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Richard Feynman and computation

TONY HEY

The enormous contribution of Richard Feynman to modern physics is well known, both to teaching through his famous Feynman Lectures on Physics, *and to research with his* Feynman diagram *approach to quantum field theory and his* path integral *formulation of quantum mechanics. Less well known perhaps is his long-standing interest in the physics of computation and this is the subject of this paper. Feynman lectured on computation at Caltech for most of the last decade of his life, first with John Hopfield and Carver Mead, and then with Gerry Sussman. The story of how these lectures came to be written up as the* Feynman Lectures on Computation *is briefly recounted. Feynman also discussed the fundamentals of computation with other legendary figures of the computer science and physics community such as Ed Fredkin, Rolf Landauer, Carver Mead, Marvin Minsky and John Wheeler. He was also instrumental in stimulating developments in both nanotechnology and quantum computing. During the 1980s Feynman re-visited long-standing interests both in parallel computing with Geoffrey Fox and Danny Hillis, and in reversible computation and quantum computing with Charles Bennett, Norman Margolus, Tom Toffoli and Wojciech Zurek. This paper records Feynman's links with the computational community and includes some reminiscences about his involvement with the fundamentals of computing.*

1. Introduction

The *Feynman Lectures on Computation* [1] were finally published in September 1996, some eight years after his death. How did an English Professor of Computer Science come to be editing Feynman's lectures given at Caltech which he did not even attend? In November 1987, I received a phone call in Southampton from Helen Tuck, Feynman's secretary for many years, saying that Feynman wanted me to help write up his lecture notes on computation. Sixteen years earlier, as a post-doc at Caltech, I had declined the opportunity to work with Finn Ravndal on editing Feynman's 'Parton' lectures [2] on the grounds that it would be a distraction from my research. I had often regretted my decision so I did not take much persuading this time around. At Caltech in the early 1970s, I had been a theoretical particle physicist, but ten years later, on a sabbatical visit to Caltech in 1981, I became interested in computational physics—playing with Monte Carlo and variational methods that I later found out were similar to techniques Feynman had used years before at Los Alamos. While I was there in 1981, Carver Mead gave a memorable lecture about the future of VLSI—Very Large Scale Integration—and the semiconductor industry. I returned to Southampton inspired by Mead's vision of the future and set about exploring the potential of parallel computing for computational science. Four years later, I completed my move from physics to computer science, when I moved to the Department of Electronics and Computer Science at Southampton. Two years after that, I received the call from Helen Tuck.

The official record at Caltech [3] lists Feynman as joining with John Hopfield and Carver Mead in the fall of 1981 to give an interdisciplinary course entitled 'The Physics of Computation'. The course was given for two years although Feynman was ill with cancer during the first year and Mead on sabbatical for much of the second. A handout from the course of 1982/83 reveals the flavor of the course: a basic primer on computation, computability and information theory followed by a section titled 'Limits on computation arising in the physical world and 'fundamental' limits on computation.' The lectures that year were mainly given by Feynman and Hopfield with guest lectures from experts such as Marvin Minsky, Charles Bennett and John Cocke.

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In the fall of 1983, Feynman first gave a course on computing by himself, listed in the Caltech record as being called ‘Potentialities and Limitations of Computing Machines’. In the following years 1984/85 and 1985/86, the lectures were taped and it was from those tapes and Feynman’s notebooks that the lectures were reconstructed. In reply to Helen Tuck, I told her I was visiting Caltech in January 1988 to talk at the *Hypercube Conference*. This was a parallel computing conference that originated from the pioneering work at Caltech by Geoffrey Fox and Chuck Seitz on the ‘Cosmic Cube’ parallel computer. I talked with Feynman in January and he was very keen that his lectures on computation should see the light of day. I agreed to take on the project and we agreed to keep in touch. Alas, Feynman died a month later and there was no chance for a more detailed dialogue about the proposed content of the published lectures.

As advertised, Feynman’s lecture course set out to explore the limitations and potentialities of computers. Although the lectures were given over ten years ago, much of the material is relatively ‘timeless’ and represents a Feynmanesque overview of some fairly standard topics in computer science. Taken as a whole, however, the course was unusual and definitely interdisciplinary in content and analysis. Besides giving the ‘Feynman treatment’ to subjects such as computability, Turing machines (or as Feynman said ‘Mr Turing’s machines’), Shannon’s theorem and information theory, Feynman also discussed reversible computation, thermodynamics of computation and quantum computation. Such a wide-ranging discussion of the fundamental basis of computers was undoubtedly unique for its time and a ‘sideways’ Feynman-type view of the whole of computing. Not all aspects of computing are discussed in the lectures and there are many omissions, programming languages and operating systems to name but two. Nevertheless, the lectures did represent a survey of the fundamental limitations of digital computers.

