# Centennial Conference in Honor of Nobel Laureate Richard Feynman

LARS BRINK
DEPARTMENT OF PHYSICS, CHALMERS UNIVERSITY OF TECHNOLOGY, S-41296 GÖTEBORG, SWEDEN

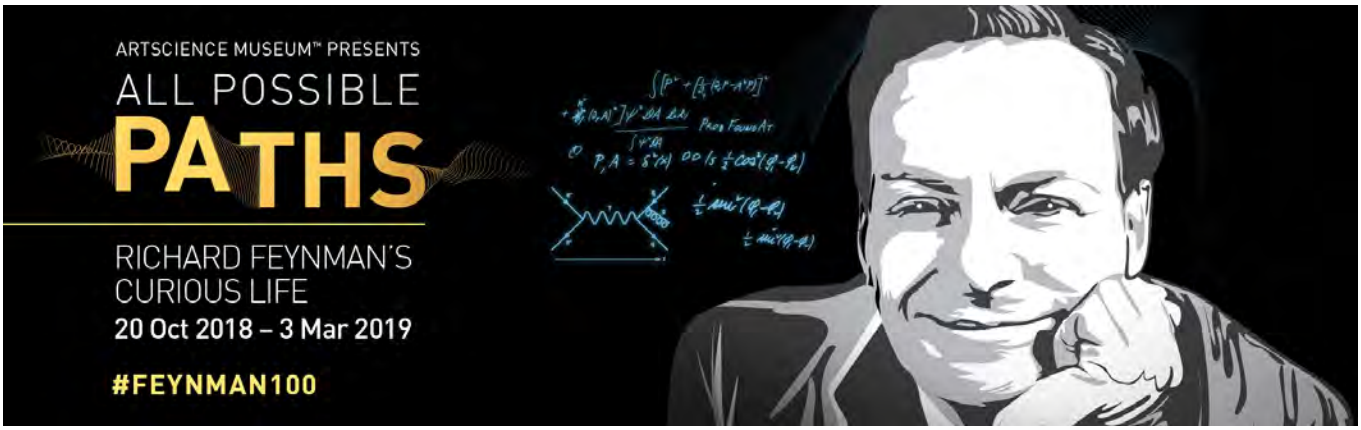
In 2018, two of the greatest scientists of the last century had their centennial, Julian Schwinger and Richard Feynman. Both were, of course, celebrated at Harvard and Caltech respectively, but there were also memorial conferences in Singapore, one for Schwinger in February and one for Feynman in October.

There were in fact two events celebrating Richard Feynman in Singapore. At the ArtScience Museum, there is an exhibition "All Possible Paths, Richard Feynman's curious life" organized by the Museum together with Nanyang Technological University, the Nobel Museum and the Centre for Quantum Technologies in Singapore with Caltech and Michelle Feynman as lenders. The exhibition was inaugurated on Oct 20, 2018 and will go on until March 3, 2019. The website is https://www.marinabaysands.com/museum/richard-feynman.html.

More than 20.000 visitors had seen it before the end of last year. The exhibition will probably tour the rest of world later if there are suitable exhibition halls elsewhere. The exhibition provided a comprehensive perspective of Feynman and his involvement in the Arts.

The memorial conference was held at the Institute of Advanced Studies at Nanyang Technological University from Oct 22 to Oct 24 2018. This is probably the last large international conference to be held there since the university has decided to use the institute more for internal events.

The conference was co-chaired by Lars Brink, K K Phua and Frank Wilzcek. The format was a bit different from most conferences. It consisted of twelve mini-sessions, which would highlight twelve different aspects of Richard Feynman's science and life. Every session consisted of a one-hour talk and an ensuing 45-minute discussion. All the talks and discussions can be found in: https://www.ntu.edu.sg/ias/upcomingevents/RF100/Pages/Speakers.aspx.



