UNIFICATION OF FUNDAMENTAL FORCES

THE FIRST OF THE 1988 DIRAC MEMORIAL LECTURES

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1. INTRODUCTION

I am honoured to speak about P. A. M. Dirac whom we all loved and whom I so greatly admired. I am also glad to see so many friends in the audience. As an old Johnian myself, I would particularly like to mention Sir Harry Hinsley, the Master of St. John’s (Dirac’s College). Sir Harry is an eminent historian. To him I shall address my remarks, so as to assure you all that you will be spared as many technical details as possible.*

Paul Adrian Maurice Dirac was undoubtedly one of the greatest physicists of this or of any century. In three decisive years,† 1925, 1926, and 1927, with

* Professor Stephen Hawking, a worthy successor to Newton and Dirac, in his admirable new book (A Brief History of Time: Bantam books, 1988) says that he was told that if a popular science book contains one formula, the sale of the book becomes halved. I shall try to use no formulae at all (except in the footnotes) – apart from Einstein’s notorious equation, “E = mc²”, and powers of 10 – which are inevitable in this subject.
† I owe this remark to Victor Weisskopf.
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three papers, he laid the foundations, first of the Theory of Quantum Mechanics, second of the Quantum Theory of Fields, and third – with his famous equation of the electron – of the Theory of Elementary Particles. (In the course of this lecture, I shall explain the relevant concepts of the Quantum Theory of Fields and the Dirac equation for the electron.) When one met Dirac, one could see the complete and utter dedication of a great scientist. One could feel with him the pleasure of scientific creation at its noblest, and the highest personal integrity. He had a childlike simplicity about him. His lucidity and clarity of thought made him a legend. He was undoubtedly one of the greatest human beings I have had the privilege of meeting during my life.

For those of you who never met Dirac, I would like to quote from a reporter’s article which was written about him in 1934 by a newspaperman at the University of Wisconsin. It says:

I have been hearing about a fellow they have up at the University this Spring. A mathematical physicist or something they call him, who has been pushing Sir Isaac Newton, Einstein and all the others off the front pages. His name is Dirac and he is an
Englishman. So the other afternoon I knocks on the door of Doctor Dirac’s office in Stirling Hall and a pleasant voice says ‘Come in’.

And I want to say here and now that this sentence ‘Come in’ was one of the longest ones emitted by the doctor during our interview.

I found the doctor a tall, youngish man and the minute I sees the twinkle in his eyes I knew I was going to like him. He did not seem at all to be busy. When I want to interview an American scientist of his class, he would blow in carrying a big briefcase, and while he talked he would be pulling lecture notes, proofs, books, reprints, manuscripts and what-have-you out of his bag.

Dirac is different. He seems to have all the time that is in the world and his heaviest work is looking out of the window.

‘Professor,’ says I, ‘I notice you have quite a few letters in front of your last name. Do they stand for anything in particular?’ ‘No’ says he.

‘Fine’ says I, ‘now will you give me the lowdown on your investigations?’ ‘No’ says he.
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I went on. ‘Do you go to the movies?’.
‘Yes’ he says. ‘When?’ ‘In 1920.’

Dirac described his own life in physics in a lecture he gave in Trieste in 1968.* I was reading it last night and I came across some parts which seem particularly relevant to the theme of unification of fundamental forces. Dirac describes in this lecture how he got his ideas, particularly the distinction between two methods of investigation in theoretical physics.

According to Dirac, first one may try to make progress by searching for a mathematical procedure for the removal of inconsistencies† which may be

* Reprinted in its entirety on p. 125 of this volume.
† The inconsistencies Dirac had in mind referred to the so-called infinity problem. The problem was that all higher-order calculations in quantum field theories yield the result logarithm infinity (log ∞). Dirac, before World War II, had suggested that all these inconsistencies can be lumped together into an unobservable “renormalisation” of the electron rest-mass. F. J. Dyson, in 1949, showed that Dirac’s conjecture was right for electrodynamics and that all inconsistencies could be incorporated into two “renormalisations”, one for the electron rest-mass and the second for the electron charge.

Dirac, although he had suggested the idea in the first place, disliked these so-called renormalisable theories. He kept hoping that this last vestige of inconsistency would also disappear eventually, with the final theory emerging as pure as driven snow. In the version of unified superstring theories, where gravity is also united with gauge forces (see p. 75), we believe we are in sight of Dirac’s goal.
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present in a physical theory like electrodynamics of electrons – I shall mention some of Dirac’s own work in this connection later and the relevance of his ideas today. Second, one may try to unite theories that were previously disjoint. Dirac says that this second method had not proved very fruitful. He was perhaps speaking from the exasperation felt by many of his generation with attempts that had been made, particularly by Einstein, to unify fundamental theories and which had met with scant success.