Feynman was not a professional computer scientist and he covered a large amount of material very rapidly, emphasizing essentials rather than exploring all the details. Having said this, his approach to the subject was resolutely practical and this is underlined in his treatment of computability theory with his decision to approach the subject via a detailed discussion of Turing machines. Feynman takes obvious pleasure in explaining how something apparently as simple as a Turing machine can arrive at such momentous conclusions. His philosophy of learning and discovery also comes through very strongly in the lectures. Feynman constantly emphasized the importance of working things out for yourself, trying things out and playing around before looking in the book to see how the ‘experts’ have done things. The lectures constitute a fascinating insight into Feynman’s way of working.

In at least one respect the published lectures do not do justice to Feynman’s course. Included along with the topics discussed above were lectures by invited speakers on a variety of what Feynman called ‘advanced applications’ of computers. The choice of speaker not only reflected topics that Feynman thought important but also the figures in the computational community with whom he had interacted over the years. The purpose of this article is to put on record these relationships and shed light on Feynman’s contribution to the field of computation.

2. Feynman’s course on computation

We begin with a look at the evolution of the Feynman computation lectures from the viewpoint of the three colleagues who participated in their construction. As we have seen, in 1981/82 and 1982/83, Feynman, John Hopfield and Carver Mead gave an interdisciplinary course at Caltech entitled ‘The Physics of Computation’. The different memories that John Hopfield and Carver Mead have of the course are an interesting contrast. Feynman was hospitalized with cancer during the first year and Hopfield remembers this year of the course as ‘a disaster’, with him and Mead wandering ‘over an immense continent of intellectual terrain without a map’ [4]. Mead is more charitable in his remembrances [5] but both agreed that the course left many students mystified. After a second year of the course, in which Feynman was able to play an active role, the three concluded that there was enough material for three courses and that each would go his own way.

The next year, 1983/84, Gerry Sussman was visiting Caltech on sabbatical leave from MIT intending to work on astrophysics. Back at MIT, Sussman supervised Feynman’s son, Carl Feynman, as a student in Computer Science, and at Caltech, Feynman had enjoyed Abelson and Sussman’s famous ‘Yellow Wizard Book’ on ‘The Structure and Interpretation of Computer Programs’. Feynman therefore invited Sussman to lunch at the Athenaeum, the Caltech Faculty Club, and agreed a characteristic ‘deal’ with Sussman—Sussman would help Feynman develop his course on the ‘Potentialities and Limitations of Computing Machines’ in return for Feynman having lunch with him after the lectures. As Sussman says, ‘that was one of the best deals I ever made in my life’ [6].

The topics on which Feynman interacted with these three are an indication of the breadth of his interests. With Hopfield, Feynman discussed the problem of how to implement Hopfield’s neural networks [7], in parallel, on the Connection Machine. Hopfield found it curious that Feynman was not himself interested in building models of the brain—although there are many stories testifying to Feynman’s interest in the way the brain worked.

From Mead, Feynman learnt about the physics of VLSI and the reasons for the silicon scaling behaviour underlying

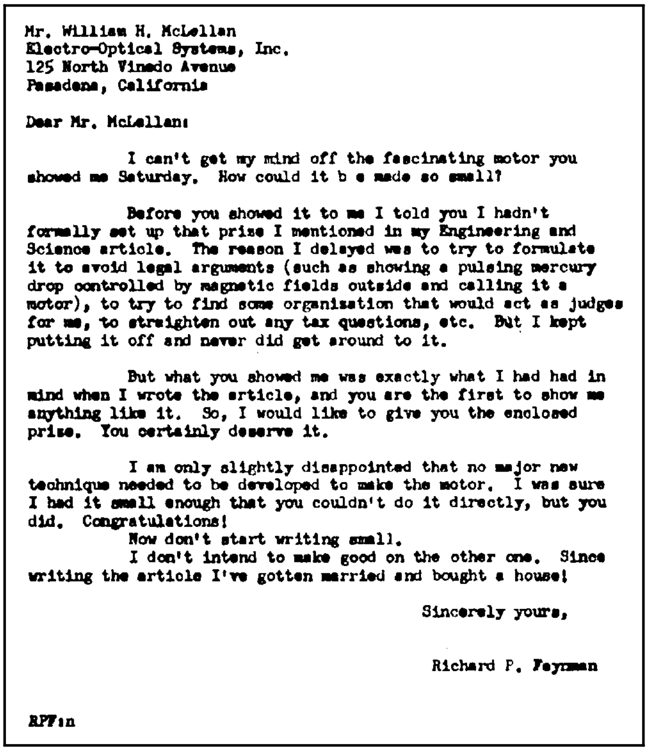
Moore's Law. In 1968, Gordon Moore had asked Mead 'whether [quantum] tunnelling would be a major limitation on how small we could make transistors in an integrated circuit'. This question and its answer took Mead 'on a detour that lasted thirty years' [5]. Mead and Feynman also had many arguments about the right way to present electrodynamics and in particular about the role of the vector potential. Mead always thought Feynman evaded the issue in his famous red *Feynman Lectures on Physics* [8].

