Richard Feynman's popular lectures on quantum electrodynamics: The 1979 Robb lectures at Auckland University

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The subject of quantum electrodynamics (QED) was the subject of *QED—The Strange Theory of Light and Matter*, the popular book by Richard Feynman which was published by Princeton University Press in 1985. On p. 1, Feynman makes passing reference to the fact that the book is based on a series of general lectures on QED which were, however, first delivered in New Zealand. At Auckland University, these lectures were delivered in 1979, as the Sir Douglas Robb lectures, and videotapes of the lectures are held by the Auckland University Physics Department. We have carried out a detailed examination of these videotapes, and we discuss here the major differences between the original Auckland lectures and the published version. We use selected quotations from the lectures to show that the original lectures provide additional insight into Feynman's character, and have great educational value. © *1996 American Association of Physics Teachers.*

INTRODUCTION

Richard Feynman's popular book *QED—The Strange Theory of Light and Matter*[1] presents a very readable account of the theory of quantum electrodynamics (QED) aimed at a general audience. The content of the book is based on The Alix G. Mautner Memorial Lectures delivered at UCLA by Feynman in 1983. Feynman had prepared a series of general lectures on QED for Alix Mautner much earlier, but as he admits on the first page of the book, however, was unsure of their accessibility. So instead of delivering the lectures at his native Caltech, he first tried them out far away from California, choosing remote New Zealand as his testing ground. These early lectures were delivered as the Sir Douglas Robb lectures at Auckland University in 1979, and the series of four lectures was entitled *Quantum Electrodynamics: Today's Answers to Newton's Queries about Light.* The lectures were tremendously successful, or "at least for New Zealand" as Feynman adds, so he therefore returned to Caltech with confidence that the level of his explanation of QED was suitable for a general audience. Appropriately, after Alix Mautner's death, he chose to honour her memory by delivering again the lectures which he had originally written at her request.

The 1979 Robb lectures were videotaped, and the videotapes were used as supplementary material in the preparation of the published version of *QED—The Strange Theory of Light and Matter.* We have recently examined these original tapes, with the aims of carrying out a historical comparison between the Robb lectures and the published book, and assessing the suitability of the tapes as supplementary material in undergraduate courses in physics. There are many similarities between the Robb lectures and the book, the contents of each of the four lectures corresponding closely to each of the four chapters of the book. There are, however, some noteworthy differences: The original unedited tapes provide additional insights into the subject of QED, and reveal Feynman's character and his enthusiasm in a way which is impossible in a printed medium. The question sessions in the Auckland lectures also provide some significantly different, and sometimes very entertaining, material. In what follows, each of the four Robb lectures is summarized, and selected quotations are used to illustrate some of these differences.

LECTURE 1: PHOTONS: CORPUSCLES OF LIGHT (DELIVERED 31 JULY 1979)

The content of the first of the 1979 lectures is similar to that of the introductory chapter of the book. Feynman begins by describing the diverse history of physics, and the attempts by physicists to synthesize seemingly unrelated phenomena into a unifying theory. Given the New Zealand context of the lectures, Feynman makes specific reference to the contribution of Sir Ernest Rutherford in the development of quantum theory. At this point, however, he interrupts his historical discussion to provide an insightful comment on New Zealand society, noticing as have many visitors to New Zealand, that New Zealanders spend a surprisingly large amount of time in negative self-criticism. He comments

> "You know...I've only been here a few days, and everybody's talking themselves down. I thought this would be a happy country, but something's happened to you. You've got plenty of room, and not too many people, and it looks like it ought to be good."

He reminds the audience that there are still some things that New Zealanders ought to be proud of, and offers the advice "... don't forget, you had Rutherford, so it's okay."

