The Birth of String Theory

Edited by
Andrea Cappelli
Elena Castellani
Filippo Colomo
Paolo Di Vecchia

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THE BIRTH OF STRING THEORY

String theory is currently the best candidate for a unified theory of all forces and all forms of matter in nature. As such, it has become a focal point for physical and philosophical discussions. This unique book explores the history of the theory's early stages of development, as told by its main protagonists.

The book journeys from the first version of the theory (the so-called Dual Resonance Model) in the late 1960s, as an attempt to describe the physics of strong interactions outside the framework of quantum field theory, to its reinterpretation around the mid-1970s as a quantum theory of gravity unified with the other forces, and its successive developments up to the superstring revolution in 1984. Providing important background information to current debates on the theory, this book is essential reading for students and researchers in physics, as well as for historians and philosophers of science.

ANDREA CAPPELLI is a Director of Research at the Istituto Nazionale di Fisica Nucleare, Florence. His research in theoretical physics deals with exact solutions of quantum field theory in low dimensions and their application to condensed matter and statistical physics.

ELENA CASTELLANI is an Associate Professor at the Department of Philosophy, University of Florence. Her research work has focussed on such issues as symmetry, physical objects, reductionism and emergence, structuralism and realism.

FILIPPO COLOMO is a Researcher at the Istituto Nazionale di Fisica Nucleare, Florence. His research interests lie in integrable models in statistical mechanics and quantum field theory.

PAOLO DI VECCHIA is a Professor of Theoretical Physics at Nordita, Stockholm, and at the Niels Bohr Institute, Copenhagen. He has worked on several aspects of theoretical particle physics, and has contributed to the development of string theory since its birth in 1968.

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Edited by

ANDREA CAPPELLI
INFN, Florence

ELENA CASTELLANI
Department of Philosophy, University of Florence

FILIPPO COLOMO
INFN, Florence

PAOLO DI VECCHIA
Nordita, Stockholm and Niels Bohr Institute, Copenhagen

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Contents

Contributors

Marco Ademollo
Dipartimento di Fisica, Università di Firenze, and INFN, Sezione di Firenze,
Via G. Sansone 1, 50019 Sesto Fiorentino (FI), Italy

Daniele Amati
SISSA, Trieste, and INFN, Sezione di Trieste, via Bonomea 265, 34136 Trieste, Italy

Korkut Bardakci
Department of Physics, University of California, and Theoretical Physics Group,
Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720,
USA

Lars Brink
Department of Fundamental Physics, Chalmers University of Technology,
S-412 96 Göteborg, Sweden

Richard C. Brower
Physics Department, Boston University, 590 Commonwealth Avenue, Boston, MA 02215,
USA

Andrea Cappelli
INFN, Sezione di Firenze, Via G. Sansone 1, 50019 Sesto Fiorentino (FI), Italy

Elena Castellani
Dipartimento di Filosofia, Università di Firenze, Via Bolognese 52, 50139 Firenze, Italy

Louis Clavelli
Department of Physics and Astronomy, University of Alabama, Tuscaloosa, AL
35487-0324, USA

Filippo Colomo
INFN, Sezione di Firenze, Via G. Sansone 1, 50019 Sesto Fiorentino (FI), Italy

Edward Corrigan
Department of Mathematical Sciences, Durham University, Durham, DH1 3LE, UK

Eugène Cremmer
Laboratoire de Physique Théorique, École Normale Supérieure, 24 rue Lhomond, 75231 Paris Cedex 05, France

Paolo Di Vecchia
Niels Bohr Institute, Blegdamsvej 17, 2100 Copenhagen, Denmark, and Nordita, Roslagstullsbacken 23, 10691 Stockholm, Sweden

David B. Fairlie
Department of Mathematical Sciences, Durham University, Durham, DH1 3LE, UK

Peter G. O. Freund
Enrico Fermi Institute and Department of Physics, University of Chicago, 5720 S. Ellis Avenue, Chicago, IL 60637, USA

Murray Gell-Mann
Santa Fe Institute, 1399 Hyde Park Road, Santa Fe, NM 87501, USA

Jean-Loup Gervais
Laboratoire de Physique Théorique, École Normale Supérieure, 24 rue Lhomond, 75231 Paris Cedex 05, France

Ferdinando Gliozzi
Dipartimento di Fisica Teorica, Università di Torino, and INFN, Sezione di Torino, Via P. Giuria 1, 10125 Torino, Italy

Peter Goddard
Institute for Advanced Study, Olden Lane, Princeton, NJ 08540, USA

Michael B. Green
DAMTP, Wilberforce Road, Cambridge, CB3 0WD, UK

Martin B. Halpern
Department of Physics, University of California, and Theoretical Physics Group, Lawrence Berkeley National Laboratory, University of California, Berkeley, CA 94720, USA

Claud Lovelace
Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Road, Piscataway, NJ 08854-8019, USA

Stanley Mandelstam
Department of Physics, University of California, and Lawrence Berkeley Laboratory, University of California, Berkeley, CA 94720, USA

Claus Montonen
Department of Physics, University of Helsinki, P.O. Box 64, 00014 Helsinki, Finland

Renato Musto
Dipartimento di Scienze Fisiche, Università di Napoli Federico II, and INFN, Sezione di Napoli, 80126, Napoli, Italy

Yoichiro Nambu
Department of Physics, University of Chicago, 5720 S. Ellis Avenue, Chicago, IL 60637, USA

André Neveu
Laboratoire de Physique Théorique et Astroparticules, Case 070, CNRS, Université Montpellier II, 34095 Montpellier, France

Francesco Nicodemi
Dipartimento di Scienze Fisiche, Università di Napoli Federico II, and INFN, Sezione di Napoli, 80126, Napoli, Italy

Holger B. Nielsen
Niels Bohr Institute, Blegdamsvej 17, 2100, Copenhagen, Denmark

David I. Olive
Department of Physics, Swansea University, Singleton Park, Swansea, SA2 8PP, UK

Alexander M. Polyakov
Joseph Henry Laboratories, Princeton University, Princeton, NJ 08544, USA

Pierre Ramond
Institute for Fundamental Theory, Physics Department, University of Florida, Gainesville, FL 32611, USA

Hector R. Rubinstein
AlbaNova University Center, Royal Institute of Technology, Stockholm University, 106 91 Stockholm, Sweden

John H. Schwarz
Department of Physics, Mathematics and Astronomy, California Institute of Technology,
456 Lauritsen Laboratory Caltech 452-48, Pasadena, CA 91125, USA

Stefano Sciuto
Dipartimento di Fisica Teorica, Università di Torino, and INFN, Sezione di Torino,
Via P. Giuria 1, 10125 Torino, Italy

Joel A. Shapiro
Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Road,
Piscataway, NJ 08854-8019, USA

Leonard Susskind
Department of Physics, Stanford University, Stanford, CA 94305-4060, USA

Gabriele Veneziano
Theory Division, CERN, CH-1211 Geneva 23, Switzerland, and Collège de France,
11 place M. Berthelot, 75005 Paris, France

Tamiaki Yoneya
Institute of Physics, University of Tokyo, Komaba, Meguro-ku, Tokyo 153-8902, Japan

Photographs of contributors

From left to right and from top to bottom: Marco Ademollo, Daniele Amati, Korkut Bardakci, Lars Brink, Richard C. Brower and Louis Clavelli.