While Sussman was at Caltech, he initiated the building of a 'Digital Orrery', a special-purpose computer designed to do high-precision numerical integrations of planetary motions. Much to Sussman's surprise, relatively little was known about the numerical analysis for this classical problem. A serious problem with such very long integrations—Sussman set a new record of 845 million years with Jack Wisdom [9]—is the build-up of numerical errors. Feynman spent a considerable amount of time during that year helping Sussman understand this problem.

3. Reducing the size

Feynman had a long-standing interest in the limitations due to size, beginning with his famous 1959 lecture 'There's Plenty of Room at the Bottom', subtitled 'an invitation to enter a new field of physics' [10]. In this astonishing lecture, given as an after-dinner speech at a meeting of the American Physical Society, Feynman talked about 'the problem of manipulating and controlling things on a small scale', by which he meant the 'staggeringly small world that is below'. He went on to speculate that 'in the year 2000, when they look back at this age, they will wonder why it was not until the year 1960 that anybody began seriously to move in this direction'. In his talk Feynman also offered two prizes of $1000—one 'to the first guy who makes an operating electric motor . . . [which] is only 1/64 inch cube', and a second 'to the first guy who can take the information on the page of a book and put it on an area 1/25 000 smaller in linear scale in such a manner that it can be read by an electron microscope'. He paid out on both—the first, less than a year later, to Bill McLellan, a Caltech alumnus, for a miniature motor which satisfied the specifications but which was a disappointment to Feynman in that it required no new technical advances (figures 1 and 2). Feynman gave an updated version of his talk in 1983 to the Jet Propulsion Laboratory. He then predicted 'that with today's technology we can easily . . . construct motors a fortieth of that size in each dimension, 64 000 times smaller than . . . McLellan's motor, and we can make thousands of them at a time' [11].

It was not for another 26 years that he had to pay out on the second prize, this time to a Stanford graduate student named Tom Newman. The scale of Feynman's challenge was equivalent to writing all twenty-four volumes of the *Encyclopedia Brittanica* on the head of a pin (figure 3). Newman calculated that each individual letter would be only about fifty atoms wide and, using electron-beam lithography, he was eventually able to write the first page of Charles Dickens *A Tale of Two Cities* at 1/25 000 reduction in scale (figure 4). Feynman's paper is often credited with



Mr. William H. McLellan
Electro-Optical Systems, Inc.
125 North Vinedo Avenue
Pasadena, California

Dear Mr. McLellan:

I can't get my mind off the fascinating motor you showed me Saturday. How could it b e made so small?

Before you showed it to me I told you I hadn't formally set up that prise I mentioned in my Engineering and Science article. The reason I delayed was to try to formulate it to avoid legal arguments (such as showing a pulsing mercury drop controlled by magnetic fields outside and calling it a motor), to try to find some organisation that would act as judges for me, to straighten out any tax questions, etc. But I kept putting it off and never did get around to it.

But what you showed me was exactly what I had had in mind when I wrote the article, and you are the first to show me anything like it. So, I would like to give you the enclosed prise. You certainly deserve it.

I am only slightly disappointed that no major new technique needed to be developed to make the motor. I was sure I had it small enough that you couldn't do it directly, but you did. Congratulations!

Now don't start writing small.

I don't intend to make good on the other one. Since writing the article I've gotten married and bought a house!