Feynman continues and discusses the development of QED. He stresses the accuracy of the theory, pointing out the precision to which it predicts the numerical value of the magnetic moment of the electron. He compares the value measured experimentally with that calculated using the techniques of QED, quoting values of 1.001 159 6524 (±2) and 1.001 159 6523 (±3) respectively, where the errors are in the last decimal place. He comments that there is uncertainty in both the experimental and the theoretical values for the magnetic moment, and explains succinctly why it is that the theorists quote an error on their calculated value:

> "Why should the theory have a plus or minus? Well, they get exhausted in computing the number of decimal places that they need to keep up with experimenters."

Both the experimental and theoretical values are known to several parts in 10^{10}, and Feynman explains how

> "... this degree of accuracy, that number of decimal places, corresponds to a precision something like this: If you were

> measuring the distance of me to the moon, the question would come up: Do you mean from my chin or from the top of my head?''

In the book, Feynman uses a different analogy: the ratio of the thickness of a human hair to the distance between Los Angeles and New York. It is interesting to note that this change may not have been completely arbitrary, but may reflect the fact that at the time the book was published, the experimental and theoretical values were known to greater precision, being 1.001 159 652 21 (±4) and 1.001 159 652 46 (±20) respectively.

Feynman discusses the wide range of phenomena that QED encompasses, and stresses the simplicity of the underlying physical laws. Although they are simple, however, Feynman is honest when he acknowledges that they defy common sense:

> ``... the rules that are going to be obeyed, that I'm going to tell you about, by which this stuff is analysed, by which we understand nature ... are so screwy you can't believe them!''

Nonetheless, the counter-intuitive nature of the rules of QED is not sufficient reason to reject them. Feynman is direct and states:

> ``... you'll have to accept it. Because it's the way nature works. If you want to know the way nature works, we looked at it, carefully. Looking at it, that's the way it looks. You don't like it? Go somewhere else. To another universe, where the rules are simpler, philosophically more pleasing, more psychologically easy. I can't help it, okay? If I'm going to tell you honestly what the world looks like to the human beings who have struggled as hard as they can to understand it, I can only tell you what it looks like.''

Carrying out calculations with QED involves knowledge of elaborate mathematical methods, but Feynman describes these as ``tricks'' which make the calculations efficient. The basic rules are simple. He uses the example of the system of the Mayan Indians for calculating the rising and setting times of Venus, and the discussions in the book and the Auckland lectures are essentially the same on this point. What is different, however, is a thought-provoking comment in the Robb lectures about our limited knowledge of Mayan civilization:

> ``... I don't know about philosophy of Mayans. We have very little information due to the efficiency of the Spanish conquistadores—well, mostly their priests, who burnt all the books. They had hundreds of thousands of books, and there's three left ... just imagine our civilization reduced to three books—the particular ones left by accident, which ones?''

The discussion so far has been introductory, and Feynman now moves on to explain the ideas of QED in more detail. He considers modern evidence for the particle nature of light, and the probabilistic rules which must be used to describe the phenomenon of interference observed in thin films. The method of calculation that Feynman describes is simple, just involving drawing arrows on the blackboard. Each arrow is associated with a particular event, and if there is more than one way for a particular event to happen, then the probability is obtained by the head-to-tail addition of the arrows associated with the individual possibilities. By combining arrows associated with the partial reflection from each surface of a thin film, he is able to show how the total intensity of the reflected light depends on the thickness of the film. He concludes with the promise that he will continue in the next lecture to show how these same simple rules are used to explain other familiar properties of light such as the law of reflection and the focusing properties of lenses.

The most noteworthy questions at the end of the first lecture concern Feynman's opinions on the philosophical aspects of QED. When asked whether he *likes* a picture of the world based on probability, his answer reveals his dislike of personal philosophical considerations, and his emphasis on just trying to understand the physical nature of the world:

> ``... I never think 'This is what I like, this is what I don't like'. I think, 'This is what it is, and this is what it isn't.' Okay? And whether I like it, or I don't like it, is really irrelevant, and believe it or not, I have extracted it out of my mind. I do not even ask myself whether I like it or I don't like it, because it's a complete irrelevance.''