From left to right and from top to bottom: Edward Corrigan, Eugène Cremmer, Paolo Di Vecchia, David B. Fairlie, Peter G. O. Freund, Sergio Fubini (1928–2005), Murray Gell-Mann, Jean-Loup Gervais and Ferdinando Gliozzi.

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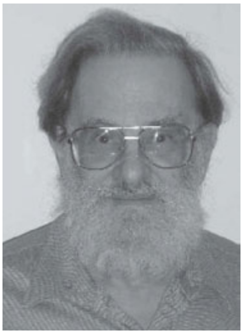
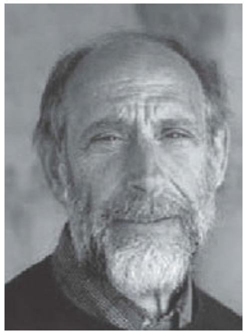

From left to right and from top to bottom: Stefano Sciuto, Joel A. Shapiro, Leonard Susskind, Gabriele Veneziano and Tamiaki Yoneya.

Participants at the meeting 'The Birth of String Theory', 18–19 May 2007, GGI, Arcetri, Florence.

Preface

In May 2007 we organized a workshop on the origin and early developments of string theory at the Galileo Galilei Institute for Theoretical Physics in Arcetri (Florence). A fair number of researchers who had contributed to the birth of the theory participated and described, according to their personal recollections, the intriguing way in which the theory developed from hadron phenomenology into an independent field of research. It was the first occasion on which they had all been brought together since the 1975 conference in Durham, which represented the last meeting on string theory as applied to hadronic physics.

The workshop in Arcetri was a success: the atmosphere was enthusiastic and the participants showed genuine pleasure in discussing the lines of thought developed during the years from the late Sixties to the beginning of the Eighties, mutually checking their own reminiscences. This encouraged us to go on with the project we had been thinking of for some time, of an historical account of the early stages of string theory based on the recollections of its main exponents. We were fortunate enough to have on board practically all the physicists who developed the theory. While some of the contributions to this Volume originated from the talks presented at the meeting, most of them have been written expressly for this book.

In starting this project we were motivated by the observation that the history of the beginnings and early phases of string theory is not well accounted for: apart from the original papers, the available literature is rather limited and fragmentary. A book devoted specifically to the historical reconstruction of these developments – the formulation of a consistent and beautiful theory starting from hadron phenomenology, its failure as a theory of strong interactions, and, finally, its renaissance as a unified theory of all fundamental interactions – was not available. This Volume aims to fill the gap, by offering a collection of reminiscences and overviews, each one contributing from the Author's own perspective to the general historical account. The collection is complemented with an extended editorial apparatus (Introductions, Appendices and Editors' Chapters) according to criteria explained below.

In addition to the historical record, this book is of interest for several reasons. First, by showing the dynamics of the ideas, concepts and methods involved, it offers precious background information for a better understanding of the present status of string theory, which has recently been at the centre of a widespread debate. Second, it provides an illustration of the fruitfulness of the field, from both a physical and a mathematical perspective. A number of ideas that are central to contemporary theoretical physics of fundamental interactions, such as supersymmetry and extra spacetime dimensions, originated in this context. Furthermore, some theoretical methods, for example two-dimensional conformal symmetry, found important physical applications in various domains outside the original one. Finally, from a philosophical point of view, early string theory represents a particularly interesting case study for reflections on the construction and evaluation of physical theories in modern physics.

In the following, we illustrate the structure of the book and offer some guidelines to the reader. The Volume is organized into seven Parts: the first one provides an overview of the whole book; the others correspond to significant stages in the evolution of string theory from 1968 to 1984 and are accompanied by specific introductory Chapters.

In Part I, the Introduction summarizes the main developments and contains a temporal synopsis with a list of key results and publications. The following two Chapters, by Veneziano and by Schwarz, offer a rather broad overview on the early (1968–1973) and later (1974–1984) periods of the history of string theory, respectively. They introduce all the themes of the book that are then addressed in detail in the following Parts. The last Chapter of Part I, by Castellani, presents some elements for the philosophical discussion of the early evolution of the theory and the scientific methodology employed in it.

The Introductions to the other Parts and the Appendices are meant to fit the needs of undergraduate/early graduate students in theoretical physics, as well as of historians and philosophers, who have a background in quantum mechanics and quantum field theory, but lack the specific vocabulary to appreciate fully the Authors' contributions. The Introductions and Appendices, taken together with the final Chapter, can also be used as an entry-level course in string theory, presenting the main physical ideas with a minimum of technique.

For a broader audience, we suggest beginning with the first, nontechnical paragraph in each Introduction, and then approaching the less technical and more comprehensive Authors' Chapters which are located first in each Part. The rich material presented in the Chapters, together with the original literature, can be the starting point for in-depth historical study of the many events that took place in the development of string theory. The final Chapter of the book, by Cappelli and Colomo, provides a nontechnical overview of string theory from 1984 up to the present time, which complements the historical and scientific perspective.

We hope that the book can be read at different levels and, as such, will be useful for scientific, historical and philosophical approaches to this fascinating, but complex, subject.

The book has associated the webpage

http://theory.fi.infn.it/colomo/string-book/

which gives access to the original talks of the 2007 GGI workshop and to additional material already provided by some Authors or to be collected in the future.

We are very grateful to all those who have helped us in preparing this Volume. First and foremost, our thanks go to all the Authors who agreed to contribute their reminiscences. Many thanks go also to all those who gave us valuable comments and suggestions during the preparation of the Volume, in particular Leonardo Castellani, Camillo Imbimbo, Yuri Makeenko, Raffaele Marotta, Giulio Peruzzi, Igor Pesando, Franco Pezzella, Augusto Sagnotti, John H. Schwarz, Domenico Seminara, Gabriele Veneziano, Guillermo R. Zemba and Hans v. Zur-Mühlen. We are indebted to the Galileo Galilei Institute for hosting the 2007 workshop. We also wish to thank the staff of Cambridge University Press for assistance and Sara De Sanctis for helping with the bibliography. Finally, we are grateful to our collaborators and to our families for their patience and support.

