Feynman After 40
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Slides: www.theory.caltech.edu/~preskill/talks/APS-April-2018-Feynman-4-3.pdf
See the slides for the sources of quotes included in this transcript
(30 minute talk)

I'm calling this talk "Feynman After 40" because I like the sound of all the Fs in that title. I don't think the title obligates me to speak only about Feynman after 40, though mostly I will.

Since Paul Halpern talked about Wheeler and Feynman, I'll start with an anecdote about Feynman's influence on Wheeler. I took a course from Wheeler when I was a sophomore at Princeton. Wheeler seemed unimaginably old at the time, having worked with Niels Bohr, but he was younger then than I am now. For a full year course covering all of physics, the very first lecture went like this: "An electron wants to go from point A to point B. But how does it know what path to follow? It follows all the paths, and adds then together weighted by e to the i action, and the paths constructively interfere on a path we call the classical trajectory …"

Wheeler thought the best way to introduce classical mechanics to sophomores was to start with the Feynman sum over histories. I found this wonderful, but some students complained that the lecture didn't help us do the homework, classical mechanics problems assigned from Goldstein's book.

My first encounter with Feynman had occurred earlier, when at age 9 I acquired a marvelous book called *The World of Science* by Jane Werner Watson. There was a chapter on theoretical physics, which began with the story of a boy whose little red wagon has a ball in the back. He notices that when he pulls the wagon forward the ball rolls backward, and when he stops pulling the ball rolls forward. He asks his father why, and his father replies: That's called inertia, but nobody knows why.

Some 20 years later I watched the terrific interview of Feynman by Christopher Sykes, called *The Pleasure of Finding Things Out*, where Feynman tells the same story. Whoa!, I thought --- did Feynman steal the story from the Golden Book I read as a child? Looking at the book for the first time in years, I realized what had happened. Jane Werner Watson was married to Earnest Watson, the Caltech Dean of the Faculty, and she based the book on interviews with faculty members. Now I wondered … why is Feynman wearing a bow tie, and where are Murray's glasses?

What's most impressive about this book is that it contains a lucid discussion of the experimental evidence for nonconservation of parity in nuclear beta decay, a discovery made only a year before the book was published, which I found tremendously exciting.

One can read about Richard Feynman in many places, and here are some of my favorites. Ralph Leighton did an amazing job of capturing Feynman's voice in editing the two volumes of Feynman stories, versions of which were well known to many of Feynman's friends. The biography by James Gleick contains many revealing interviews, with sources compiled in the end notes. Physics Today published a special issue about Feynman the year after he died, and the book *Most of the Good Stuff* contains those articles plus a few more. The book *Feynman and Computation* contains reminiscences about Feynman's interest in computing, and the foreword I wrote with Kip for the *Feynman Lectures on Gravitation* was informed by communication with his colleagues regarding Feynman's impact on gravitation theory. And in the 2005 Physics Today, Matt Sands tells a compelling story about how *The Feynman Lectures on Physics* came to be.

Feynman and I overlapped at Caltech for 4 ½ years. One day soon after I arrived, I heard someone drumming on the wall while walking down the hallway, knew it must be Feynman, and stepped out of my office to greet him. Our theory group admin Helen Tuck introduced us: "Dr. Feynman, this is Dr. Preskill, our new faculty member." Feynman replies: "What group?" Does Feynman really not know who I am? "Um … particle theory." Feynman: "People who say they do particle theory do many different things. What do you do?" I ramble incoherently for a minute about the connection between particle physics and cosmology, then unwisely conclude: "And lately, I have been working, without much success, on models in which quarks and leptons are composite." Long pause, then: "Well, your lack of success has been shared by many others." Feynman turns and disappears into his office. We were off to a good start.

Actually, Feynman and I had already met a few times before that, when I had come to Caltech to give seminars. Doing the Caltech particle theory seminar in the days of Feynman and Gell-Mann was a memorable experience. Here is how Steve Weinberg described it:

"Years ago, when I was an assistant professor of physics at Berkeley [1960-66], I used to be invited down to Caltech about once a year to give a talk. It was usually the low point of my year. In the audience at Caltech were two leaders of modern physics, Murray Gell-Mann and Richard Feynman, who interrupted with frequent questions, ruthlessly probing to see if I really knew what I was talking about and had anything new to say. Of the two, Feynman was the more frightening. Gell-Mann was mostly interested in finding out whether there was anything in my talk that he should know about, so he was no problem if I did have anything worthwhile to say. Feynman was having fun."

15 years later, when I gave my first seminar at Caltech, the experience was not quite so terrifying. By then, I discovered, one could play Feynman and Gell-Mann against one another. When Dick attacked, Murray defended me. And when Murray raised an objection, Dick would be on my side. It was an eventful seminar, but not "the low point of my year."

