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Excerpt
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Part I

Overview

1

Introduction and synopsis

String theory describes one-dimensional systems, like thin rubber bands, that move in spacetime in accordance with special relativity. These objects supersede pointlike particles as the elementary entities supporting microscopic phenomena and fundamental forces at high energy.

This simple idea has originated a wealth of other concepts and techniques, concerning symmetries, geometry, spacetimes and matter, that still continue to astonish and puzzle the experts in the field. The question 'What is string theory?' is still open today: indeed, the developments in the last fifteen years have shown that the theory also describes higher-dimensional extended objects like membranes, and, in some limits, it is equivalent to quantum field theories of point particles.

Another question which is also much debated outside the circle of experts is: 'What is string theory good for?' In its original formulation, the theory could not completely describe strong nuclear interactions; later, it was reproposed as a unified theory of all fundamental interactions including gravity, but it still needs experimental confirmation.

This book will not address these kinds of questions directly: its aim is to document what the theory *was* in the beginning, about forty years ago, and follow the threads connecting its development from 1968 to 1984. Over this period of time, the theory grew from a set of phenomenological rules into a consistent quantum mechanical theory, while the concepts, physical pictures and goals evolved and changed considerably. These developments are described by the direct narration of thirty-five physicists who worked in the field at the time. From this choral ensemble, an interesting 'scientific saga' emerges, with its ups and downs, successes and frustrations, debates, striking ideas and preconceptions.

String theory started from the general properties of scattering amplitudes and some experimental inputs; it then grew as an independent theory, by progressive generalization and through the exploitation of symmetries and consistency conditions. It required plenty of imagination and hard work in abstract formalisms, and was very appealing to young researchers in the early Seventies. They collectively undertook the enterprise of

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understanding the Dual Resonance Model, as string theory was originally called, attracted by its novelty, beauty and deep intricacy. They were helped by some mentors, senior theorists who supported them, often against general opinion. Among them, we mention Amati (CERN), Fubini (MIT and CERN), Gell-Mann (Caltech), Mandelstam (Berkeley) and Nambu (Chicago).

The evolution of physical ideas in this field is fascinating. Let us just underline that in early string theory we can find the seeds of many new concepts and mathematical methods of contemporary theoretical physics, such as supersymmetry, conformal symmetry and extra spacetime dimensions. The mathematical methods helped to refine the tools and scope of quantum field theory and were also applied to condensed matter physics and statistical mechanics. The new concepts of supersymmetry and extra dimensions have been introduced in the theories of fundamental interactions beyond the Standard Model, which are awaiting experimental testing by the Large Hadron Collider now operating at CERN, Geneva.

A brief overview of early string history and the book

The book is divided into seven Parts that correspond to major steps in the development of the theory, arranged in logical/chronological order. The first Chapter in each Part is an Editors' Introduction to the main topics discussed, which helps the reader to understand the Authors' Chapters and follow the line of ideas.

Part I provides an introduction to the whole book: the present Chapter includes a synopsis of early string history and points to the essential references. Chapters 2 and 3, by Veneziano and Schwarz respectively, introduce the first (1968–1973) and second (1974–1984) periods into which the evolution of early string theory can be divided. They are followed by the Chapter by Castellani, which highlights some of the main aspects of philosophical interest in the developments narrated in the Volume.

Part II, 'The prehistory: the analytic *S*-matrix', discusses the panorama of theoretical physics in the Sixties from which the Veneziano amplitude, the very beginning of string theory, originated. The first steps of the theory were made in close connection with the phenomenology of strong interactions: experiments showed a wealth of particles, the hadrons, that could not all be considered elementary and had large couplings among themselves. The methods of perturbative quantum field theory, developed in earlier studies of the electromagnetic force, could not be applied since they relied on the existence of only a few, weakly interacting, elementary particles.

The dominant approach was the theory of the *S*-matrix (scattering matrix), which only involved first-principle quantum mechanics and empirical data, as originally advocated by Heisenberg. Approximated solutions to the scattering matrix were searched for starting from some phenomenological assumptions on particle exchanges and asymptotic behaviour, and then solving self-consistently the general requirements of relativistic quantum mechanics. A simplified form of these conditions, called Dolen–Horn–Schmid duality, allowed for the closed-form solution of the famous Veneziano four-meson scattering amplitude in 1968.

Veneziano's result had a huge impact because it provided a simple, yet rich and elegant solution after many earlier attempts. It was immediately clear that a new structure had been found, involving infinite towers of particles organized in linearly rising Regge trajectories.