Another question is worth recording in full here, illustrating Feynman's well-known intolerance of woolly philosophy and philosophers. When asked: ``When you are looking at something, do you see only light, or do you see the object?'' he replies:

> ``The question of whether or not when you see something, you see only the light, or you see the thing you're looking at, is one of those dopey philosophical things that an ordinary person has no difficulty with. Even the most profound philosopher, who's been sitting eating his dinner, hasn't any difficulty in making out, that what he looks at perhaps might be only the light from the steak, but it still implies the existence of the steak which he's able to lift by the fork to his mouth. The philosophers that were unable to make that analysis on that idea, have fallen by the wayside through hunger.''

The next question also provokes a rather impatient response. When asked: ``Can you tell us whether in the future, your theory will be found to be wrong, or is it complete?'' he replies

> ``No, of course not. How can we know what the final thing is? I tell you only what we know today. Can I tell you more? Do you want me to tell you more? Would you like me to tell you what we know tomorrow? I'm sorry, I have a Nobel Prize from the past, not from the future. I do not know the future.''

LECTURE 2: FITS OF REFLECTION (DELIVERED 2 AUGUST 1979)

The second Robb lecture is to be compared with Chap. 2 (Photons: Particles of Light) of the book, and continues the discussion of interference which began in lecture 1. Here, Feynman mentions how Newton had observed interference in thin films, and describes Newton's corpuscular theory of light where interference was explained in terms of ``fits of easy reflection and easy transmission.'' This theory has clear inconsistencies, but then Newton did not have available to him all the experimental evidence that we have. Feynman implies that it was a sign of Newton's genius that he knew his theory was incomplete because his explanations in *Opticks*[2] are posed in the form of questions. He advises us that we are not in a position to be too critical, because although we can observe the same behaviour as Newton, we still have difficulties in understanding its explanation:

> "I can tell from reading it that in the back of his mind he knows there's something the matter with it. He knows the explanation is going to get him into trouble somewhere—he can feel it—because he puts that part in the form of queries, or questions ... Now you're all happily laughing at poor Newton. But you have to laugh at yourself. Because you live in the world, and this happens, and you have these very good ideas about how things happen, and you can't figure out how such a thing can happen from common sense ideas."

Although the failures of Newton's corpuscular theory are explained by a classical wave theory of light, experiments in the early 20th century eventually confirm that despite his flawed reasoning, Newton was right and light is indeed fundamentally particle-like in nature, with particles now called photons. The problem for QED is to explain this so-called "wave-particle duality," and this brings Feynman back to the probabilistic rules of QED described in the first lecture. He illustrates the ideas of lecture 1 by presenting a "sum over paths" analysis of reflection from a plane mirror to derive the familiar law of reflection. His discussion of the diffraction grating and lenses extends these ideas even further, providing beautiful examples of the elegance of his approach to explain familiar effects. He summarizes the idea of the probability amplitude in QED, and for those who have studied mathematics at university, he identifies these amplitudes as complex numbers. A concluding statement at the end of lecture 2 stands out, when Feynman discusses the physical origin of phenomena such as reflection and the apparent slowing down of light in air. His summary is memorable:

> "... I'll summarize. A most wonderful fact is that light never does anything, really, when you get down to it. Except go, in a vacuum, from one place to the other. It's emitted by one atom or particle and absorbed by another, and it never goes and gets slowed down, or gets reflected. What reflection really is, is that light goes down, is absorbed by something which shakes ... and that emits a new light which comes back. Reflected light is really not the same photon coming back as went in. Photons from the source went into the glass, and from the glass comes out a new photon. This is an interesting thing, that makes light in the end simpler, and simpler, and simpler."