Pierre Ramond gave the first talk and he talked about "Feynman's Path to Nobel and Beyond". He gave a very personal talk, based partly on Feynman's Nobel lecture interspersed with anecdotes from his time at Caltech. Ramond's office was right next to Feynman's office and he was subsequently the one who took over Feynman's quantum field theory course. His talk covered many aspects with plenty of discussions about QED and the development of quantum field theory.

He first started by discussing Feynman's time as an undergraduate at MIT and his first paper as an undergraduate before he proceeded to work with his graduate advisor John Wheeler at Princeton. He worked very hard to understand the electron propagator. Wheeler had the idea that there was just one electron traveling back and forth in time. If you take a time slice, you will then see both electrons and positrons. Even if this picture contradicts our knowledge today that there is a surplus of electrons in our world, it was a starting point. When Feynman returned to the idea after his years at Los Alamos this idea actually led him to formulate the Feynman propagator. It was a key to the Feynman diagrams that he formulated to compute the Lamb shift and other quantities. This idea also gave him the machinery to understand renormalization. Ramond also told how Feynman had met Herbert Jehle as a graduate student, and Jehle had then told him about Dirac's idea of summing over histories. When Jehle asked Feynman a few days later about it, he had said that he had understood it all and derived the Schrödinger equation from it. Finally, Ramond talked about Feynman's participation in the conference in Chapel Hill in 1957, where he first talked about his way of constructing a field theory for gravity and also about gravitational waves and how to measure them. This conference is often regarded as the watershed for discussions on how to measure gravitational waves.

The next talk was given by Michael Creutz who talked about "QCD beyond Feynman Diagrams". He started by saying that he was probably the first non-Indian person born in Los Alamos. His father was a scientist there who in fact collaborated with Feynman both there and as a graduate student in Princeton before.

He talked about QCD and showed in some details how QCD is inherently non-perturbative. As we know the physical parameters like the proton mass is not in the QCD Lagrangian. He showed how the path integral is necessary to be able to work on non-perturbative issues. He further showed how quantum mechanics in D dimensions is the same as statistical physics in D+1 dimensions and this is heart of lattice gauge Monte Carlo that was pioneered by Michael Creutz himself many years ago. He then went through the various limits of setting quark masses to zero to check various symmetries and how the θ-parameter is an important parameter of the non-perturbative theory. He ended by a realistic prediction how far one can go with lattice QCD.

Frank Wilczek provided the ensuing talk and he talked about "Plenty more Room at the Bottom". Richard Feynman gave a famous after-dinner talk in 1959 on "There is Plenty of Room at the Bottom" that has become legendary. It foreshadowed many developments in technologies that work on the molecular level. It made it seem credible and exciting that you could do big things at that scale. It gave a vision that the entire 24 volumes of Encyclopedia Brittanica could be put on the head of a pin and the Caltech library on a library card. It gave all kinds of visions and arguments that we would be able to work at the molecular level.

After highlighting Feynman's vision from some 60 years ago, Wilczek analyzed the current research situation and concluded directly that there is plenty of more room in Hilbert space. He described the modern developments with entangled states and such phenomena as quantum cryptography, quantum computation and quantum simulations. He went on to discuss another vision of Feynman, plenty of room for tiny machinery. This is still futuristic but we have proofs of it in biology. We also have the enabling technologies in the various scanning microscopes. Wilczek then talked about "plenty of room" for time and he discussed also the enormous accuracy of present day atomic clocks and ended with a note on plenty of room for intelligence comparing the human brain with modern artificial intelligence. To him, the field is wide open and there are many things to be learnt.

The last talk the first day was given by Robbert Dijkgraaf who talked about "The Art and Science of Feynman's physics". Dijkgraaf who has a background from an art school in his youth gave a comprehensive discussion about the interplay between art and science both in the society as well as in Feynman's life and thinking. He pointed out how important beauty is, not only in Nature, but also in science discussing the beauty of mathematics as the language of science. He showed the two approaches to physics, geometry and algebra and he showed how

**Fig. 1:** Lar Brinks addressing the audience.

one connects beauty in both approaches. He gave many examples as well as quotations from leading scientists over the centuries. At the inauguration of the exhibition at the ArtScience Museum, Dijkgraaf adapted the talk for a more general audience and emphasized the importance of using both art and science to describe the world.