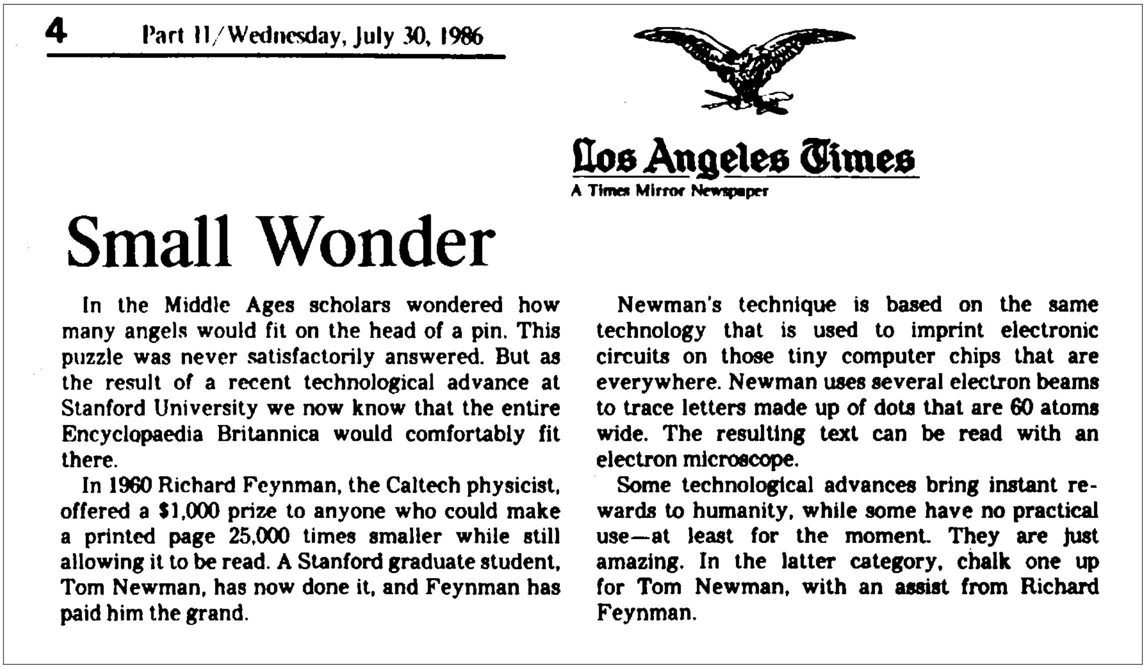
Sincerely yours,

Richard P. Feynman

RPF:n

Figure 1. Letter from Feynman to Bill McLellan about his invention of a miniature motor.

Figure 2. Feynman examines Bill McLellan's motor, 1960.



4 Part II/Wednesday, July 30, 1986

Los Angeles Times
A Times Mirror Newspaper

Small Wonder

In the Middle Ages scholars wondered how many angels would fit on the head of a pin. This puzzle was never satisfactorily answered. But as the result of a recent technological advance at Stanford University we now know that the entire Encyclopaedia Britannica would comfortably fit there.

In 1960 Richard Feynman, the Caltech physicist, offered a $1,000 prize to anyone who could make a printed page 25,000 times smaller while still allowing it to be read. A Stanford graduate student, Tom Newman, has now done it, and Feynman has paid him the grand.

Newman's technique is based on the same technology that is used to imprint electronic circuits on those tiny computer chips that are everywhere. Newman uses several electron beams to trace letters made up of dots that are 60 atoms wide. The resulting text can be read with an electron microscope.

Some technological advances bring instant rewards to humanity, while some have no practical use—at least for the moment. They are just amazing. In the latter category, chalk one up for Tom Newman, with an assist from Richard Feynman.

Figure 3. Newspaper report on Stanford graduate student, Tom Newman, winning the second prize offered by Feynman, 1986.

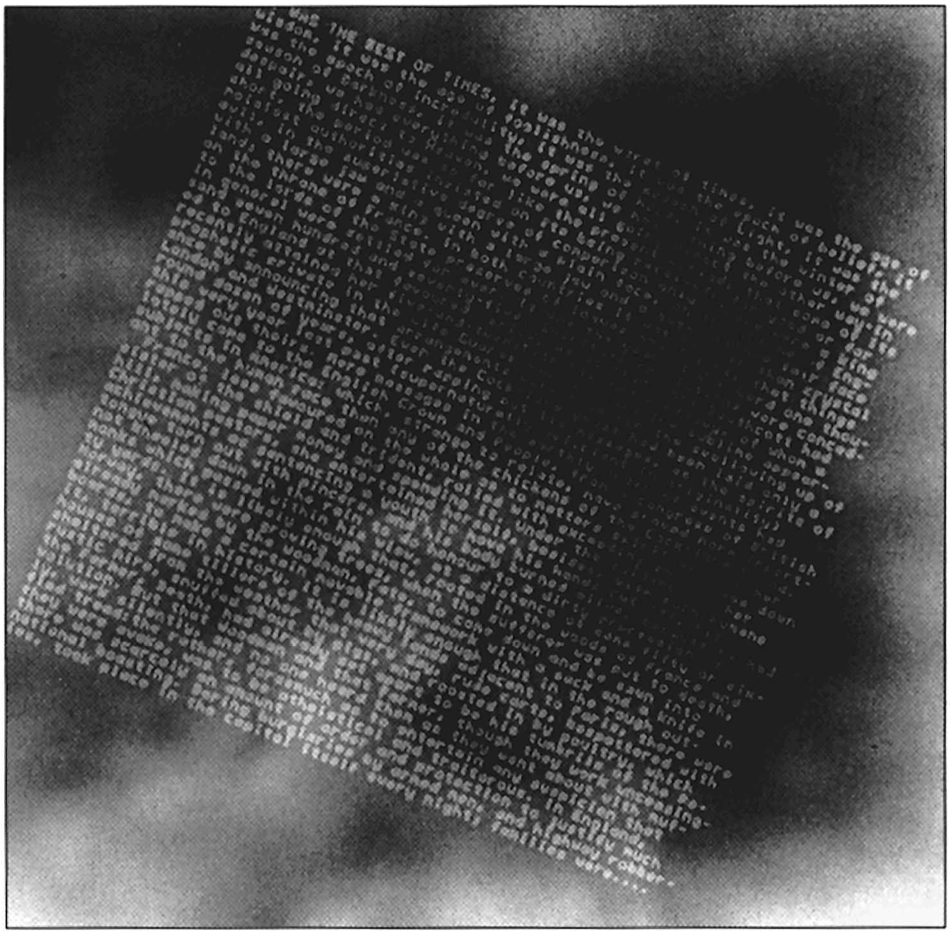


Figure 4. The first page of Charles Dickens' *A Tale of Two Cities* at 12 characters per micron. (Reproduced with permission from Professor F. Pease, Stanford University, USA)

starting the field of nanotechnology and there are now regular 'Feynman Nanotechnology Prize' competitions.