Abbreviations and acronyms

AdS	Anti de Sitter (spacetime)
AdS/CFT	Anti de Sitter/conformal field theory (correspondence)
APS	American Physical Society
BRST	Becchi–Rouet–Stora–Tyutin (quantization)
Caltech	California Institute of Technology, Pasadena, CA
CERN	European Centre for Nuclear Research, Geneva
CFT	conformal field theory
CNRS	Centre National de la Recherche Scientifique, France
CP	Chan–Paton (factors)
CPT	charge conjugation, parity, time reversal (symmetries)
DAMTP	Department of Applied Mathematics and Theoretical Physics, Cambridge
DDF	Del Giudice–Di Vecchia–Fubini (states, operators)
DHS	Dolen–Horn–Schmid (duality)
Dp-brane	Dirichlet p-dimensional membrane
DRM	Dual Resonance Model
ENS	École Normale Supérieure, Paris
Fermilab	Fermi National Accelerator Laboratory (or FNAL), Illinois
FESR	finite energy sum rule
FNAL	Fermi National Accelerator Laboratory (or Fermilab), Illinois
GGI	Galileo Galilei Institute, Florence
GGRT	Goddard–Goldstone–Rebbi–Thorn (quantization)
GR	general relativity
GSO	Gliozzi–Scherk–Olive (projection)
GUT	Grand Unified Theories
IAS	Institute of Advanced Study, Princeton, NJ
ICTP	International Center for Theoretical Physics, Trieste
IHES	Institut des Hautes Études Scientifiques, Bures-sur-Yvette
IMF	infinite momentum frame
INFN	Istituto Nazionale di Fisica Nucleare, Italy
IR	infrared
ISR	Intersecting Storage Ring, CERN

ITP	(Kavli) Institute of Theoretical Physics, Santa Barbara, CA
KK	Kaluza–Klein (compactification)
KM	Kac–Moody (algebra)
KN	Koba–Nielsen (amplitudes)
KZ	Knizhnik–Zamolodchikov (equation)
LEP	Large Electron–Positron (collider), CERN
LHC	Large Hadron Collider, CERN
LPTENS	Laboratoire de Physique Théorique, École Normale Supérieure, Paris
LPTHE	Laboratoire de Physique Théorique et Hautes Energies, Orsay
MIT	Massachusetts Institute of Technology, Boston, MA
MSSM	Minimal Supersymmetric Standard Model
M-theory	matrix (or membrane) theory
NAL	National Accelerator Laboratory (FNAL after 1972), Illinois
NATO	North Atlantic Treaty Organization
Nordita	Nordic Institute for Theoretical Physics, Stockholm
NS	Neveu–Schwarz (model, sector)
NSF	National Science Foundation, USA
NYU	New York University
PCAC	partially conserved axial current
PS	Proton Synchrotron, CERN
QCD	quantum chromodynamics
QED	quantum electrodynamics
QFT	quantum field theory
R	Ramond (model, sector)
RIMS	Research Institute for Mathematical Sciences, Kyoto
RNS	Ramond–Neveu–Schwarz (model)
SISSA	Scuola Internazionale Superiore di Studi Avanzati, Trieste
SLAC	Stanford Linear Accelerator Center
S-matrix	scattering matrix
SM	Standard Model
SSC	Superconducting Super Collider
SSR	superconvergence sum rule
SUGRA	supergravity
SUSY	supersymmetry
SVM	Shapiro–Virasoro model
TOE	Theory of Everything
UV	ultraviolet
WZ	Wess–Zumino (model)
WZWN	Wess–Zumino–Witten–Novikov (model)
YM	Yang–Mills (gauge theory)

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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Part IV – The string

Developments during 1970–1973

- Nambu, Nielsen and Susskind suggest independently that the dynamics underlying the dual model is that of a relativistic string [Nie69, Sus69, Nam70a, Nam70b, Nie70, Sus70].
- Nambu and then Goto write the string action [Nam70b, Got71].
- The analogue model, proposed by Fairlie and Nielsen and related to the string picture, is used to compute dual amplitudes [FN70, FS70].
- Goddard, Goldstone, Rebbi and Thorn quantize the string action in the light-cone gauge; the spectrum is found to be in complete agreement with that of the Dual Resonance Model for $d = 26$ [GGRT73]; apart from the tachyon, string theory is now a consistent quantum-relativistic system.
- The computation by Brink and Nielsen [BN73] of the zero-point energy of the string gives a relation between the dimension of spacetime and the mass of the lowest string state.
- The interaction among strings is introduced within the light-cone path-integral formalism [Man73a] and within the operator approach by letting the string interact with external fields [ADDN74]; the coupling between three arbitrary physical string states is computed both in the path-integral [Man73a, CG74] and operator [ADDF74] formalisms, finding agreement.

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Part V – Beyond the bosonic string

Developments during 1970–1974

- The Dual Resonance Model is generalized to spacetime fermions by Ramond [Ram71]; an extension of the Dual Resonance Model for pions is constructed by Neveu and Schwarz [NS71]; the two models are recognized as the two sectors of the Ramond–Neveu–Schwarz model [Tho71].
- The fermion emission vertex is constructed by Corrigan and Olive [CO72]; the scattering amplitude involving four fermions is computed within the light-cone path-integral [Man73b] and operator [CGOS73, SW73] formalisms.
- The one-loop [GW71] and multiloop [Mon74] amplitudes of the Ramond–Neveu–Schwarz model are computed.
- Gervais and Sakita find that the RNS model possesses a symmetry relating bosons to fermions, the world-sheet supersymmetry [GS71].
- Further extensions of the bosonic string involve the introduction of internal symmetry groups [CP69], current algebra symmetries [BH71], and extended supersymmetries [ABDD76].

Other developments in theoretical physics

- The gauge theory of quarks and gluons, quantum chromodynamics, is proposed for strong interactions; it is shown to be weakly interacting at high energy (asymptotic freedom).
- The proof of renormalization of non-Abelian gauge theories is completed.

- The renormalization group is understood as a general method to relate the physics at different energy scales in quantum field theory.

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Part VI – The superstring

Developments during 1974–1977

- In the limit of infinite string tension, string theory reduces to quantum field theory [Sch71]: the open string leads to non-Abelian gauge theories [NS72, Yon74] and the closed string to gravity [Yon73, SS74]; therefore, string theory provides a framework for unifying all fundamental interactions [SS74, SS75].
- Wess and Zumino extend the world-sheet supersymmetry of the Ramond–Neveu–Schwarz model to four-dimensional field theory [WZ74]; supersymmetric extensions of all known quantum field theories are obtained.

- By performing a projection of states in the Ramond–Neveu–Schwarz model, Gliozzi, Scherk and Olive construct the first string theory that is supersymmetric in spacetime [GSO76]. This theory is free of tachyons and unifies gauge theories and gravity: modern superstring theory is born.
- To cope with experiments, the six extra dimensions can be compactified by using the Kaluza–Klein reduction [CS76], that also provides a mechanism for supersymmetry breaking [SS79].
- Supergravity, the supersymmetric extension of Einstein's field theory of gravitation, is formulated [DZ76a, FNF76].
- The supersymmetric action for the Ramond–Neveu–Schwarz string is obtained [BDH76, DZ76b].

Other developments in theoretical physics

- Quantum chromodynamics is widely recognized as the correct theory of strong interactions.
- The Standard Model of electro-weak and strong interactions is completed and receives experimental verification.
- Attempts are made to unify electro-weak and strong interactions beyond the Standard Model; the Grand Unified Theory is formulated.