In the years that followed, Feynman and I found that we had a common interest in nonperturbative aspects of quantum chromodynamics, and we often talked about that. Sometimes I would impress Feynman with an idea or calculation I had learned from the literature; I would tell him the source, but he would be interested in the ideas, not the reference. Once I overheard Feynman tell Helen, as he returned to his office after our discussion: "He's like an encyclopedia. No, he's *better* than the encyclopedia!" That made my day. But sometimes I wondered whether Feynman knew my name, as he sometimes seemed to confuse "Preskill" and "Peskin" --- with whom, I presumed, he had discussed similar things.

Feynman and Gell-Mann had once been close, but there was evident tension between them by the 1980s. After I had gotten to know them better, I asked each one what had gone wrong. Both gave the same answer --- they had gotten along well until around 1969, when Feynman was working on the parton model. Years later, Murray spoke derisively about Feynman's "put-ons," still resentful that Feynman had refused to call them "quarks." Feynman for his part, recalled that Gell-Mann had scathingly ridiculed the idea that quarks would behave as nearly free particles inside hadrons. What started out as a scientific disagreement had become increasingly personal and hostile, and their relationship never fully recovered.

Here they are in happier times, enjoying a discussion together outdoors on the Caltech campus.

Of all his scientific contributions, Feynman felt that the Feynman Lectures on Physics would have an especially enduring impact. Matt Sands tells the back story in his Physics Today article. Sands felt that the Caltech undergraduate physics curriculum badly needed updating, and his exhortations resulted in the appointment of a committee on which Sands and Bob Leighton served. But Leighton and Sands had very different views about what changes were needed, until Sands had an inspired thought about how to break the impasse. Why not ask Feynman to give the lectures? Not everyone was convinced this was a good idea, including Feynman himself, who finally asked Sands: "Has there ever been a great physicist who has presented a course to freshmen?" Sands said no, and that did the trick; Feynman said: "I'll do it!"

Sands recounts how each lecture was a meticulously prepared performance. Feynman had notes, but rarely referred to them. The use of the chalkboard was carefully choreographed, the timing of each lecture was nearly perfect. The lectures were recorded, then transcribed, and then edited to readable text by Leighton and Sands. When it came time to publish them, a book was planned with the uninspired title *Introductory Physics*, by Feynman, Leighton, and Sands. Feynman pushed back hard about sharing the authorship credit, feeling the Lectures had been his creation, until Sands proposed an acceptable compromise: *The Feynman Lectures on Physics*, by Feynman, Leighton, and Sands.

The books contain Feynman's preface, expressing his melancholy view that the lectures had not succeeded pedagogically. Sands explained how the preface was written. Sands asked Feynman to provide a preface at a time when Feynman was about to leave on a long trip and had little time. So Sands suggested that Feynman dictate the preface then and there into a recording device. But Sands had also just told Feynman that the average grade in the class had been 65%, which Feynman was distressed to hear, and his pessimistic assessment was colored by that undigested news. Sands thinks that Feynman would have expressed a different view if granted the time to produce a well considered judgment on the success of the class.

Here are Feynman and Leighton with Caltech students after one of the lectures. We don't seem to have a photo of Feynman, Leighton, and Sands together. And here is the only photo we know showing Feynman's audience for the lectures. They are all men. Caltech did not admit women as undergrads until 7 years later.

In 2015, we had an event at Caltech for the 50th reunion of the class that attended Feynman's lectures, which was recorded and can be viewed on YouTube. There you can hear testimonials from the students about the Feynman's profound influence on his audience. And it's also interesting to hear the remarks of Robbie Vogt, who became the "Feynman Lecturer" starting in 1963. Vogt echoes Sands regarding the suitability of the Feynman Lectures for teaching Freshmen and Sophomores: "There are other people who say the Feynman books are not suitable as textbooks. They are wrong. If you do it right, you let them have Feynman, and then you help them to digest it." Vogt compares Feynman's lectures on quantum mechanics to those of Fermi, which he also attended, noting that Feynman was better.

The Feynman Lectures were used at Caltech for some years, before eventually being replaced by a new course in the face of complaints from some students and some faculty that the Feynman course was too hard. Vogt and a few others resisted this change --- he told me recently that the course "should not be a cake-walk … that's what made them Techers."