Rolf Landauer, who himself has made major contributions to our understanding of computational and informational limits, has contrasted the reception given to Feynman's paper with that given to a seminal paper by his late IBM colleague John Swanson, which addressed the question of 'how much memory could be obtained from a given quantity of storage material' [12]. Swanson's paper appeared in 1960, around the same time as Feynman's 'Room at the Bottom' paper. In Landauer's opinion, 'Feynman's paper, with its proposal of small machines making still smaller machines, was that of a supremely gifted visionary and amateur; Swanson's that of a professional in the field' [13]. Landauer also deplores the impact of fashions in science—while acknowledging that Feynman 'was very far from a follower of fashions'. Nevertheless, such was Feynman's influence that he could very often *start* fashions, and an unfortunate side-effect of his somewhat cavalier attitude to referencing relevant prior work—that he himself had not needed to read—was that scientists such as Rolf Landauer and Paul Benioff did not always get the credit they deserved. This was an unfortunate and unintended side-effect of Feynman's way of working and in the published *Lectures on Computation* [1] I used my editorial prerogative to set the record a bit straighter with regard to references.

Marvin Minsky was a long term friend of Feynman who also participated in the lecture course. He recalls Feynman's suspicions of continuous functions and how he liked the idea that space–time might in fact be discrete [14]. Feynman was fascinated by the question 'How could there possibly be an infinite amount of information in any finite volume?'

4. Quantum limits

The study of the computational limitations due to quantum mechanics really became respectable as an academic field after Feynman attended a 1981 conference at MIT on the 'Physics of Computation', organized by Ed Fredkin, Rolf Landauer and Tom Toffoli. As Landauer has remarked 'Feynman's mere participation, together with his willingness to accept an occasional lecture invitation in this area, have helped to emphasize that this is an interesting subject' [13]. Feynman's keynote speech—'Simulating Physics with Computers'—contained the suggestion of the possibility of constructing a 'quantum computer' [15]. At the conference, after claiming not to 'know what a keynote speech is', Feynman proceeded to give a masterful keynote speech. In the talk he credited his entire interest in the subject to Ed Fredkin and thanked him for 'wonderful, intense and interminable arguments'. Feynman begins by discussing the question of whether a universal computer can simulate physics *exactly* and then goes on to consider whether a 'classical' computer can efficiently simulate quantum mechanics with its quantum probabilities. Only Feynman could discuss 'hidden variables', the Einstein–Podolsky–Rosen paradox and produce a proof of Bell's Theorem, without mentioning John Bell. In fact, the paper contains no references at all—but it does contain the idea of simulating a quantum system using a new type of non-Turing, quantum computer. Feynman had the insight that a quantum computer would be able to simulate quantum systems more efficiently than a classical computer. It is also interesting to see Feynman confessing that he's 'not sure there's no real problem' with quantum mechanics.

Feynman learnt much of his initial knowledge of reversible computation from Charles Bennett. A colleague of Rolf Landauer at IBM Research in Yorktown Heights, Bennett is famous for his resolution of the problem of Maxwell's Demon and for his demonstration of the feasibility of reversible computation. He has also made important contributions both to the theory of quantum cryptography and quantum teleportation. In a wonderful advertisement, shown to me gleefully by Rolf Landauer, IBM Marketing Department went overboard on Bennett's work on teleportation. Invoking images of 'Star Trek', the ad proclaimed 'An IBM scientist and his colleagues have discovered a way to make an object disintegrate in one place and reappear intact in another'. An elderly lady pictured in the ad talking on the telephone to a friend says 'Stand by. I'll teleport you some goulash.' Her promise may be 'a little premature,' the ad says, but 'IBM is working on it'. Charles Bennett was embarrassed by these claims and was later quoted as saying 'In any organization there's a certain tension between the research end and the advertising end. I struggled hard with them over it, but perhaps I didn't struggle hard enough'. Bennett has recently been actively involved in exciting developments of quantum information theory, including applications of 'quantum entanglement'—a term used by Schrödinger as long ago as 1935 [16]—and possible 'entanglement purification' techniques [17].

5. Parallel computation

Feynman's first involvement with parallel computing probably dates back to his time at Los Alamos during the Manhattan Project. There was a problem with the 'IBM group', who were performing calculations of the energy released for different designs of the implosion bomb. At this date in 1944, the IBM machines used by the IBM group were not computers but multipliers, adders, sorters and collators. The problem was that the group had only managed to complete three calculations in nine months prior to Feynman taking charge. After he assumed control, there was a complete transformation and the group were able to complete nine calculations in three months, three times as many in a third of the time. How was this done? As Feynman explains in *Surely You're Joking, Mr. Feynman* [18], his team used parallel processing to allow them to work on two or three problems at the same time. Unfortunately, this spectacular increase in productivity resulted in management assuming that a single job took only two weeks or so—and that a month was plenty of time to do the calculation for the final test configuration. Feynman and his team then had to do the much more difficult task of figuring out how to parallelize a single problem.