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Part VII – Preparing the string renaissance

Developments during 1978–1984

- Using techniques developed in non-Abelian gauge theories, Polyakov quantizes the string by covariant path-integral methods, opening the way to modern treatments of string theories [Pol81a, Pol81b]; the Polyakov approach is further developed [DOP82, Fri82, Fuj82, Alv83].
- The unique and most symmetric supergravity in eleven dimensions is constructed [CJS78].
- Green and Schwarz introduce a new light-cone formalism where the fermionic coordinate is an $SO(8)$ spinor [GS81, GS82a, GS82b]; they construct type IIA and IIB closed string theories [GS82c] and write the covariant spacetime supersymmetric action for the superstring [GS84a].
- The contribution of chiral fields to the gauge and gravitational anomalies is computed and shown to vanish in type IIB supergravity [AW84].
- Type I superstring and supergravity theories with gauge group $SO(32)$ are shown to be free from gauge and gravitational anomalies [GS84b, GS85].
- Two other anomaly-free superstring theories are constructed, the heterotic strings with $E_8 \times E_8$ and $SO(32)$ groups [GHMR85].
- Calabi–Yau compactifications of the $E_8 \times E_8$ heterotic string give supersymmetric four-dimensional gauge theories with realistic features for the description of the Standard Model and gravity [CHSW85].

Other developments in theoretical physics 1976–1984

- The Standard Model of electro-weak and strong interactions is fully confirmed by experiments.
- Attempts aiming at the unification of all interactions including gravity are based on supergravity theories, which are extensively studied.
- Phenomenological consequences of supersymmetry are investigated; the Minimal Supersymmetric Standard Model is formulated.
- This is the ‘golden era’ of modern quantum field theory, with several results in gauge theories: nonperturbative methods, numerical simulations, the study of anomalies and the interplay with mathematical physics.

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2

Rise and fall of the hadronic string

GABRIELE VENEZIANO

Abstract

A personal account is given of the six to seven years (1967–1974) during which the hadronic string rose from down-to-earth phenomenology, through some amazing theoretical discoveries, to its apotheosis in terms of mathematical beauty and physical consistency, only to be doomed suddenly by the inexorable verdict of experiments. The a posteriori reasons for why the theorists of the time were led to the premature discovery of what has since become a candidate Theory of Everything, are also discussed.

2.1 Introduction and outline

In order to situate historically the developments I will be covering in this Chapter, let me start with a picture (see Figure 2.1) illustrating, with the help of Michelin-guide-style grading, the amazing developments that took place in our understanding of elementary particle physics from the mid-Sixties to the mid-Seventies. Having graduated from the University of Florence in 1965, I had the enormous luck to enter the field just at the beginning of that period which, a posteriori, can rightly be called the 'golden decade' of elementary particle physics.

The theoretical status of the four fundamental interactions was very uneven in the mid-Sixties: only the electromagnetic interaction could afford an (almost[1]) entirely satisfactory description (hence a 3-star status) according to quantum electrodynamics (QED), the quantum-relativistic extension of Maxwell's theory. Gravity too had a successful theoretical description, this time according to Einstein's general relativity, its 2-star rating being related to the failure of all attempts to construct a consistent quantum extension. In the middle part of Figure 2.1 I have put the other two interactions, the weak and the strong,

[1] The 'almost' refers to what is now known as the triviality problem, meaning that QED cannot be extended without changes to arbitrarily high energies.

The Birth of String Theory, ed. Andrea Cappelli, Elena Castellani, Filippo Colomo and Paolo Di Vecchia.
Published by Cambridge University Press.

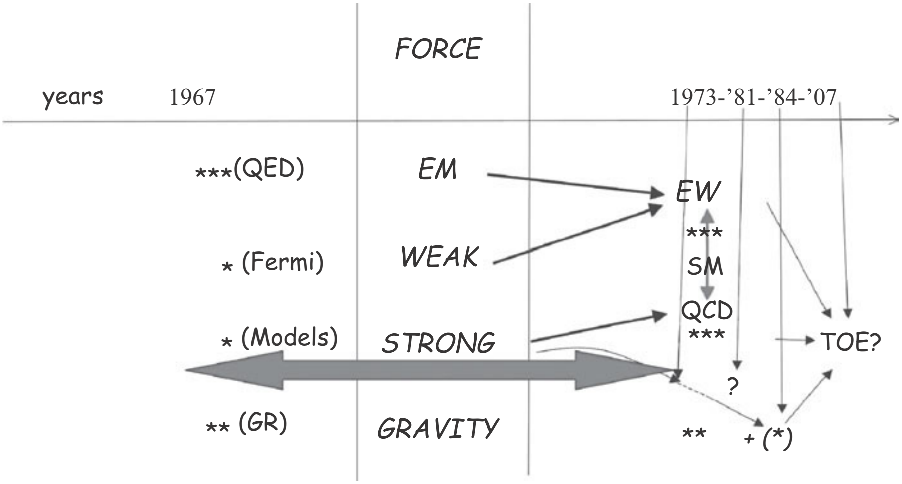

Figure 2.1 Evolution of our theories of fundamental forces during the 'golden decade'.

which, being still in search of something deserving the name of a theory, could only afford a single star.

If we look again at the situation some six or seven years later (say around 1973) we cannot fail to notice a striking improvement: the theory of weak interactions had been upgraded and unified with the electromagnetic theories in what became known as the electro-weak sector of the Standard Model, while the strong interaction had also found a beautiful description in the second sector of the Standard Model, quantum chromodynamics (QCD). Thus, by the mid-Seventies, all three nongravitational interactions had reached 3-star status, while the situation had basically remained unchanged for gravity.

This Chapter covers a parallel attempt to find a good theory for the strong interactions which, instead of succeeding in its goal, gave rise to a completely different theoretical framework, string theory. The string theory of hadrons met with phenomenological difficulties and could not compete eventually with QCD; it was abandoned as such for about a decade until it was brought back into the spotlight by the daring proposal that, upon a huge rescaling of the string characteristic size, it could become a serious candidate for a unified quantum theory of all interactions, including gravity, a Theory of Everything (TOE), as indicated at the far right of the figure.

The rest of the Chapter is organized as follows: in Section 2.2 I will recall the developments that, within a year of exciting work, culminated in the first example of a Dual Resonance Model, the beta-function ansatz, a mathematical expression later understood to describe quantum mechanically a reaction in which two open strings collide to give rise to two other open strings. In Sections 2.3 and 2.4 I will recall the striking developments which, in spite of many apparent theoretical obstacles, led to what appeared to be a fully consistent mathematical and physical framework for dealing with strong interactions. In Section 2.5 I will describe how those developments gave, at the same time, numerous hints for a string-like structure lying at the basis of Dual Resonance Models; largely missed for some time, these hints led eventually to the formulation of (super)string theory as it is basically known even today. Finally, in Sections 2.6 and 2.7, I will recall how, on the basis of several experimental tests, string theory had to concede defeat to its quantum-field-theory competitor, QCD. I will also outline the reasons why a crucial property of QCD, quark confinement, together with the idea of a $1/N$ expansion, does imply the existence of narrow string-like excitations in the hadronic world as well as the duality property of their mutual interactions, and thus explain the discovery of string theory many years before it could find an even more ambitious potential application in physics.