Part III, 'The Dual Resonance Model', describes the intense activity taking place in the period 1969–1973: the Veneziano model was generalized to the scattering of any number of mesons and the structure of the underlying quantum theory was understood, separating the physical states from the unphysical states. The operator formalism was introduced and first loop corrections were computed in open and closed string theories, at the time called the Dual Resonance Model (DRM) and the Shapiro–Virasoro Model (SVM), respectively. Some theoretical methods were imported from the study of quantum electrodynamics, while others were completely new. It is surprising how far the theory was developed before a clear understanding of the underlying string dynamics, i.e. before the quantization of the string action.

The consistency conditions in the quantum theory of the DRM brought two striking results. First, the linear Regge trajectories were uniquely fixed, leading to the presence of tachyons (unphysical particles with negative mass squared) with spin zero, and of massless particles with spins one and two in the open and closed string theories, respectively. Second, unitarity of the theory required $d = 26$ spacetime dimensions, in particular for loop corrections, as observed by Lovelace in 1971. On the one hand, these results showed the beauty of the theory, stemming from its high degree of consistency and symmetry; on the other hand, they were in clear contradiction with hadron phenomenology, requiring $d = 4$ dimensions and no massless particle with spin.

Part IV, 'The string', illustrates how the DRM was eventually shown to correspond to the quantum theory of a relativistic string. The analogy between the DRM spectrum and the harmonics of a vibrating string was soon noticed in 1969, independently by Nambu, Nielsen and Susskind. The string action, proportional to the area of the string world-sheet, was also proposed by Nambu and then by Goto in analogy with the action of the relativistic point particle, proportional to the length of the trajectory.

Although the string action was introduced rather early, its quantization was not straightforward. Goddard, Goldstone, Rebbi and Thorn eventually worked it out in 1973, using the so-called light-cone gauge, involving the $(d - 2)$ transverse string coordinates. After quantization, they showed that Lorentz invariance was maintained only in $d = 26$ spacetime dimensions, where the DRM spectrum of physical states was recovered.

Part V, 'Beyond the bosonic string', collects the Authors' Chapters describing the addition of extra degrees of freedom to the DRM in the quest for a better agreement with hadron phenomenology. The addition of fermions, i.e. half-integer spin hadrons, was achieved by Ramond, while a new dual model for pions was developed by Neveu and Schwarz. These models were recognized as the two sectors of the Ramond–Neveu–Schwarz (RNS) fermionic string. This theory had a rich spectrum of states, including both bosons and fermions, and required $d = 10$ spacetime dimensions.

The RNS theory was the starting point for many modern developments. Gervais and Sakita observed a symmetry of the theory corresponding to transformations mapping fermionic and bosonic degrees of freedom among themselves: this was the beginning of supersymmetry. Moreover, the introduction of additional symmetries allowed for non-Abelian gauge symmetries in the massless spectrum and extended current-algebra invariances.

Part VI, 'The superstring', describes the transformation of string theory into its modern formulation. Around 1974, the application to hadron physics was abandoned in favour of the successful description provided by quantum chromodynamics (QCD), a non-Abelian gauge field theory. At the same time, it was understood by Scherk, Neveu, Schwarz and Yoneya that the presence of the massless spin one (two) states in the open (closed) string spectrum meant that the theory could reproduce gauge theories and Einstein gravity in the low energy limit, where all other states in the Regge trajectories become infinitely massive and decouple. Therefore, string theory could be considered as an extension of field theory rather than an alternative to it, as originally thought.

This result led Scherk and Schwarz to propose in 1974 the unification within string theory of all four fundamental interactions: the electromagnetic, weak and strong forces, described by gauge theories, together with gravity, described by Einstein's general relativity theory. This remarkable idea was much ahead of its time and could not be appreciated immediately: the theoretical physics community was mostly busy developing the gauge theories that form the Standard Model. Other ingredients of modern string theory, such as the Kaluza–Klein compactification of the extra dimensions and a mechanism for supersymmetry breaking, were also introduced by Scherk and Schwarz.

In the meanwhile, supersymmetry was formulated by Wess and Zumino in quantum field theory, independently of strings, as a spacetime symmetry relating particle spectra in four dimensions. Furthermore, the Ramond–Neveu–Schwarz string was proved to be spacetime supersymmetric by Gliozzi, Scherk and Olive in 1976, upon performing a projection of its spectrum that also eliminated the unwanted tachyon. To sum up, by 1976 open superstring theory was fully developed in its modern formulation of a unifying theory. However, it was left aside in favour of gauge theories, which were more economical and concrete.

Part VII, 'Preparing the string renaissance', describes the 'dark age' of string theory, between 1977 and 1983, when only a handful of people continued to work at it. They nevertheless obtained further results that were instrumental for its comeback in 1984. Towards the end of the Seventies, the main theoretical and experimental features of the Standard Model were being settled, and the issue of further unification became relevant in the theoretical physics community. Unification of electro-weak and strong interactions above the Standard Model energy scale, and unification with gravity, were addressed in the context of supersymmetric field theories and supergravities, respectively. Supergravity theories were the supersymmetric generalization of Einstein's general relativity, offering greater consistency and extra dimensions. Although they are low energy limits of superstring theories, they were mostly developed and analyzed within field theory.