During the question session at the end of the second lecture, Feynman is asked why it has taken so long for the ideas of QED to become generally known. He replies that it is due to the resistance of people to abandon a common sense description of the world, and accept the methods and interpretations of QED. The fact that the techniques of QED appear somewhat absurd is also a barrier:

> "People who hear that all I'm going to do is make a couple of arrows on a board to calculate the chance that something happens, say 'This guy doesn't know physics!' But this is the guy who knows that that's what you have to do, and admits therefore that he doesn't know why he's doing what he does, and you can have the confidence that when I say I don't know what I'm doing, that probably nobody else does either."

Another interesting question concerns the relationship between the theory of QED that Feynman describes, and the wave mechanics of Schrödinger. Feynman replies that they are essentially the same thing, except that the correct interpretation of QED removes the confusion associated with wave-particle duality which was prevalent in the early days of quantum mechanics:

> "... 'wave-particle duality' is a description of ... a condition of the mind of physicists before 1926, in which it was best described as saying: 'It looks exactly like a wave, but that's on Thursday, and it looks exactly like a particle, but that's on Tuesday.' But the answer is, that it does not look exactly like an ordinary particle 'bullet' with normal probabilities, and it does not look exactly like ordinary waves, because it ends up that you measure it in particles."

LECTURE 3: ELECTRONS AND THEIR INTERACTIONS (DELIVERED 7 AUGUST 1979)

This lecture has the same title as Chap. 3 in the book. The first two lectures were about light, and this lecture extends the discussion to include the interaction of light with electrons. Before considering the details of this interaction, however, Feynman revisits briefly the phenomenon of interference in thin films to make an important point regarding interpretation in the case of just a single incident photon. He stresses that when considering the partial reflection from two surfaces, the interference phenomenon cannot be described if an incident photon is considered to reflect solely from either of the two surfaces. Because calculations in QED are based on probability *amplitudes*, we cannot specify exactly which surface (or which path) a particular photon happened to take, and any attempts to detect the specific paths taken by photons results in a destruction of the interference pattern. Interestingly, the fact that "interference" in quantum mechanics involves probability amplitudes, and not "individual photons" is still a cause of confusion among physicists.[3]

To discuss the interaction of photons and electrons, Feynman introduces space-time diagrams, and uses them to describe the trajectories of electrons and photons as they travel in space and time. The junctions on space-time diagrams where the trajectories of photons and electrons intersect are identified as very significant, and the probability amplitude associated with the junction is a very important number which in 1979 was known as: 1/137.035 99 (±3). Feynman stresses its significance:

> "That's a magical number, a mysterious number. Good theoretical physicists put that up the top of their bed at night, and dream and dream if they can figure out *why* that's the right number. The fact that we have no idea where that number comes from ... is one of the mysteries and incompletenesses of the theory, because it would be nice to get that number out of something."

The interaction between two electrons is now used as a first example to illustrate how all the concepts and rules of QED combine together. Other examples are also given, but Feynman explains how the calculations rapidly get complex if all the possible interactions between interacting particles are considered. Complex, but nonetheless possible, especially with computers to carry out the calculations. And it is because these calculations are possible that QED has been able to explain atomic structure, and with it most of the macroscopically observable aspects of the world.

The discussion of spacetime during the lecture prompts a particularly interesting question at the end regarding whether the direction of time is reversible. Feynman explains the essence of this well, stating that: "... on the microscopic scale, all the laws of physics are exactly reversible." Macroscopic phenomena, on the other hand, are more complex, and require more consideration:

> "... all those phenomena (and there are many of course; life and frying eggs are two examples,) which go in one direction only in time, have to be interpreted by the complexity of the circumstances."

LECTURE 4: NEW QUERIES (DELIVERED 9 AUGUST 1979)

The last of the Robb lectures at Auckland is to be compared with Chap. 4 (Loose Ends) of the book. Although this is the final lecture, it is far from just a summary of what has gone before. Feynman begins by discussing the problems of QED, and in particular renormalization. He describes it as "... a dippy way to do mathematics," but one which is justified by its success:

> "... we do know, that if we do it this dippy way, we get results that agree with experiment."