2.2 String prehistory

I will start my account from around 1967. At that time the status of the theory of strong (nuclear) interactions was not very brilliant. Data were abundant, but we could only confront them with a handful of models, each one capturing one or another aspect of the complicated hadronic world (hadron is a generic name for any particle feeling the strong force). The following features were noteworthy.

- Strong interactions are short ranged (implying the absence of massless hadrons).
- They are characterized by several (exact or approximate) symmetries and the corresponding conservation laws.
- Many hadrons had been identified, most of them metastable (resonances), and with large mass and angular momentum (spin): the ‘hadronic zoo’ seemed to be increasing in size every day.

The problem was to find a way to put some order and simplicity in this complex situation.

Today, with hindsight, we can easily assert that, in the late Sixties, we took the wrong way by rejecting, a priori, a description of these phenomena based on quantum field theory (QFT), the framework that had already been so successful for the electromagnetic interactions via quantum electrodynamics (QED). There were (at least) two very good excuses for having chosen this wrong way:

- unlike in QED, the theory of interacting photons and electrons, there were too many particles to deal with, actually, as I just said, an ever increasing number;
- QFTs of particles with high angular momentum were known to be very difficult, if not impossible, to deal with in a QFT framework.

Instead, a so-called S-matrix approach looked much more promising. Let’s describe it briefly. The idea, originally due to J. H. Wheeler [Whe37] and W. Heisenberg [Hei43] (see Eden *et al.* [ELOP66] for a more modern account), is that a good theory should only deal with quantities that can be measured directly. When one considers a reaction in which a given initial state evolves into a final state according to the laws of quantum mechanics, the relevant object is the so-called probability amplitude, a complex number whose absolute

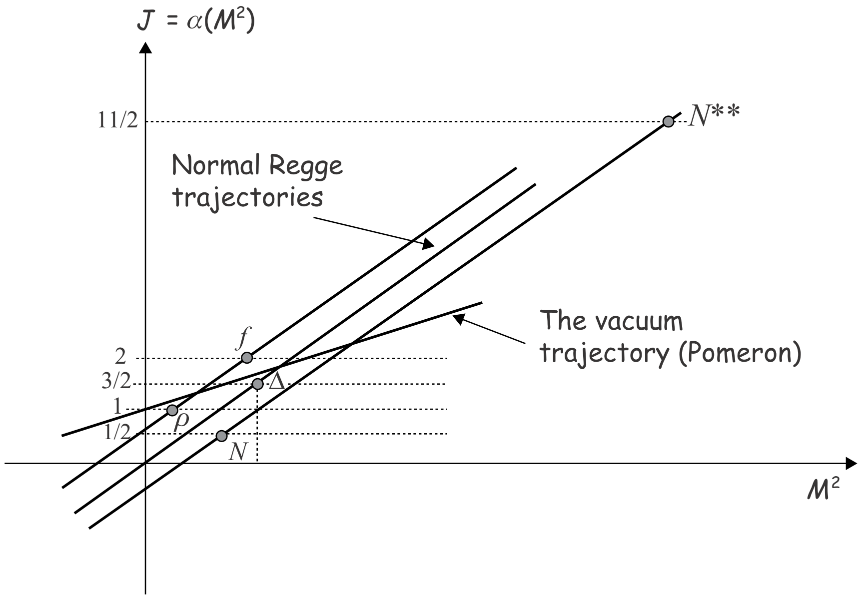

Figure 2.2 Regge trajectories at positive and negative values of M^2.

value squared gives the usual probability for that particular process to occur. Considering all possible initial and final states, the set of all these complex numbers defines a huge (actually infinite) matrix called the S-matrix (S for scattering) which, by conservation of probability, should be unitary.

The constraints of relativistic causality force the S-matrix elements to be analytic functions of the kinematical variables they depend upon, like the energy of the collision. Also, the symmetries of the strong interactions can easily be implemented at the level of the S-matrix. These symmetries could also be used to put some order in the hadronic zoo by grouping particles with the same spin into families.

Finally, the recently developed Regge theory (see Collins [Col77]) was also able to assemble together particles of different angular momentum. One amazing empirical observation at the time was that the masses M and angular momenta J of particles lying on the same 'Regge trajectory' satisfied a simple relation:

$$J = \alpha(M^2) = \alpha_0 + \alpha' M^2, \tag{2.1}$$

with α_0 a parameter depending on the particular Regge family under consideration and α' a universal constant ($\alpha' \sim 0.9\ \text{GeV}^{-2}$ in natural units where $c = \hbar = 1$).

Regge theory had a second important facet, pointed out later by Chew and Mandelstam [Col77]: it could be used to describe the behaviour of the S-matrix at high energy. These two uses of Regge theory are illustrated in Figure 2.2, where we see the linear and parallel Regge trajectories (with one exception, the so-called vacuum or Pomeranchuk trajectory)

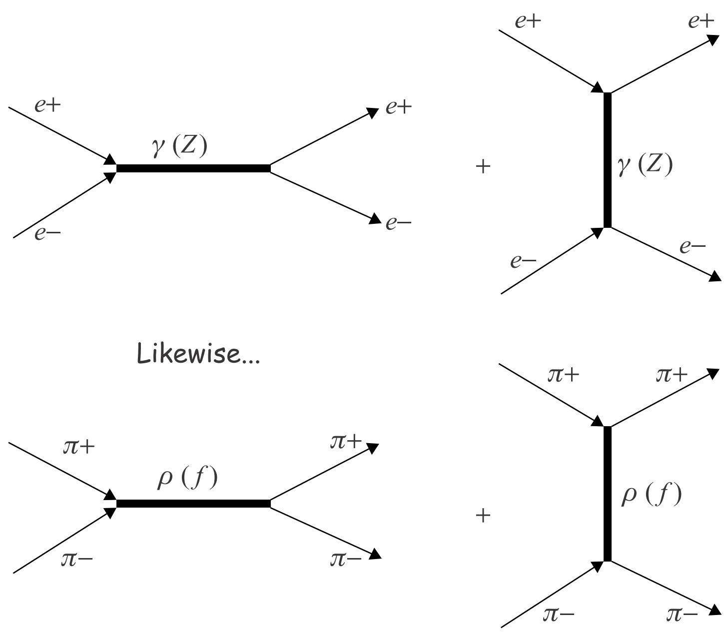

Figure 2.3 Feynman diagrams for QED and for strong interactions.

and the fact that the trajectory interpolates among different particles at positive J, M^2 while it determines high energy scattering at negative M^2.