Lance Dixon gave the first talk on the second day and he spoke about the "Seven decades of particle scattering, from Feynman diagrams to the LHC". In this talk, he gave an exposé of how the introduction of Feynman diagrams revolutionized the calculations of scattering amplitudes. The key was the introduction of the Feynman propagator that took into account processes propagating particles forward in time as well as antiparticles propagating backwards in time. He talked about the precision calculations in QED for the electron anomalous magnetic moment, where one now have reached the five-loop order with 12.672 diagrams with an accuracy that is now challenging the accuracy of the fine-structure constant. He continued to discuss how to use Feynman diagrams to understand more complicated scatterings such as deep inelastic scattering of electron on protons and how one can observe the scattering between electrons and quarks as well as the importance of asymptotic freedom and Feynman's parton picture. He then ended by describing how the theoretical calculations are performed now at LHC where a multitude of particles are created at every collision, where one has to use QCD calculations together with unitarity and analyticity. The technical developments have been staggering and very important for the understanding of the complex experimental data.

Cristiane Morais-Smith gave the second talk. She talked about "Feynman integrals: setting the path and the pace in physics." Being Brazilian by birth she started by discussing Feynman's visits to Brazil in the 50's and 60's and the huge influence he had on Brazilian physics and physics education. She then went on to discuss the path integral, its origin and usefulness, comparing Hamiltonian and Lagrangian formulations and how important it was for perturbative QED. She moved on to modern use of path integrals in condensed matter and described her work on two-dimensional systems such as for graphene. She showed how the formalism applies to quantum Brownian motion. She talked about path integrals in Euclidean space and their use for dissipative quantum tunneling. Finally, she discussed quantum computers and quantum simulations using surface states of metals and artificial graphene. She also talked about the possibility to manipulate the dimensions of materials in order to get fractal dimensions.

George Zweig gave a talk on "Remembering Feynman". He is certainly the most famous of Feynman's students. He vividly talked about his time as a graduate student at Caltech where he first encountered Feynman as a teacher. He told the story how Feynman in the beginning

of the 60's wanted to renormalize quantum gravity and then gave a graduate course on gravity. Feynman had challenged how particle physicists would discuss gravity if Einstein were not born. He then concluded that there must be a spin-2 particle mediating the force and by the second lecture, he had computed the precession of the perihelium of Mercury. Zweig had taken a regular course by the famous relativist H. P. Robertson the year before and he had taught it in the usual way and reached the precession after several months of teaching. However, Feynman did not succeed to renormalize and this affected him for years.

Zweig then gave his own story how he invented aces as the basic constituents of matter and how much time it took for him to convince Feynman about them. He also gave many stories about Feynman and the life at Caltech in the shadows of the great man.

The last talk of the second day was given by Danny Hillis. He had met Richard Feynman as a young graduate student in 1981 at a Digital Physics conference. He then went on to establish the Thinking Machines Corporation. After that, he had gone to Caltech and ask Feynman if he knew any graduate students that could work for the company over the summer. Feynman had replied that he knew somebody who was crazy enough, namely himself. Feynman then worked for the company several summers in the 1980's taking part in the development of the first massive parallel computer. Feynman and Hillis had formed strong bonds even though Feynman had been almost 40 years older. Hillis gave a vivid talk on their collaboration and on some of the problems that they had addressed.

He told the story how they had set up some differential equations for biological evolution and solved them and they had been very proud of their results. When Hillis came back to MIT he found that this problem had been solved in a similar way some twenty years ago. Instead of being upset Feynman had been very excited saying: "Boy we got it right! We are just a bunch of amateurs and we got it right!." This shows how generous Feynman was to other people's achievements.