Feynman then discusses the relationship between QED and other areas of physics, considering the physics of the nucleus and the many different subatomic particles which have been observed as the result of experiments probing its structure. The challenge for physicists is to apply the techniques and methods developed to describe electron–photon interactions to all these other particles. There appear to be regular rules and symmetries in the structure of the particles, but the underlying structure in Nature is not well understood. As Feynman explains

> "We don't understand that at all. That makes it very interesting to be a theoretical physicist—because you have these wonderful puzzles. Why does She repeat herself?"

Feynman continues, outlining the standard model as it was understood in 1979, including a brief discussion of the quark model of the nucleus. He concludes the lecture with a discussion of the search for unification in physics, but acknowledges the difficulties that are involved when attempts are made to include gravitation.

The possibility of a unified field theory in physics is the subject of the first question at the end of this lecture, as Feynman is asked if he could discuss a possible relationship between QED and gravitation. He is honest when he answers "No. I don't see it." He reviews the history of the search for a unified field theory in physics, but is unable to provide any hints as to its possible future direction. A related question follows, as Feynman is asked why gluons have not yet been experimentally observed. He answers that one difficulty is that the expected behavior of the particles is unknown, because the calculations involved in predicting their properties are too complicated. As a theoretician, he feels guilty at the lack of progress in carrying out calculations while the amount of effort being put in by the experimental community to detect the new subatomic particles is enormous:

> "When you think of how much money is put into doing these experiments, and the big apparatus and so forth, and here we just sit around, with a beautiful theory, and mumble about it, and can't calculate any numbers ... We shouldn't get our salaries I think. Or maybe they should be raised—we'd work faster. I don't know"

After the questions, Feynman closes the Auckland lectures with comments that echo the opening pages of the published version of *QED—The Strange Theory of Light and Matter*. He thanks the audience, and explains

> "... I've never been able to figure out how to explain electrodynamics and quantum electrodynamics, and I thought that this was an opportunity to try, on a poor unhappy audience, to see whether it was at all possible to explain this subject in a finite number of lectures. And I chose to come to a part of the world, as far distanced as possible from my home, so that if I were not quite successful, I would not have to suffer so directly."

CONCLUSIONS

Although there are few major differences in content between the original 1979 Robb lectures and the book *QED—The Strange Theory of Light and Matter*, the videotapes of the original unedited lectures provide additional insight into both the subject of quantum electrodynamics and the character of Richard Feynman. The original Auckland lectures are, naturally, less structured than the book, but they do convey clearly Feynman's enthusiasm for his subject, and his skill in explaining a very difficult subject to a general audience.

Physics students can benefit in many ways by studying Feynman's popular accounts of quantum electrodynamics. Feynman's approach to physics teaching is unconventional, and in some respects, requires a more mature and sophisticated approach from students than more traditional methods. It is important that a physics education presents students with the idea that there may be more than just one way to explain a particular physical phenomenon, and the videotapes of the 1979 Robb lectures on QED can be used very effectively for this purpose. The advantage of seeing first hand Feynman's enthusiasm, far outweighs any objections on the grounds that there are slight inconsistencies in his delivery. In any case, the carefully edited book provides a definitive reference to refer to if necessary.

Feynman's ability to make a very difficult subject accessible without great mathematical complexity is also of great benefit to teachers at all levels. Feynman outlines the methods of calculation in QED without confusing the audience with mathematical formalism, yet revealing honestly the difficulties in reconciling the concepts of quantum mechanics with common sense notions. Feynman's lectures show that it is not necessary to disguise physics as mere mathematical computation, but neither is it necessary to compromise and dilute the subject matter so it has little relation to the methods of practising physicists.

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[1] R. P. Feynman, *QED—The Strange Theory of Light and Matter* (Princeton U.P., Princeton, NJ, 1985).