Chew [Che66] had invoked these two appealing features of Regge's theory to formulate what I will call (for reasons that will become clear later) an 'expensive bootstrap'. Chew's idea was to add to the already mentioned constraints (unitarity, analyticity, symmetry) the assumption of 'nuclear democracy' according to which:

- *all* hadrons, whether stable or unstable, lie on Regge trajectories (at $M^2 \geq 0$) and are on the same footing;
- the high energy behaviour of the S-matrix is *entirely* given in terms of the same Regge trajectories (at $M^2 \leq 0$).

The hope was that an essentially unique S-matrix would come out after imposing this set of constraints. Actually, in Chew's programme Regge trajectories would appear twice in determining the structure of the S-matrix: once by giving the set of (unstable) intermediate states through which the process could proceed; and once by giving the set of (virtual) particles that could be exchanged. In this sense the situation would mimic that of QED. In Figure 2.3 we show the lowest order QED Feynman diagrams for electron–positron scattering (one-photon exchange) as well as the analogous diagrams for elastic $\pi^+\pi^-$ scattering through formation or exchange of a ρ^0-meson. The difference was that while electrons and

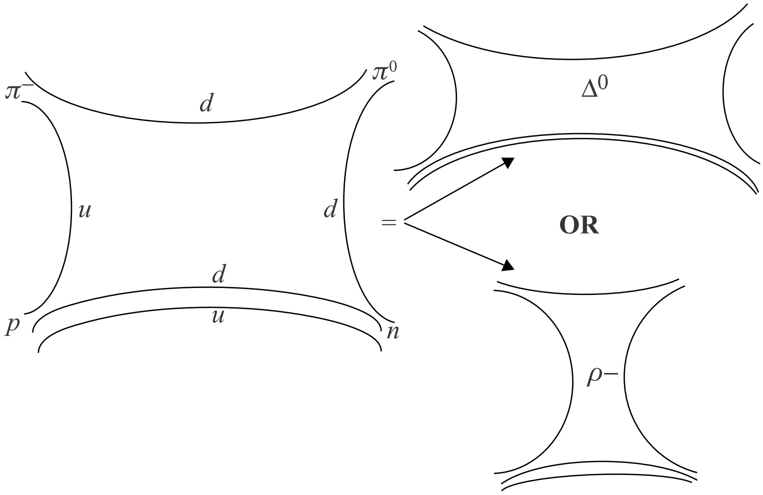

Figure 2.4 Duality diagrams for pion–nucleon scattering.

photons were not supposed to lie on Regge trajectories, the opposite was supposedly true for the pions and the ρ-meson.

However, an interesting surprise came out in 1967 through a fundamental observation made by Dolen, Horn and Schmid [DHS68, Sch68] who, after looking carefully at some pion–nucleon scattering data, concluded that contributions from resonance formation and those from particle exchange should *not* be added but were actually each one a complete representation of the process. This property became known as DHS duality.

In the spring of 1967 several attempts were made to couple DHS duality with another tool, developed by Sergio Fubini and collaborators, the so-called superconvergence equations [DFFR66, Fub66]. The combination of both ideas led Logunov, Soloviev and Tavkhelidze [LST67] and Igi and Matsuda [IM67] to write down the so-called 'finite energy sum rules' (FESR). In the summer of 1967, at a summer school in Erice, I was strongly influenced by a talk given by Murray Gell-Mann on DHS duality, stressing that such a framework could lead to what he defined as a 'cheap bootstrap' as opposed to Chew's expensive one. In order to get interesting constraints on the Regge trajectories themselves it was enough to require that the two dual descriptions of a process would produce the same answer.

I will open a short parenthesis here. Around the same time Harari [Har69] and Rosner [Ros69] gave an interesting graphical representation of DHS duality by drawing 'duality diagrams' (see Figure 2.4) where hadrons are represented by a set of quark lines (two for the mesons, three for the baryons) and the scattering process is described in terms of the flow of these quark lines through the diagram. By looking at the diagram in different directions (channels), the process is seen to proceed in different – but equivalent in the sense of DHS duality – ways. Duality diagrams are therefore very different from the Feynman diagrams of Figure 2.3. Notice that in those days quarks were just a mnemonic to keep track of quantum

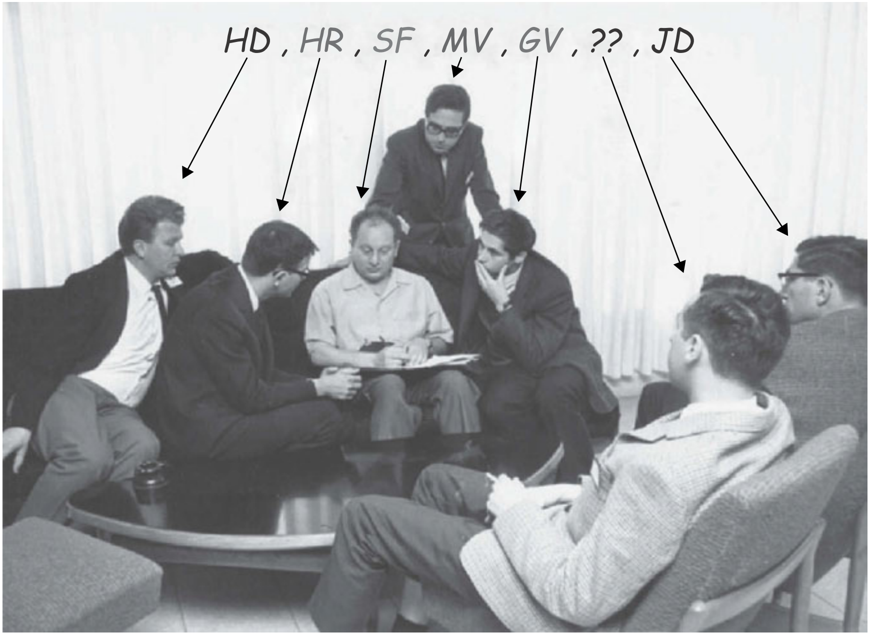

Figure 2.5 At the Weizmann Institute in 1967. From left to right: Hans Dahmen, Hector Rubinstein, Sergio Fubini, Miguel Virasoro, Gabriele Veneziano, unknown, Joe Dothan.

numbers and internal symmetries: they were not considered as having any real substance. Also, the duality diagrams were supposed to represent processes dominated by Regge trajectories other than the one carrying the vacuum quantum number: that exchange was supposed not to be dual to any resonances but rather to some non-resonating multiparticle background (see Harari [Har68] and Freund [Fre68]).

Coming back to the 'cheap bootstrap' the problem was that of finding a simple way to implement it. The original pion–nucleon process considered by Dolen, Horn and Schmid looked too complicated; it also represented a relation between mesons and baryons rather than a self-consistency condition among mesons only. Instead, in the fall of 1967, Ademollo, Rubinstein, Virasoro and myself (ARVV) [ARVV67, ARVV68] decided to apply the idea to a theoretically easier (even if experimentally unpractical) process: $\pi\pi \to \pi\omega$. This reaction has the property of being the same in all three channels and of allowing only very selective quantum numbers in each of them, basically those of the ρ-meson and its orbital excitations.

