he was brandishing in photocopy form. "Look at this," he said. "I said this long before they sent the first mission into space." This was probably at the time of one of the Viking orbiters and landers, which were particularly exciting events at Caltech, since JPL was running the show. By then we had all learned that life was not going to be discovered in the solar system as many had originally hoped, but still the pictures of Mars coming back from the Vikings were an extraordinary experience for us all. And just as he claimed, he had, way back in 1962, anticipated just what would happen. Let me quote to you what he said. It comes from book II, chapter 41, verse 6:

> There are those who are going to be disappointed when no life is found on other planets. Not I—I want to be reminded and delighted and surprised once again, through interplanetary exploration, with the infinite variety and novelty of phenomena that can be generated from such simple principles. The test of science is its ability to predict. Had you never visited the Earth, could you predict the thunderstorms, the volcanos, the ocean waves, the auroras, and the colorful sunset? A salutary lesson it will be when we learn of all that goes on on each of those dead planets—those eight or ten balls, each agglomerated from the same dust cloud and each obeying exactly the same laws of physics.

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