During the 1980s, Feynman became familiar with two pioneering parallel computing systems—the Connection Machine, made by Thinking Machines Corporation in Boston, and the Cosmic Cube, built by Geoffrey Fox and Chuck Seitz at Caltech. Parallel computing was one of the 'advanced topics' discussed in the lecture course and both types of parallel architecture exemplified by the Connection Machine and the Cosmic Cube were analysed in some detail. Parallel computing was in its infancy and in 1985 Feynman talked optimistically of the future for parallel computing. In a little-known talk he gave in Japan as the 1985 Nishina Memorial Lecture [19], besides discussing the perceived problems of energy consumption and size limitations for future computers, Feynman also takes a position on the place of parallel computing in the future. However, as Geoffrey Fox has said [20], the problem is *not* that parallel computing cannot be made to work effectively for many types of scientific problems. The outstanding problem is that the size of the market for parallel computers has been insufficient to allow the development of high quality, high-level parallel programming environments that are easy to use. In addition, there is no straightforward migration path for users with large quantities of 'legacy' sequential software. Feynman's optimistic suggestion that 'programmers will just have to learn how to do it', while true for the 'Grand Challenge' type of scientific problems, has not yet come true in a commercial sense.

Over a decade on from the heady days of the Cosmic Cube, Fox has reflected on the failure of parallel computing and computational science to become a major focus for growth over the last ten years. Instead, he argues that parallel computing and computational science have evolved into the new field of 'Internetics'. This term, first coined by Fox's colleague Xiaoming Li, embodies both the technology and the expertise required to build large-scale distributed computing systems, together with the exploding number of applications engendered by the Internet and the World Wide Web.

Feynman's first-hand involvement with parallel computing has been chronicled by Danny Hillis [21]. Feynman's son Carl, then an undergraduate at MIT, was helping Hillis with his ambitious thesis project to design a new type of parallel computer powerful enough to solve common sense reasoning problems. Over lunch, one day in the spring of 1983, Hillis told Feynman he was founding a company to build this machine. After saying that this was 'positively the dopiest idea I ever heard', Feynman agreed to work as a consultant for the new company. As Hillis recounts, when Feynman was told the name of the company 'Thinking Machines Corporation' he was delighted. 'That's good. Now I don't have to explain to people that I work with a bunch of loonies. I can just tell them the name of the company.' What shines through the article by Hillis is Feynman's need to be involved with the details—with the implementation of Hopfield's neural networks, with a clever algorithm for computing a logarithm, and with Quantum Chromo-Dynamics using a parallel-processing version of BASIC he had devised. Feynman's triumph came with the design of the message router that enabled the 64 000 processors of the machine to communicate. Using an unconventional method of analysis based on differential equations, he had come up with a more efficient design than that of the engineers who had used conventional discrete methods in their analysis. Hillis describes how engineering constraints on chip size forced them to set aside their initial distrust of Feynman's solution and use it in anger.

One of the earliest applications on the Connection Machine was John Conway's 'Game of Life'. This is an example of a simple cellular automaton model. Feynman was always interested in the idea that down at the bottom, space and time might actually be discrete. What we observe as continuous physics might be merely the large-scale average of the behaviour of vast numbers of tiny cells. In one of the original lecture schedules, Norman Margolus, one of leaders of current research into cellular automata [22], gave a lecture on 'billiard ball computers'.

6. Fundamentals

As Rolf Landauer has said of John Archibald Wheeler [23], '[his] impact on quantum computation has been substantial—through his papers, his involvement in meetings, and particularly through his students and associates'. Feynman was an early student of Wheeler, of course, and so was Wojciech Zurek, now a major figure in the field. In Zurek's view, Wheeler's 1989 paper, entitled 'Information, Physics, Quantum—The Search for Links' [24], is 'still a great, forward-looking call to arms' [25]. The credo of the paper is summarized by the slogan *It from Bit*—the hypothesis that every item of the physical world, be it particle or field of force, ultimately derives its very existence from apparatus-solicited answers to binary, yes/no questions.

Another influential figure in the computational community is Ed Fredkin, who first met Feynman in 1962. Fredkin and Marvin Minsky were in Pasadena with nothing to do one evening and they 'sort of invited themselves' to Feynman's house. The three discussed many things until the early hours of the morning and, in particular, the problem of whether a computer could perform algebraic manipulations. Fredkin credits the origin of MIT's MACSYMA algebraic computing project to that discussion in Pasadena [26].