Between the fall of 1967 and the summer of 1968 ARVV (with the help of M. Bishari and A. Schwimmer and the advice and encouragement of S. Fubini, see Figure 2.5) made much progress in finding approximate solutions to this 'cheap bootstrap'. A rather simple ansatz was working remarkably well provided the ρ-Regge trajectory was taken to be straight and to be accompanied by lower parallel 'daughter' trajectories. I recall thinking (and telling people) that something even simpler was probably hiding behind all that . . .

The ARVV ansatz that worked amazingly well for the DHS bootstrap in $\pi\pi \to \pi\omega$ referred to the imaginary part of the scattering amplitude $A(s,t)$ and had the expression:

$$\begin{gathered} \operatorname{Im} A(s,t) = \frac{\pi\beta(t)}{\Gamma(\alpha(t))} \left(\alpha' s\right)^{\alpha(t)-1} (1 + O(1/s)), \\ \beta(t) \sim \text{constant}, \qquad \alpha(t) = \alpha_0 + \alpha' t, \end{gathered} \tag{2.2}$$

where Γ is the familiar Euler gamma function and the $1/s$ corrections represent the contribution from the parallel daughter trajectories. By tuning such corrections more and more we could make the agreement with DHS duality better and better and could extend it to a larger and larger range of t.

Which were the ingredients that led from that ansatz to an 'exact solution'? They were essentially three.

- Look for an expression for the full amplitude A rather than for its imaginary part; unlike Im A, A is an analytic function and thus easier to work with.
- Impose crossing symmetry, meaning in this case $A(s,t) = A(t,s)$; no such property is supposed to hold for Im A.
- Emphasize the resonance side of DHS duality rather than the Regge side, i.e. look for an amplitude $A(s,t)$ with just poles (a meromorphic function) in s and t.

At this point one notices that the analytic function whose imaginary part is given by Eq. (2.2) is simply:

$$A(s,t) = \beta(t)\Gamma(1-\alpha(t)) \left(-\alpha' s\right)^{\alpha(t)-1} (1 + O(1/s)). \tag{2.3}$$

However, this function does not obey crossing symmetry. It has poles in t but only a branch point in s. In order to introduce poles in s that follow exactly the pattern of those in t we can replace the factor $\left(-\alpha' s\right)^{\alpha(t)-1}$ by $\Gamma(1-\alpha(s))$ and, in order not to change the high energy behaviour, we divide by a third Γ-function:

$$\left(-\alpha' s\right)^{\alpha(t)-1} (1 + O(1/s)) \to \frac{\Gamma(1-\alpha(s))}{\Gamma(2-\alpha(s)-\alpha(t))}, \tag{2.4}$$

and note, not without satisfaction, that imposing the right asymptotic behaviour has automatically provided a crossing-symmetric amplitude. Indeed the end result [Ven68] is the well-known Euler beta function:

$$A(s,t) = \beta \frac{\Gamma(1-\alpha(s))\,\Gamma(1-\alpha(t))}{\Gamma(2-\alpha(s)-\alpha(t))} \equiv \beta\; B(1-\alpha(s), 1-\alpha(t)). \tag{2.5}$$

The full scattering amplitude for $\pi\pi \to \pi\omega$ is actually obtained by adding to Eq. (2.5) the same object with $s \leftrightarrow u$ and the one with $t \leftrightarrow u$, so as to make it completely symmetric in all three Mandelstam variables.

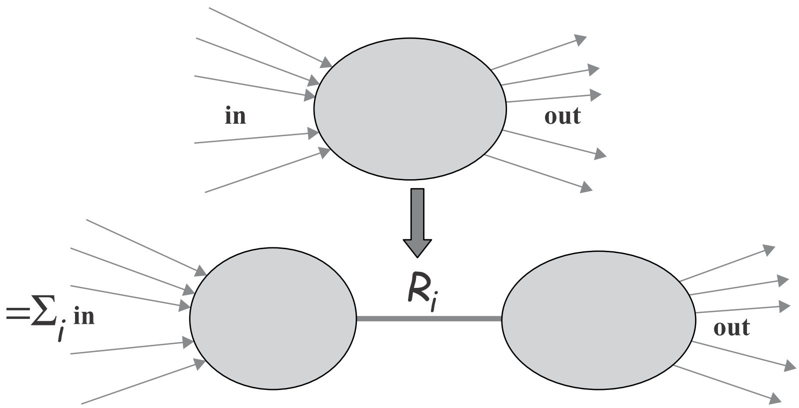

Figure 2.6 Counting states via factorization.

2.3 Dual Resonance Models

There was a big worry based on previous experience: possibly, in order to satisfy all the constraints, the beta function model had to contain 'ghosts', i.e. states produced with negative probability. If so the model would be inconsistent. Sergio Fubini was particularly insistant on this crucial test.

To answer that question one had to identify first all the states/resonances. The way to do this was to use a property of the S-matrix known as factorization. It is basically what unitarity reduces to in the single-particle-exchange approximation. The problem could be formulated as follows: how many terms were necessary and sufficient in order to write the residue of a pole in the S-matrix as a sum of products of a coupling to the 'initial' and 'final' states (see Figure 2.6)?

This question could not be answered by using just the beta function, but, fortunately, in the fall of 1968 several groups (Bardakci and Ruegg [BR69a, BR69b], Virasoro [Vir69a], Goebel and Sakita [GS69], Chan and Tsou [CT69], Koba and Nielsen [KN69], Chan and Paton [CP69]) had found a (pretty unique) generalization of the original ansatz to multiparticle initial and final states. Sergio Fubini and I at MIT (where I had just arrived for my first postdoc), as well as Bardakci and Mandelstam at Berkeley, started to look into this rather complex counting problem.

The result (Fubini and Veneziano [FV69] and Bardakci and Mandelstam [BM69]) turned out to be very surprising. Because of the parallel daughters, we were expecting a mild degeneracy (increasing, say, like a power of energy). Instead, the number of states grew much faster, like $\exp(bM)$, with b some known constant (with dimensions of 1/mass and of order $\sqrt{\alpha'}$).

Although unexpected, this was just the behaviour postulated by R. Hagedorn a few years earlier [Hag65] on more phenomenological grounds (for example, in order to get a Boltzmann-like factor in the particle spectra produced in high energy hadronic collisions). Taken at face value, such a density of states leads to a limiting (maximal, Hagedorn) temperature T_H given by (k_B is Boltzmann's constant):

$$k_B T_H = b^{-1} = O\left(\frac{1}{\sqrt{\alpha'}}\right). \tag{2.6}$$

The other (unfortunate but not unexpected) discovery was that, indeed, some of the states had negative norm, a major problem. In our original paper [FV69] we noticed that the lightest ghost particles actually 'decoupled'. In other words the full set of states was sufficient in order to achieve factorization but not absolutely necessary. Unfortunately, our original formalism was too cumbersome to check whether the more massive ghost states would also decouple. However, the original formalism was soon replaced by a much more handy one, based on harmonic oscillator operators (see Fubini, Gordon and Veneziano [FGV69] and Nambu [Nam69]).

