Part III:
Quantum Effects in the Early Universe and Approaches to the Unification of Fundamental Forces

The dynamics of the universe is governed by gravity, the best classical description of which is Einstein's general relativity discussed in Part I. As discussed in Part II, the microscopic world – the constituents of all matter and the forces between them – on the other hand is best described in the language of quantum field theory which developed as a sort of unification of the principles of quantum mechanics and special relativity. This unification also led to radically new concepts such as that of electron spin, antiparticles, and so on. Though in all practical problems discussed so far, the principles of general relativity and those of quantum mechanics can each go their own way, for a consistent description of all phenomena, one would like a unification of the two. Such a marriage is yet to be and, in spite of a lot of hard work, one still does not have a quantum theory of the gravitational field. In two concrete problems, at least, one would expect the quantum effects of the gravitational field to play a very significant role. Firstly, in the behaviour of the universe near the initial singularity and, secondly, in the determination of the end state of the Hawking evaporation of black holes. In the absence of a viable quantum theory of gravitation, 'one does what one can rather than not do what one cannot'. And this leads to Part III of the book, in particular, quantum field theory in curved spacetime wherein in the spirit of semiclassical radiation theory, one quantizes the matter fields in the background of a fixed classical gravitational field given by Einstein's equations. Canonical quantization methods within this framework are presented in the article by B. R. Iyer. This is then used to discuss particle creation effects in typical cosmological models and define notions like conformal vacua and adiabatic vacua. As in the flat spacetime, quantum field theories in arbitrary gravitational fields are also plagued by the problem of divergences. Sophisticated regularization and renormalization techniques are needed to extract finite answers and, in his article, D. Lohiya expounds on one such technique in detail: the zeta function regularization and its application to a variety of problems. The effective action in curved spacetime is obtained and used to discuss phase transitions in the De Sitter Universe. One of the exciting possibilities that emerged in recent years is the Inflationary Universe scenario. This is discussed in detail in N. Panchapakesan's article which covers the old, new and chaotic inflations, as also Hawking's constraints on inflationary universe models. It concludes with a discussion of back reaction effects of quantum particle creation in the early Universe using effective action techniques.

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Quantum gravity, as mentioned earlier, is as yet the stuff dreams are made of. Another approach, much less ambitious, is that of quantum cosmology. It is to quantum gravity what the Bohr model is to the full quantum mechanical description of the hydrogen atom. In quantum cosmology, one attempts to give a quantum-mechanical meaning to classical solutions of general relativity. This is discussed in the article by T. Padmanabhan. The approach is illustrated by quantizing only the conformal degree of freedom of the gravitational field, in particular, the Friedmann–Robertson–Walker (FRW) models. And, as in the hydrogen atom, the classical singularity of general relativity is avoided and one has analogous stationary states in the quantum Universe. The section ends with a model of the fundamental role that the Planck length may play as the universal cutoff in all field theories, thus ridding the theory of ultra-violet divergences. Two appendices introduce field theory in the Schrödinger representation and the Schrödinger equation for quantum gravity, namely the Wheeler–De Witt equation.

The above articles summarize the new viewpoints of the general relativists. But what of the particle theorists? The unification of electromagnetic and weak interaction and its subsequent experimental verification has given credibility to the grand unified theories of strong and electroweak interactions. Can this success of gauge theories be extended to include the fourth force gravity? An approach dating back to 1920 is the idea of Kaluza and Klein. In a series of articles, A. Maheshwari discusses this aspect. The section begins with a pedagogic introduction to spin 1, 2 and 3/2 fields and then proceeds to introduce the mathematical machinery of Vierbeins (tetrads) and spinors and their appropriate generalizations to higher dimension. He then proceeds to discuss the old Kaluza–Klein theory in five dimensions for unification of electromagnetism and gravitation and then puts it in a modern perspective so that one can now generalize the approach to unify arbitrary (non-Abelian) gauge fields with gravitation. The internal and spacetime symmetries are unified by making the internal symmetries as spacetime symmetries of 'unobservable' dimensions. This necessitates the introduction of higher dimensions – eleven in particular to accommodate the standard theory. But one has to face up to the fate of the extra dimensions. Spontaneous compactification is one solution and this is treated in detail, as also is the harmonic expansions necessary to obtain the particle spectrum of Kaluza–Klein theories. The article ends with a discussion of the problem of chiral fermions in these theories, which was first raised by E. Witten.

J. Samuel takes off from this point and in his article builds up the relevant background to discuss applications of Kaluza–Klein theories to obtain higher-dimensional cosmological models. The fate of the extra dimensions is governed by dynamical evolution: dimensional reduction. A number of models and their significant features are discussed, one, in particular, which 'explains' the unexplained feature of high entropy in classical cosmologies.

All successful theories in particle physics are gauge theories today. Can all the forces be unified by a gauge group? Can we get a clue by studying gravity itself which is also a gauge theory obtained by gauging the Poincaré group? The main problems have been in the understanding of the role of the invariants of the Lie algebra of the group if one has general covariance. One is led to theories more general than general relativity in that, in addition to curvature, one also has torsion. These and other aspects of gravitation as a gauge theory are treated in the article by N. Mukunda, who in particular, critically expounds on the Utiyama–Kibble approach.

The main stumbling block to incorporating both internal symmetries and spacetime symmetries in a unified framework is the Coleman–Mandula theorem that forbids the mixing of the two symmetries. This theorem whose proof depends on the Lie properties of the algebra, is circumvented by the use of graded Lie algebras where, in addition to commuting objects, one also has anticommuting Grassman variables. Such more general structures are discussed in the article by B. Sitaram. This article introduces graded Lie algebras with examples and then proceeds to discuss their representations and classifications. The extended algebra acting as local fields, has the effect of transforming a fermion field into a boson field and vice-versa and is, hence, called supersymmetry (SUSY). In addition to theoretical elegance, if supersymmetry is extended to a local symmetry one necessarily obtains general coordinate invariance, i.e. one gets gravity for free! The various aspects of supersymmetry (SUSY) and supergravity (SUGRA) are discussed in the article by R. K. Kaul. It also deals with representations of the SUSY algebra, SUSY breaking Schemes, $N = 1$ SUGRA in four, eleven and ten dimensions.

The last chapter of the book provides yet another approach to quantum gravity. In recent years, the theory of superstrings (SST) has been a candidate for the Theory of Everything (TOE). Strings are idealized one-dimensional extended objects, a natural generalization of relativistic point particles. With SST, one may have a fine quantum field theory whose internal consistency moreover requires a unique number of spacetime dimensions 26 for bosonic strings and 10 for superstrings. This is the subject of Sharatachandra's overview which proceeds from dual models and Veneziano formula to a discussion of the relativistic string. Light cone and Hamiltonian quantization is then followed by a treatment of Lorentz covariance and the spectrum of string excitations. The field theory limit of interacting strings leads to higher derivative corrections to the Einstein action. It ends with a discussion of superstrings, current problems and future prospects.

By the time this book is published, much has happened in the exciting arena of SST, e.g. new principles of conformal invariance, the relation of SUSY and finiteness, the question of the reduction of idealized string theory in 10 dimensions to a realistic theory in four dimensions, Calabi–Yau idealogy, and orbifold compactification. Surprises will not cease. Even in the placid waters of conventional canonical quantum gravity, there is ongoing excitement caused by new developments such as the construction of spinorial variables which lead to a more manageable set of cubic constraints. But all that, as every story teller knows, is yet another story ....