In contrast, our generation has been mainly concerned with this second method, and my talk will almost entirely be devoted to it.*

* F. J. Dyson in his beautiful recent book *Infinite in all Directions* (Harper and Row, Cornelia and Michael Bessie books, 1988) has this to say about the second of Dirac’s ideas: “Now it is generally true that the very greatest scientists in each discipline are unifiers. This is especially true in physics. Newton and Einstein were supreme as unifiers. The great triumphs of physics have been triumphs of unification. We almost take it for granted that the road of progress in physics will be a wider and wider unification bringing more and more phenomena within the scope of a few fundamental principles. Einstein was so confident of the correctness of this road of unification that at the end of his life he took almost no interest in the experimental discoveries which were then beginning to make the world of physics more complicated. It is difficult to find among physicists any serious voices in opposition to unification”.

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2. THE UNIFYING CONCEPTS OF PHYSICS IN THE PAST

I shall start by giving you an idea of the variety of unifying concepts that have been used in physics from the beginning. Figure 1 outlines the history of the unification of physical theories, and by the end of this lecture I shall have reached the ‘Theory of Everything’ (TOE) at the bottom of the figure, which is where the fun lies at the moment. Most of my talk, however, will be devoted to describing today’s ‘Standard Model’ of particle physics, which has emerged as a consequence of our generation’s efforts to determine what the elementary entities are and to unify some of the forces of nature between these elementary entities.

The Galilean principle

The first name I would like to mention in this context is that of Al-Biruni who flourished in Afghanistan a thousand years ago. One might not think of modern Afghanistan as a likely place where high class physics could be done. Al-Biruni however, to my knowledge, was the first physicist to say
Fig. 1  A diagram showing the history of unification of physical theories.
explicitly that physical phenomena on the Sun, Earth and the Moon obey the same laws.*

This deceptively simple idea is the basis of all of science as we know it. This was independently stated and demonstrated by Galileo six hundred years later. Galileo used his telescope (imported from Holland) to observe the shadows cast by mountains on the moon. By correlating the direction of the shadows with the direction of the sunlight, he was able to assert that the laws of shadow making were the same on the Moon as on the Earth. This was the first demonstration of the fundamental principle—now known as the 'Galilean Symmetry'†—which asserted the universality of physical laws.

* This was one of the “arguments” which occupied the minds of men in the Middle Ages. Clearly, there would be no universal Science if the basic laws depend on where we happen to be situated in the universe, or when the experiments were done.

† Suprisingly, one consequence of this symmetry is the conservation of momentum; that is to say, total momentum in any initial state equals the total momentum of a system in the final state, irrespective of what interaction takes place in between the initial and final stages. Symmetry principles almost always give rise to conservation laws, of which the above is an example.
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Isaac Newton and the unification of terrestrial and celestial gravities

The next person to mention in this context is Isaac Newton. Around 1680 he asserted that the force of “terrestrial” gravity (which makes apples fall to the ground, and which in Newton’s view was a universal force) was the same as “celestial” gravity (the force which keeps planets in motion around the Sun). Such a force is long-range. Its effects can be felt at any distance, though attenuated by the square of the distance between the two “gravitating” objects concerned.

Newton introduced a new fundamental constant of nature, $G$, which characterises the strength of the gravitational force. The constant $G$ is very small in magnitude:

Gravity is always attractive in contrast to other forces of nature which, as we shall see, can be

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G = 6.670 \times 10^{-11} \text{ N m}^{-2} \text{ kg}^{-2}.
\]

As we shall see later, when Planckian units are used, this number works out to be $10^{-40}(\text{proton mass})^{-2}$. For those who find it difficult to think in terms of powers of 10, it is perhaps useful to have the following glossary:

- $10^3 = \text{one thousand}$
- $10^6 = \text{one million}$
- $10^9 = \text{one billion}$
- $10^{12} = \text{one trillion}$
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repulsive as well as attractive. This gives gravity the edge in that the force always adds up.

*Faraday and Ampere;*  
*The unification of electricity and magnetism*  
*(1820s to 1830s)*

The next unification of fundamental forces was postulated some 150 years later. I wish to recall Faraday and Ampere in the context of electromagnetism – the ‘force of life’ (so-called because all chemical binding is electromagnetic in origin, and so are all phenomena of nerve impulses).

Before 1820, electricity and magnetism were regarded as two distinct forces. Faraday and Ampere, in the greatest unification of modern times, were the first to show that electricity and magnetism were but two aspects of one single force – *electro-magnetism*. If one considers an electrically charged object, an electron for example, and places it on a table so that it is stationary, one could detect (by placing another electron near it) an electric force of repulsion. But as soon as the first electron is moved, one