Fredkin later visited Caltech as a Fairchild Scholar in 1974. The deal this time was that Feynman would teach Fredkin quantum mechanics and Fredkin would teach Feynman computer science [27]. Fredkin believes he got the better of the deal: 'It was very hard to teach Feynman something because he didn't want to let anyone teach him anything. What Feynman always wanted was to be told a few hints as to what the problem was and then to figure it out for himself. When you tried to save him time by just telling him what he needed to know, he got angry because you would be depriving him of the satisfaction of discovering it for himself.' Besides learning quantum mechanics, Fredkin's other assignment to himself during this year was to understand the problem of reversible computation. They had a wonderful year of creative arguments and Fredkin invented Conservative Logic and the 'Fredkin Gate'—which led to Fredkin's billiard ball computer. During one of their arguments Feynman got so exasperated that he broke off the argument and started to quiz Fredkin about quantum mechanics. After a while he stopped the quiz and said 'The trouble with you is not that you don't understand quantum mechanics.'

7. Feynman stories

Murray Gell-Mann, Feynman's long-time colleague at Caltech, always deplored the way Feynman 'surrounded himself with a cloud of myth' and the fact that 'he spent a great deal of time and energy generating anecdotes about himself' [28]. In fact, I think the stories generate themselves. For example, in 1997 Ed Fredkin came to Southampton to help us celebrate the 50th anniversary of our Department of Electronics and Computer Science—as far as we know the first, specifically 'electronics' department in the world. Ed gave a talk which included an amusing Feynman story. With apologies to Ed, I would like to tell it here.

The story concerns the so-called 'twin paradox' in relativity. In his book, Feynman had written 'You can't make a spaceship clock, by any means whatsoever, that keeps time with the clocks at home.' Now Fredkin happened to be teaching a course and this subject came up. In thinking about the paradox, Fredkin came up with a trivial way to make a spaceship clock that *did* keep time with the clock at home. Before making a fool of himself in front of his students, Fredkin thought he'd check with Feynman first. There was, of course, an ulterior motive for doing this and that was to 'sandbag' Feynman—a thing that Fredkin loved to do but rarely succeeded. The telephone conversation went something like this. Fredkin said 'It says in your book that it is impossible for a clock on the spaceship to keep time with a clock at home. Is that correct?' Feynman replied 'What it says in the book is absolutely correct.' Having set him up, Fredkin countered 'OK, but what if I made a clock this way . . . .' and then proceeded to describe how his proposed clock had knowledge of the whole trajectory and could be programmed to put the 'back home' time on the face of the clock. 'Wouldn't that keep time with the clocks back home?' Feynman said 'That is absolutely correct.' Fredkin replied 'Then what does that mean about what's in your book?' Feynman's instant response was 'What it says in the book is absolutely wrong!'

Anyone who has had any long-term contact with Feynman will have a fund of stories such as this one. In all the things he did, Feynman was never afraid to admit he was mistaken and he constantly surprised his audience with his direct and unconventional responses. In this way, the Feynman stories generated themselves without any overt act of creation by Feynman himself.

8. Research and teaching

What these anecdotes, and what the lectures illustrate, is how intimately research and teaching were blended in Feynman's approach to any subject. Danny Hillis remembers how Feynman worked on problems at Thinking Machines [21]. While he was engaged in solving a problem he hated to be interrupted, but once he had found a solution 'he spent the next day or two explaining it to anyone who would listen.' Explanation and communication of his understanding were an essential part of Feynman's methodology. He also had no problem about the fact that he was sometimes re-creating things that other people already knew—in fact I don't think he could learn a subject any other way than by finding out for himself.

Carver Mead remembers another, more combative side to Feynman [5]. Besides improving his skills on integrals in duels with Hans Bethe, the hot-house atmosphere of Los Alamos during the war had honed Feynman's skills in argument: 'The one who blinked first lost the argument.' As Mead says, 'Feynman learned the game well—he never blinked.' For this reason, Feynman would never say what he was working on: he preferred 'to spring it, preferably in front of an audience, after he had it all worked out'. Mead learnt to tell what problems Feynman cared about by noticing which topics made him mad when they were brought up. Furthermore, Mead goes on to say, if Feynman was stuck about something, 'he had a wonderful way of throwing up a smoke screen' which Mead calls Feynman's 'proof by intimidation'.

Feynman's grasp of the big picture, coupled with his love for knowing first-hand of practical details—from low-level programming to lock-picking—gave him an almost unique perspective on any subject he chose to study. It was this mastery, both of the minutiae of a subject and of its overall intellectual framework, that gave him the seemingly effortless ability to move back and forth between the two levels at will, without getting lost in the detail or losing the overall plot.

9. How to be an editor

Feynman also declined the 'easy' option of giving the same course every year: He chose to spend a large part of the last decade of his life thinking about the fundamentals of computation. Stan Williams, who works at Hewlett-Packard on nanostructures, quotes me as saying that the *Feynman Lectures on Computation* were the most important thing I have done in my career. Now I am not sure that I quite said that, but it *is* true that I am glad his lectures have seen the light of day. Furthermore, with the publication of a companion volume, the links and connections with the people in the computational community that he was inspired by, or who were inspired by him, are recorded.