[2] I. Newton, *Opticks* (Dover, New York, 1954), 4th ed., corrected (1730), pp. 280–281.

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Test of the Biot–Savart law to distances of 15 m

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We present direct tests of the Biot–Savart law to distances of 15 m. This undergraduate experiment involves an audio-frequency signal generator, magnetic coils, and a lock-in amplifier. The major experimental difficulty was geophysical magnetic fields resulting from induced eddy currents. The Biot–Savart law was confirmed to a precision of about 1%. *© 1996 American Association of Physics Teachers.*

I. INTRODUCTION

Physics lends itself to description by a few simple, comprehensive physical laws, which the practitioners of the discipline are obligated to test in all aspects. This research describes careful measurements of the Biot–Savart law to distances of 15 m, at signal frequencies of 1 kHz. The law was confirmed to a precision of about 1%.

The Biot–Savart law connects current to the production of magnetic fields. It is an essential component of the classical theory of electrodynamics discussed in all introductory physics texts.[1] Although electrodynamics has, in totality, been tested quantitatively for well over a century, we are not aware of any reports of modern, direct tests of the Biot–Savart law to distances of over about a meter. This experiment provides such results. It also provides an instructive example of the detection of very small, sinusoidally varying magnetic fields with a coil and a lock-in amplifier.

At the outset, let us say that we did not undertake this project with any reason to disbelieve the laws of basic electromagnetism. If deviations from these laws existed at the precision of this experiment, they would almost surely have manifested themselves in other, more accurate, electromagnetic measurements. In addition, we point out that geophysicists[2,3] use magnetic fields over long distances to probe subsurface structures, interpreting deviations from free space laws as evidence for underground minerals. Although such work begins by assuming the validity of the laws, one would think it unlikely that deviations at the precision of the experiment in this paper could have been overlooked.

Nevertheless, the geophysical measurements do not generally feature the Biot–Savart law, so the work reported here may have some value other than purely pedagogical. It certainly extends the tests of this law reported in this journal at lesser range and precision.[4,5]

II. BASIC THEORY

Consider a wire magnetic field production loop C_p carrying a current $I_p(t)$; as shown in Fig. 1. At some point $\mathbf{r}$ off the wire and at some time t the magnetic field is given by the Biot–Savart law:

$$\mathbf{B}_p(\mathbf{r},t)=\frac{\mu_0 I_p(t)}{4\pi}\oint_{C_p}\frac{\mathbf{dl}'\times(\mathbf{r}-\mathbf{r}')}{|\mathbf{r}-\mathbf{r}'|^3}, \tag{1}$$

where the integration vector $\mathbf{r}'$ sweeps over the wire loop and $\mu_0=4\pi\times10^{-7}$ H/m. The vectors have their tails at some origin O. We assume that the geometry is fixed in time.

The Biot–Savart law applies strictly only for steady-state currents. For time-varying currents, relativistic corrections, described in Sec. VI, are called for. In addition, the form given in Eq. (1) works only in free space, with no account given to secondary magnetic fields resulting from either the presence of magnetic materials or eddy currents induced in conducting materials. The latter, in particular, proved to be a significant complication here.

If the production coil is small compared with the distance from it, its magnetic properties can be characterized entirely by its magnetic dipole moment

$$\mathbf{m}_p(t)=N_p I_p(t)\mathbf{A}_p, \tag{2}$$

where $\mathbf{A}_p$ is the directed area of the coil and N_p is the number of turns. For a magnetic dipole located at the origin, it is a standard exercise in electricity and magnetism[6] to prove that

$$\mathbf{B}_p(\mathbf{r},t)=\frac{\mu_0}{4\pi}\left(\frac{3(\mathbf{m}_p(t)\cdot\mathbf{r})\mathbf{r}}{r^5}-\frac{\mathbf{m}_p(t)}{r^3}\right). \tag{3}$$

Our magnetic fields were both produced and detected by circular wire coils. Let us discuss briefly the theory of coils,