The first talk of the third day was given by Maria Spiropulu. She was the only speaker from the Caltech faculty and began by showing how Feynman is remembered at Caltech. She then gave a tour de force talk about the present status of particle physics showing in great details the most recent results from the LHC at CERN. She informed the audience that nine months of running at LHC had given results that included all previous results on all the earlier accelerators. She discussed the failure to find supersymmetry and the various possibilities for dark matter. She ended by discussing how machine learning is becoming an important part of modern day analysis.

Richard Feynman's daughter Michelle Feynman followed with a talk "Growing up with Feynman" where she gave a very personal view of her father, showing him both as the family man he was and as the scientist sharing his enthusiasm for so many things in life. This talk completed the picture of Feynman given in the other talks. This talk was not recorded.

Richard Feynman was interested in biology for a long time. Curtis Callan reflected about that in his talk with the title "Do physics (and physicists) have something important to contribute to the science of life? Reflections inspired by Feynman's adventures in biology some sixty years ago". He first described Feynman's involvement in biology that started in the 50's with him "hanging out" in Max Delbruck's laboratory at Caltech. He then took a sabbatical in the beginning of the 60's to actually work in that lab and then continued to have an interest all through the 60's giving some famous Hughes Aerospace Lectures on Biology and Chemistry in 1969. In Delbruck's lab they studied phages to explore the inner molecular workings of heredity. Feynman was involved in mapping mutations in phage strain T4D and published a paper with the group. In retrospect he seemed to have been close to an interesting discovery but that was immature and was not in the paper. In the Hughes lectures he gave a grand overview of biology and chemistry but this was at the time of the parton model and somehow that interest took over. In the famous Feynman Lectures he discusses an interesting fact that the insect eye is optimized within the limits of physics.

Callan then ended with five statements of Feynman in a modern context.

- It is very easy to answer many of these fundamental biological questions; you just look at the thing.
- You know why you fellows are making so little progress? You should use more mathematics like we do. (Joke!)
- Biology is not simply writing information; it is doing something about it.

- There is nothing that living things can do that cannot be understood from the point of view that they are made of atoms according to the laws of physics.
- What I cannot create I cannot understand.

The last subject that Feynman worked hard on was quantum computing. In a sense we can say that he started that subject. It was then appropriate that Artur Ekert gave the final talk on this subject entitled "Taming Quantum Weirdness". He also started with the famous conference at MIT in 1981 where Feynman first talked about the subject. His paper from this occasion "Simulating Physics with Computers" was the first paper on quantum computers and set the ground for the present developments. Ekert talked about the concept of probability starting with Kolmogorov's axioms and showed how quantum entanglement can allow us to go beyond those if we can use the interference terms. He sketched how multi-particle interference can be used and showed how a quantum computation could be performed in theory. He so discussed the difference between polynomial and exponential computability and discussed the concepts of computational complexity. Of course the main problem now is decoherence which is limiting the possibilities and he discussed briefly various ways of building quantum computers.

A great advantage of the format was that all the speakers presented completely new talks though they had all been working on them for quite some time. It is very impressive how much time and work they had put into the talks. There were also some special guest invited as participants. They were John Schwarz, Rick Fields, Thom Curtright, Harald Fritzsch and Betsy Devine. They all contributed to the discussion sessions with memories and comments.

The conference was unique and did celebrate Richard Feynman in all his glory.

**Lars Brink** is one of the pioneers of superstring theory. He is Professor Emeritus of theoretical physics at Chalmers Institute of Technology in Gothenburg and a Visiting Professor at the Nanyang Technological University, Singapore. He coordinated the EU network Superstring Theory 1991–1995 and 2000–2008. Together with John Schwarz and Joel Scherk the first supersymmetric Yang-Mills theories. In 1997 he became a member of the Royal Swedish Academy of Sciences. In 2001 and 2004 and in 2008 to 2013 he was a member of the Nobel Committee for Physics and its chairman in 2013.