

Feynman stressed creativity—which to him meant working things out from the beginning. He urged each of us to create his or her own universe of ideas, so that our products, even if only answers to assigned classwork problems, would have their own original character.⁶

Feynman's way of teaching is perhaps best described in three words: learning by creating. As he said,

It's the way I study—to understand something by trying to work it out or, in other words, to understand something by creating it. Not creating it one hundred percent, of course; but taking a hint as to which direction to go but not remembering the details. These you work out for yourself.

In a letter to a student asking for advice, Feynman touched again on that point:

All you have to do is, from time to time—in spite of everything, just try to examine a problem in a novel way. You won't "stifle the creative process" if you remember to think from time to time. Don't you have time to think?⁷

The problem is, however, that as students we are often not given proper time to think! We are instead overwhelmed with solving problem sets, writing lab reports, and worrying about passing exams. Remarkably, Feynman emphasized creativity in physics until his very last days. He wrote on his blackboard shortly before he died, "What I cannot create I do not understand."

The Feynman Lectures on Physics clearly exhibit their author's unconventional approach. David Goodstein (PHYSICS TODAY, February 1989, page 70) says of the lectures,

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, however, his purpose was to illustrate, by example, how to think and reason about physics, then, by all indications, he was brilliantly successful.

Feynman's lectures successfully omitted proposed problems. His teaching style is also exemplified in the noncredit, no-homework, no-registration, tuition-

free Physics X course he offered at Caltech. Students met weekly, and the curriculum consisted of whatever they felt like discussing. The primary focus was to promote a culture of free inquiry and joy toward the subject. In the lectures I have attended so far at UCL, the idea of enjoying physics has not even been raised.

Feynman said,

The best teaching can be done only when there is a direct individual relationship between a student and a good teacher—a situation in which the student discusses the ideas, thinks about the things, and talks about the things.¹

Such teaching is mostly absent from my current physics education.

As a student, I have not yet been able to reconcile the traditional approach with my firm conviction that the best physics teaching puts a premium on creativity and free inquiry. Feynman has

shown that such creative teaching is possible.

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LETTERS

Approaches to studying our history

I share Matt Stanley's view that studying the history of our subject enriches our perspectives as practicing physicists ("Why should physicists study history?," PHYSICS TODAY, July 2016, page 38). In my talks to the nontechnical public and in presentations of new results to colleagues, I try to emphasize the complex network of chance influences, mistakes, collaborations, and controversies that lie behind discoveries conventionally caricatured by attributing them to one person.

Stanley and I part company when he complains about those who interpret the science of the past in terms of what we know today: "the bugbear of . . . Whig history." Of course, it is essential to study scientific advances in the social, economic, and cultural context of their times, as professional historians do. But Whig history is a complementary activity, justifiable on several grounds.

Our scientific predecessors are celebrated largely because of the science that their discoveries led to; that is why they are important, and why historians study them. And the significance of their science changes with time, so it is inevitable that we regard it differently as we look back: With the discovery of the

Aharonov-Bohm effect, the magnetic vector potential of James Clerk Maxwell and his Victorian contemporaries takes on a new meaning. In addition, many of our famous predecessors were cleverer and wiser than us; they left "time bombs," ignored for generations until, suddenly triggered by resonating with a contemporary preoccupation, they explode.

One such time bomb is Isaac Newton's query 3, which he posed¹ after decades of struggling to accommodate Grimaldi's observation of edge diffraction fringes in his ray theory of light: "Are not the Rays of Light, in passing by the edges and sides of Bodies, bent several times backwards and forwards, with a motion like that of an Eel? And do not the three Fringes of colour'd Light above-mention'd arise from three such bendings?" Now, three centuries later, and thanks to three insights, we can understand² that this apparently eccentric remark makes perfect sense.

The first insight was Sommerfeld's 1896 exact solution of Maxwell's equations for light diffracted by a conducting half plane.³ The second insight was Braunbek and Laukien's 1952 calculation⁴ exhibiting Newton's eel-like undulations by plotting the trajectories of the Poynting

vector in Sommerfeld's solution. The third was the recognition that those trajectories are the wave-physics counterparts of the rays of geometrical objects—an insight transferred from the analogous phase-gradient trajectories of quantum waves, as envisaged in Erwin Madelung's hydrodynamic picture or the equivalent de Broglie-Bohm representation.

Did Newton "prediscover" that ray-like representation of wave physics? Of course not, but Whig history enables us to recognize it as a prescient groping toward our modern insight—surely a legitimate way of engaging with our discipline's past.

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I read with great interest Matt Stanley's article on why physicists should study the history of their subject and how that history is important to physics education. I fully concur with his statement that one of the most valuable lessons from the history of science is to learn how the concepts of physics were discovered.

Unfortunately, authors of physics textbooks often make up convenient stories about the development of physics, which then are repeated endlessly. For example, one of the most important concepts in physics was Max Planck's introduction of energy discreteness in atomic physics, which led to the development of quantum mechanics. The tale in most textbooks is that he was concerned about

the UV catastrophe encountered by the application of the equipartition theorem to the electromagnetic theory of light. But there is no evidence that Planck was aware of the problem, first pointed out by Lord Rayleigh. The actual origin of Planck's fundamental new physical concept is quite different and much more interesting. He found the idea of energy discreteness in Ludwig Boltzmann's 1877 seminal paper on statistical mechanics, where it was introduced as a purely mathematical device to count configurations in a model of a molecular gas. But Planck's application to the problem of blackbody radiation was subtle, and to date historians continue to disagree on its interpretation.¹⁻⁴

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Notes on the New Big Science

Robert Crease and Catherine Westfall, in their article "The New Big Science" (PHYSICS TODAY, May 2016, page 30), describe how materials science has taken over national laboratory facilities formerly occupied by high-energy particle physics. That is an interesting transition for materials science. But unfortunately, the claim that "Big Science isn't what it used to be" seems true only in a more limited sense than the title implies.

As the authors note, US particle physics is now carried out mainly abroad. But the focus on ever-larger accelerators has simply moved to the Large Hadron Collider at CERN. The LHC's community of 10 000 and annual budget of \$1 billion dwarf the materials science effort at Brookhaven National Laboratory.¹

Crease and Westfall acknowledge that their discussion omits astronomy. But the huge 30-meter-class telescopes and the 4-meter-aperture solar instrument are presently the main arena for Big Science in the US (reference 2; see also PHYSICS TODAY, October 2005, page 30). The article also doesn't mention how university plasma research has been

marginalized since the 1970s by increasingly large fusion machines, their growth culminating in the deeply troubled ITER project. Overall, I doubt that a more balanced analysis would support the view that Big Science has changed meaningfully.

The authors do not mention that US particle physics left the national labs precisely because the discipline was devastated by the termination of the overly ambitious Superconducting Super Collider in 1993. Hundreds left the field, once the flagship of US science, for astronomy or to work for hedge funds.³ It is troubling that now Big Astronomy is following the same precarious path, closing even large telescopes to build a few behemoths.⁴

The authors describe well the increased complexity of materials science at the national labs. Perhaps that community can, in time, learn to manage the complexity in ways that will guide others to the benefits of Big Science while avoiding its dangers.

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► **Crease and Westfall reply:** The fact is that the largest projects at the US national laboratories are now devoted to materials science rather than high-energy physics. That development has been accompanied by important changes in research and the research culture at the labs, which we characterize by coining the phrase the New Big Science. ("Isn't what it used to be" was added by the editors.) We believe it is important to understand the changes. We leave it to others to explore the course of Big Science outside the US and how large astronomical projects fit into the mix; we deliberately refrained from discussing those topics in our article.

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