Though its role as a textbook for beginning physics students did not endure, the influence of the Feynman Lectures has been vast. Over 1.5 million copies have been sold in English, and no one seems to know how many copies were sold of the numerous foreign language editions, not to mention pirated copies. It is still in print, and in addition a free html edition is available at the Feynman Lectures website. That initiative was possible due to the efforts of Mike Gottlieb and Rudi Pfeiffer, who converted the lectures to LaTeX, corrected hundreds of errata, and arranged for all figures to be redrawn in scalable form.

Gottlieb in particular has now devoted 18 years of his life to this project. Mike is an independent software consultant who has said he wants to contribute more to the world than writing code and making money. He hopes that broadening access to the Feynman Lectures will inspire young people to pursue physics research and attack the great open problems, in particular the problem of reconciling general relativity with quantum mechanics.

Those two years of teaching the Feynman Lectures were the only times Feynman officially taught undergrads at Caltech, but he contributed to undergraduate education in a variety of other ways, notably including an unofficial class he taught many times --- we're not sure how many times. Known as Physics X, and intended for freshman, it was essentially Feynman standing in front of a class saying "Ask Me Anything," or talking about whatever scientific topic excited him at that moment.

There were rules: No questions about coursework. No questions about so-and-so's paper. No questions to explain what so-and-so's equation meant or so-and-so's theorem meant. Questions had to be about trying to understand something. And they could be about literally ANYTHING. And the discussion could go ANYWHERE. As Paul Steinhardt observed: "The important thing for me was that everything was considered interesting -- every corner of science. And that was a huge influence on my outlook on physics and on my career."

Here's a photo of Feynman in front of the Physics X class, from the mid-70s.

Here is another undergrad's view of Feynman, from Michael Turner. The Feynman course was "inspiring to all but frustrating to many when it came to doing problems … it wouldn't be an exaggeration to say that those lectures taught me how to think about physics." Turner recalls a one-one-one tutorial class with Feynman, in which Feynman gave him a physics puzzle to solve each week, and he was forbidden to consult any books. Turner says, "The moment I most remember was when Feynman told me he was envious of my ignorance! I believe he meant knowing too much makes you less open to new ideas." And he recalls, "In those days Feynman was everyone's hero: the students and the faculty. I am not sure who worshipped him more."

Feynman often taught graduate classes, including quantum field theory on many occasions. Rajan Gupta sent me this page from his field theory homework, which Feynman graded himself, making many detailed comments. Gupta recalls that "Feynman went through each homework line by line. Even when the calculation was right, he did not shy away from pointing out it was uninspired. `What have you learned? When can you apply this?' He wanted clarity, depth, and connections at each step." A few years later I was teaching field theory at Caltech, but I never graded the homework myself. I had a TA for that, and I thought I was too busy.

Feynman often told students to disregard what others had done, to work things out for oneself. Not everyone thought that was good advice. One who disagreed was Sidney Coleman, a Caltech grad student in the late 50s and early 60s. Coleman says: "Had Feynman not been as smart as he was, I think he would have been too original for his own good. There was always an element of showboating in his character. He was like the guy that climbs Mt. Blanc barefoot just to show it could be done. A lot of things he did were to show, you didn't have to do it that way, you can do it this other way. And the other way, in fact, was not as good as the first way, but it showed he was different. … I'm sure Dick thought of that as a virtue, as noble. I don't think it's so. I think it's kidding yourself. Those other guys are not all a collection of yo-yos. Sometimes it would be better to take the recent machinery they have built and not try to rebuild it, like reinventing the wheel. … Dick could get away with a lot because he was so goddamn smart. He really could climb Mont Blanc barefoot."

Feynman had a wide ranging intellect; this is especially evident in the talk he gave in 1959, called There's Plenty of Room at the Bottom, which foresaw the field of nanotechnology. Among other things, he claims that computer elements could be much much smaller, and that smaller size might actually improve performance. He envisions powerful new imaging technologies with much improved resolution, for studying biological systems. He muses about the use of nanoparticles in medicine, and imagines devices assembled by precise placement of single atoms. If you have not read this paper, I strongly recommend that you do.

But I'll speak at greater length about another remarkable talk he gave, in 1981 when he was 63, called Simulating Physics with Computers; here he foresaw the field of quantum computing, which I've been working in now for over 20 years.

Feynman clearly states his goal, which is to simulate quantum systems using resources that scale well with the size of the system, and he points out why digital computers are not adequate for the task, because there is no succinct way to describe classically a quantum state of many particles. He argues that for simulating quantum systems we should use a new type of computer, a quantum computer, which is not a Turing machine, but a machine of a different kind, and he challenges the computer scientists to study the power of this new model of computation.

