Preface

The quest for a unified theory of the physical world has been the goal of natural philosophy from the earliest times. Some well-known successes have been the unification of terrestrial and celestial gravity, the unification of electricity and magnetism, and the discovery that gravity was nothing but geometrical curvature. A full unification of gravitation, electromagnetism, and the other two known fundamental forces, namely, the weak and strong nuclear forces, has still to be achieved. But some steps in that direction have already been taken and the most fundamental of these has been the discovery that all of the four fundamental interactions are governed by a single principle, namely, the gauge principle.

The theory that embodies the gauge principle is known as gauge theory. One of the important features of this theory is that its interactions are mediated by mesons of the kind predicted by Yukawa in 1936: gravitation by the spin-2 graviton and the other interactions by vector mesons, namely, the photon, the gluons, and the W and Z mesons for the electromagnetic, strong, and weak interactions, respectively. An even more striking feature of gauge theory is the fact that, up to some constant parameters, the gauge principle determines the interaction of these mesons with themselves and with non-radiative matter.

The discovery of the gauge principle as a fundamental principle of physics was a slow and tortuous process that took more than sixty years. It may be convenient to separate the discovery into three separate stages.

In the first stage it was shown, mainly by Hermann Weyl, that the traditional gauge invariance of electromagnetism was related to the coordinate invariance of gravitational theory and that both were related to the gauge invariance of differential geometry. Weyl was also the first to propose that gauge invariance be elevated from the rank of a symmetry to that of a fundamental principle.

The second stage consisted in generalizing the gauge invariance used in electromagnetism to a form that could be used for the nuclear interactions. This stage began with Weyl's work and culminated in the theory that is now known as Yang-Mills gauge theory.

The third stage consisted of the gradual realization of the fact that, contrary to first appearances, the Yang-Mills gauge theory, in a suitably modified form, was suitable for describing both of the nuclear interactions.

None of the stages in the development of gauge theory were easy. Weyl's first attempt at combining electromagnetism and gravitation actually ended in disaster and was rescued only by the advent of quantum mechanics, which permitted a reinterpretation of his theory that was in accord with the experimental facts.

The second state was equally difficult. All the experimental evidence (short range of the nuclear forces, absence of neutral currents, the form of the nuclear interactions at low energy, etc.) suggested that the nuclear interactions were not gauge interactions, and the fact that any putative gauge fields would have to be electrically charged presented formidable mathematical difficulties. What is surprising is not that the theory took so long to construct but that it was constructed at all.

The third stage, the recognition of gauge theory as a reliable theory of the nuclear interactions, was as difficult as the preceding ones, though for a different reason. At this stage the difficulty was that the nature of the nuclear interactions was masked by the low-energy phenomenology, and it required the introduction of a number of new and independent concepts (parity violation, spontaneous symmetry breakdown, color symmetry, asymptotic freedom, and so on) before their true character emerged. Even today, the evidence in the case of the strong interactions is only indirect.

The third stage in the development of gauge theory is of fairly recent vintage and is thus relatively well known. The purpose of this book is to give a short sketch of the first two, lesser-known stages. The first two stages are lesser-known because, during these stages, the growth of gauge theory was not only slow and delicate but was completely overshadowed by the more spectacular developments in gravitation and quantum theory. It was only later, when much of the pioneering work had been forgotten, that the full significance of gauge theory came to be appreciated. Also, because the work done during the first stage was written in German, it was not widely accessible. Indeed one motivation for writing this book was to make this early work on gauge theory more accessible by assembling some of the relevant articles and translating them into English. The main articles included are the seminal works of Weyl in 1918 and 1929, and these are supported by articles by written by Klein, Kaluza, Fock, Schrödinger, and London in the intervening period. The list of supporting articles is, of course, not comprehensive. The choice of articles was made to mark out the path that led from Einstein's gravitational theory to Weyl's gauge theory of 1929 and to give the flavor of the general thinking on the subject at that time.

The work of Yang and Mills, which concluded the second stage in the development of gauge theory, is well known, but what is not so well known, perhaps, is that earlier studies of Yang had led to that development, and that parallel work was carried out by a number of others, notably Klein, Pauli, Shaw, and Utiyama. Recently I have been fortunate enough to obtain copies of this parallel work plus a description of his own contribution by Utiyama, and another motivation for writing this book was to assemble these contributions in an accessible manner.

The book is divided into two parts. Part I covers the development of gauge theory from the foundation laid by Einstein's theory of gravitation to Weyl's

1929 paper. Chapter 1 gives the general historical background, and in the following four chapters, the relevant article are presented, with a short description of the contents in modern terms and a commentary.[1]

Part II treats the generalization of Weyl's gauge formulation of electromagnetism to non-abelian gauge theory and contains the articles of Yang and Mills, Klein, Pauli, Shaw, and Utiyama just mentioned. Each chapter is accompanied by a commentary, which is concerned with the background and history of the articles. An interesting feature is the difference in the motivations that were used by the various authors.

It is hoped that the book will be of value not only as a description of how modern gauge theory developed in its early days but also in showing how original ideas develop and can come to fruition in spite of initial difficulties and frustrations.

[1] The descriptions of the German articles were written before it was decided to include them in translated form. Afterwards, I decided that it was better to leave the descriptions unchanged, although this would involve a certain amount of overlap with the originals. I apologize if this makes the descriptions appear a little long and detailed, especially in the case of Weyl's 1929 paper.