When I took on the job of putting together a companion volume, I fondly imagined it would be easier than constructing the first. I little knew what skills an 'editor' requires. Getting agreement in principle for a contribution is easy: Getting the contribution in reality is much more difficult. Some examples will make the point. Marvin Minsky was wonderfully encouraging about the project initially—but I felt bad about telephoning Marvin at his home at regular intervals, badgering him for his paper. Gerry Sussman daily demonstrates an incredible breadth and depth of knowledge, on subjects ranging from programming in SCHEME to the foundations of classical mechanics. On talking with him and Tom Knight at MIT, he described their current research project by holding up his hand and saying 'I want to know how to program this.' It is therefore not surprising that I found it difficult to intrude on his manifold activities and persuade him to set them aside for the time required to complete his brief contribution to this volume. I'm glad he did, since his contribution to Feynman's course was worthy of acknowledgement.

A special note of thanks is owing to Rolf Landauer: he not only was first to deliver his text but he was also wise enough to apply subtle pressure on me to complete the task. This he did by telling me he had no doubts about my skills to put together an exciting volume. There certainly were times when I doubted whether I would be able to persuade Charles Bennett to devote enough time to writing up his talk, that he had given at our Southampton Electronics celebrations, for his contribution. Since Charles was one of those who had been responsible for educating Feynman about the field, and had participated in the original lecture course, I felt it was important to persevere. Finally, I hit on the idea of telling him that his colleague, Rolf Landauer, did not think he would make my final, final deadline . . . .

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Suggestions for further reading

1. *The Beat of a Different Drum: The Life and Science of Richard Feynman* by Jagdish Mehra (Oxford University Press, New York, 1994) is generally written at a fairly technical level but contains a readable and quite detailed account of Feynman's interest in *The Fundamental Limits of Computation* (Chapter 24).
2. *Genius: The Life and Science of Richard Feynman* by James Gleick (Pantheon Books, New York, 1992) is a detailed but generally accessible biography of Feynman and an assessment of his contributions to physics.
3. *Surely You're Joking, Mr. Feynman!* (W. W. Norton, New York, 1985) and *What Do You Care What Other People Think?* (W. W. Norton, New York, 1988) contain an entertaining collection of anecdotes of Feynman's 'world line' through life.
4. *Most of the Good Stuff*, edited by Laurie M. Brown and John S. Rigden (American Institute of Physics, New York, 1993) collects together tributes to Feynman originally published in a special issue of Physics Today in 1989.
5. *Nano!* by Ed Regis (Bantam Press, New York, 1995) contains an account of nanotechnology and Feynman's role in founding the field together that of Eric Drexler.
6. *No Ordinary Genius: The Illustrated Richard Feynman*, edited by Christopher Sykes (W. W. Norton, New York, 1994) is a delightful and very accessible collection of photographs, reminiscences and articles by Feynman and his friends and colleagues, put together by Christopher Sykes who produced the last BBC television programmes on Feynman.
7. *Richard Feynman: A Life in Science* by John and Mary Gribbin (Viking, London, 1997) is a 'popular' biography of Feynman perhaps more accessible to non-scientists than the two 'heavyweight' ones of Mehra and Gleick.
8. *Memories of Richard Feynman* by Anthony J. G. Hey (*Physics Today*, 1996) is an edited version of the Afterword from *The Feynman Lectures on Computation* (Addison-Wesley, Reading, MA, 1996) and consists of an informal account of the author's interactions with Feynman over 18 years.

Anthony (Tony) J.G. Hey, after completing a D.Phil. in Theoretical Particle Physics at Oxford University, arrived at Caltech, Pasadena, in 1970, in the group of Murray Gell-Mann and Richard Feynman. After two years researching quarks and partons, and interacting with Feynman on a daily basis, he then went to the Theory Division of the CERN High Energy Physics Laboratory in Geneva before taking up a lectureship in Theoretical Physics at the University of Southampton. While at CERN his interest in 'quantum paradoxes' was aroused by working with John Bell. After periods of sabbatical leave at MIT and Caltech, Tony Hey became interested in the numerical solution of non-perturbative problems and turned to computational physics and parallel computing. In 1985, he moved to the Electronics and Computer Science Department at Southampton as Professor of Computation. He was one of the early users of parallel transputer systems for scientific computation and participated in numerous European research projects. After the demise of the transputer as a competitive chip for serious computation, Tony Hey was one of the originators of the first message-passing parallel benchmark suite and of the MPI message-passing standard. Editing Feynman's lecture notes on computation has now stimulated him to have a strong interest in quantum computing and, in particular, in the possibility of fabricating solid-state coherent quantum devices. Tony Hey is a member of the EPSRC's Technology Opportunities Panel and is currently Head of Department of Electronics and Computer Science at Southampton and is soon to become Dean of Engineering. Besides traditional scientific journal publications, Tony Hey is co-author (with Ian Aitchison) of a graduate level text on Theories in Particle Physics and co-author (with Patrick Walters) of two 'popular' science books, *The Quantum Universe* and *Einstein's Mirror*.