About half of the talk is devoted to elaborating the argument that digital computers will be inadequate for efficiently simulating quantum systems. He emphasizes that quantum theory will not admit a local hidden variable description, and there follows a lucid discussion of Bell inequalities and the experimental evidence that these are violated, without any references and without ever mentioning Bell. Feynman speculates about possible ways to avoid the conclusion, and muses about how thinking computationally might clarify the foundations of quantum mechanics.

More so that in his other writings, Feynman admits to discomfort over the quantum mechanical world view, saying: "we always have had a great difficulty in understanding the world view that quantum mechanics represents. At least I do, because I'm an old enough man that I haven't got to the point that this stuff is obvious to me. Okay, I still get nervous with it. And therefore, some of the younger students … you know how it always is, every new idea, it takes a generation or two until it becomes obvious that there's no real problem. It has not yet become obvious to me that there's no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm not sure there's no real problem. So that's why I like to investigate things."

I know from my own discussions with Feynman that he was partial to the Everett viewpoint, that all phenomena including measurement can be explained by unitary evolution of a state vector. Gell-Mann says that he and Feynman already held that view in the early 1960s, without being aware of Everett's work. But in this talk Feynman expresses dissatisfaction with the many-worlds interpretation, saying: "It's possible, but I'm not very happy with it."

This 1981 talk concludes with a clarion call for the field in which I and many others are now working: "Nature isn't classical dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy."

Here is something odd, though. With John Hopfield, Feynman co-taught a course at Caltech on the Physics of Computation in 1983 which encompassed quantum computing; then Feynman taught the course by himself in the ensuing few years. Hopfield insists that Feynman, in that class and in their private discussions, never mentioned that quantum computers are better suited than classical ones for quantum simulation. And Hopfield even asserts: "The insight that quantum computers were really different came only later, and to others, not to Feynman." From Feynman's 1981 talk, we know this is clearly wrong. And yet … it is true that Feynman does not discuss quantum computational advantage in *The Feynman Lectures on Computation*, edited by Tony Hey, which is based on transcripts from recordings of his Caltech class (the one taught by Feynman alone, not jointly with Hopfield).

I contacted 3 people who attended Feynman's lectures, a visiting professor who helped with the class, the TA, and a student, and they all told me a consistent story. They all recall that Feynman had the idea that quantum computers are more powerful than classical on his mind, because they all remember discussing it with him informally. But no one clearly remembers him mentioning this issue in his lectures. It seems likely that he omitted the topic from his lectures, but why? It's a perfect fit to a class that was called "The potentialities and limitations of computing machines." I can't explain it.

When Feynman died in 1988, the blackboard in his office was photographed, and that photo was widely disseminated. Two prominent passages appear: "What I cannot create, I do not understand" and "Know how to solve every problem that has been solved." Why those words? I may be able to shed some light on that.

In late 1986, after the Rogers Commission had finished their investigation of the Challenger disaster, Feynman was eager to dive back into physics, and particularly excited about further investigations of QCD. Feynman was interested in lattice QCD, which he recognized as a beautiful application of path integral methods, but he felt that computational power was then inadequate for getting accurate results, and would remain inadequate for some time to come. Meanwhile, he hoped to make progress with analytic methods, or a combination of numerical and analytic methods.

In particular, he hoped that tools for solving integrable models might be helpful for treating the soft part of QCD, the physics beyond the reach of renormalization-group improved perturbation theory. He wanted some students to study integrable models with him, to help him learn the subject. Well, he wanted students, and I had students, so we made an arrangement. Feynman and the students met once a week in his office, and those meetings would sometimes last all afternoon; a few times Feynman invited the students to dinner afterward.

Feynman told the students "We gotta know how to solve every problem that has been solved," and he urged them to solve the problems on their own because "What I cannot create I do not understand." To get things started he described the 6-vertex model, and told everyone to solve it without looking up any references. That went on for weeks, without notable progress, until Feynman triumphantly unveiled his own solution. The next challenge was the 8-vertex model, but the students never solved that one, and neither did Feynman!

Sandip Trivedi recalls that Feynman was becoming ill, but was "incredibly enthusiastic and extremely patient" with the students. During his final illness, he told Helen to share his notes with the students, and they were all amazed and inspired to see how meticulous and detailed the notes were, containing many intricate calculations.

We lost Richard Feynman on February 15, 1988. It was a very sad day at Caltech. Feynman was loved, admired, and held in awe by a large swath of the campus community; he was part of the soul of the place, and he's sorely missed by those who knew him. Since then, many students have come and gone who never knew Feynman personally, but they too have been deeply influenced by his contributions, writings, ideas, and unique personality. The spirit of Richard Feynman lives on among deeply curious scientists everywhere. He won't be forgotten.

Thanks for listening, and thanks to all those who shared reminiscences to help me prepare this talk.