The abrupt change of attitude that brought superstring theories back in focus is then described. The type I superstring was more appropriate and sound than the supergravity theories considered so far: it could describe the Standard Model spectrum of particles, requiring chiral fermions in four dimensions as well as the cancellation of the associated chiral anomalies, as shown remarkably by Green and Schwarz. Moreover, it provided a consistent quantum theory of gravity free of unwanted infinite quantities. On the other hand, supergravity theories, in particular the most fundamental theory in eleven dimensions, were still plagued with infinities.

These developments led to a new boom in string theory after 1984; since then the theory has been actively investigated till the present time. Recent findings show that string theory contains further degrees of freedom in addition to strings, i.e. membranes and D-branes, and that the five consistent superstring theories unify in a single theory called 'M-theory'. Furthermore, a novel relation between string and gauge theories has brought new insight into the hadronic string picture. A summary of these contemporary developments is presented in the last Chapter of Part VII.

Finally, the Volume contains five Appendices that provide more technical presentations of some key features of string theory: the *S*-matrix approach of the Sixties, the properties of the Veneziano amplitude, the full quantization of the bosonic string action, supersymmetry and the field theory limit.

Here we list the main books and review articles on early string theory. The Introductions to the Parts also provide general references on the topics discussed therein.

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Synopsis: 1968–1984

In the following we list the main developments in the early history of string theory, organized according to the Parts of the book in which they are described. Each topic is associated with some key references that are just a sample of the relevant literature. Complete lists of references can be found at the end of each Author's Chapter; a comprehensive guide to the bibliography on early string theory is given at the end of the textbook by Green, Schwarz and Witten, listed above.

Part II – The prehistory: the analytic S-matrix

Developments up to 1968

- The S-matrix approach to strong interactions, originally formulated in [Whe37] and [Hei43], is fully developed [Che61, ELOP66].
- Dolen, Horn and Schmid introduce an hypothesis on the structure of scattering amplitudes [DHS67], the so-called DHS duality, later called planar duality [Fre68, Har69, Ros69]; this is implemented in the superconvergence sum rules [ARVV68].
- Veneziano proposes a scattering amplitude obeying DHS duality: this is the beginning of the Dual Resonance Model [Ven68].

Other developments in theoretical physics

- The theory of weak nuclear interactions is developed.
- The spontaneous breaking of a symmetry is recognized as being a general phenomenon in many-body systems and quantum field theory.

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Part III – The Dual Resonance Model

Developments during 1969–1973

- The Veneziano amplitude is generalized to the scattering of N particles [Cha69, CT69, GS69]; in particular, the string world-sheet first appears in Koba and Nielsen's work [KN69].

- Shapiro and Virasoro extend the Veneziano formula and obtain the first amplitudes of closed string theory [Vir69, Sha70].
- The residues of the poles of the N-point amplitude are shown to be given by a sum of factorized terms and their number is shown to increase exponentially with the mass [BM69, FV69].
- Fubini, Gordon and Veneziano introduce an operator formalism of harmonic oscillators that allows for the analysis of the theory spectrum [FGV69, FV70]; additional decoupling conditions are obtained if the intercept of the Regge trajectory is $\alpha_0 = 1$ [Vir70]; in this case the lowest state of the spectrum is a tachyon. Fubini and Veneziano obtain the algebra of the Virasoro operators and Weis finds its central extension [FV71].
- The equations characterizing the on-shell physical states are derived [DD70] and an infinite set of physical states, called DDF states after Del Giudice, Di Vecchia and Fubini, is found [DDF72]; the Dual Resonance Model has no ghosts if $d \leq 26$ [Bro72, GT72]; for $d = 26$ the DDF states span the whole physical subspace.
- One-loop diagrams are computed to restore perturbative unitarity [ABG69, BHS69, KSV69]; Lovelace shows that the nonplanar loop diagram complies with unitarity only for 26 spacetime dimensions [Lov71].
- The three-Reggeon vertex is constructed [CSV69, Sci69] and generalized to N external particles [Lov70a]; the N-Reggeon vertex is used to compute multiloop diagrams [KY70, Lov70b, Ale71, AA71].
- Vertex operators for excited states of the string are constructed [CFNS71, CR71].
- Brink and Olive obtain the physical state projection operator and clearly show that only $(d-2)$ transverse oscillators contribute to one-loop diagrams [BO73].

Other developments in theoretical physics

- The non-Abelian gauge theory describing weak and electromagnetic interactions is formulated; this is the first step towards the Standard Model of particle physics.
- Experiments on deep inelastic scattering show the existence of pointlike constituents inside hadrons.

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