In the new formalism a sufficient (vis-à-vis of factorization) set of states consisted of the energy eigenstates of an infinite set of decoupled harmonic oscillators with quantized frequencies, i.e.

$$\begin{aligned} |N_{n,\mu}\rangle &\sim \prod_{n,\mu} \left(a^{\dagger}_{n,\mu}\right)^{N_{n,\mu}} |0\rangle, \qquad (n = 1, 2, \ldots ; \mu = 0, 1, 2, 3), \\ \alpha' M^2 &= \sum_{n,\mu} n\, a^{\dagger}_{n,\mu}\, a^{\mu}_{n} \equiv L_0 - \alpha' p^2, \end{aligned} \tag{2.7}$$

where

$$[a_{n,\mu}, a^{\dagger}_{m,\nu}] = \delta_{n,m}\eta_{\mu\nu}, \qquad \eta_{\mu\nu} = \mathrm{diag}(-1, 1, 1, 1). \tag{2.8}$$

Because of the 'wrong' sign of the timelike commutation relation (2.8), states created by an odd number of timelike operators were ghosts. Was the DRM doomed? Well, almost. The only hope was that all those states were sufficient but perhaps only a (ghost-free) subset was necessary.

In my original paper with Fubini the following (so-called 'spurious') states were found to be unnecessary:

$$L_{-1}|X\rangle \equiv \left(p \cdot a^{\dagger}_{1} + \sum_{n} \sqrt{n(n+1)}\, a^{\dagger}_{n+1} \cdot a_n\right) |X\rangle, \tag{2.9}$$

with $|X\rangle$ any state.

This was probably sufficient to eliminate the ghosts created by the time component of $a_{1,\mu}$. But what about all the others? The situation looked almost desperate ... until Virasoro [Vir70] made a crucial discovery. If $\alpha(0) = 1$ one could enlarge enormously the space of 'spurious' states to:

$$L_{-m}|X\rangle \equiv \left(p \cdot a^{\dagger}_{m} + \sum_{n} \sqrt{n(n+m)}\, a^{\dagger}_{n+m} \cdot a_n\right) |X\rangle, \tag{2.10}$$

with $m = 1, 2, \ldots$

Thus, for $\alpha(0) = 1$, there was a chance to eliminate all the ghosts! Unfortunately, $\alpha(0) = 1$ meant having a massless $J = 1$ state, something unwanted, but people kept hoping that such a problem could be solved, perhaps through loop corrections, and kept working enthusiastically.

2.4 Further developments

Between the summer of 1969 and the spring of 1970 several important developments took place in the operator formalism.

- Sciuto [Sci69] (see also Della Selva and Saito [DS70]) constructed a vertex describing the coupling of three arbitrary harmonic oscillator states, while Caneschi, Schwimmer and myself simplified Sciuto's work through the introduction of the twist operator [CSV69, CS70].
- Soon after, Gliozzi [Gli69] and, independently, Chiu, Matsuda and Rebbi [CMR69] and Thorn [Tho70] discovered that the operators L_0 and $L_{\pm 1}$ satisfy an $SU(1, 1)$ noncompact algebra.
- Fubini and myself [FV70], and independently Gervais [Ger70], constructed the field operator $Q(z)$ and the so-called 'vertex operators', $V(k)$, discussing their nontrivial correlators and transformations under the above mentioned $SU(1, 1)$ group. This opened the way to further important developments.
- Duality, factorization and the conditions characterizing spurious and physical states all came out in an elegant algebraic way.
- Then, Fubini and I [FV71] extended all this framework to the whole set of Virasoro's L_n operators [Vir70] and figured out the action of such operators on $Q(z)$ and $V(k)$. As a result we could (too) 'quickly' guess the algebra of the Virasoro operators . . . missing its crucial 'central charge', a quantum effect soon discovered by the late Joe Weis (see Note added in proofs in [FV71]). This led to what has been known since then as the Virasoro algebra.

At this point the machinery was almost ready for a final assault at the ghost-killing programme. An essential step turned out to be the construction of the DDF (Di Vecchia, Del Giudice, Fubini) positive norm states [DDF72]. They were in one-to-one correspondence with $D - 2$ sets of harmonic oscillators (D being the dimensionality of spacetime naturally taken, at the time, to be 4). These states were physical and had positive norm, but did not look sufficient to span the whole Hilbert space. I remember well a talk given by Fubini and myself to the mathematicians at MIT where the mathematical problem at hand was formulated: no proof of the absence of ghosts came out of that attempt, though. Instead, mathematicians got quite interested in some of the mathematical aspects of the DRM, like the vertex operators and the Virasoro algebra.

The no-ghost theorem was proven instead soon after by Brower [Bro72] and by Goddard and Thorn [GT72]. It only worked for $\alpha(0) = 1$, of course, but, curiously enough, only for

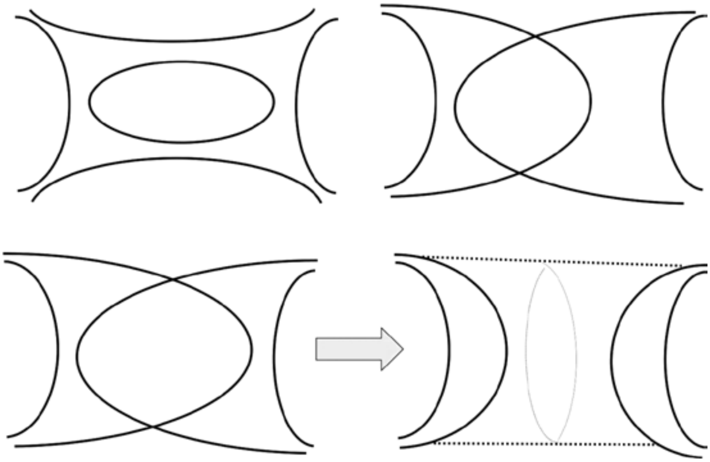

Figure 2.7 Planar and nonplanar loops; the latter give rise to new states for $D = 26$.

$D \leq 26$! At $D = 26$ the DDF states were both necessary *and* sufficient, while at $D < 26$ some other positive norm states were needed. At $D > 26$ ghosts were still present among the physical states. This basic result represented the happy conclusion of a long process and gave much confidence in the belief that the DRM was a theoretically sound and consistent starting point for a new theory of hadrons.

In what sense was it a first-order approximation? The DRM was the analogue of the tree-level approximation of a QFT. In order to implement unitarity fully (for example to give finite widths to the resonances), loop corrections had to be added. Having identified the physical states, this was (almost) a technical problem. One just had to be careful of not letting ghosts circulate in the loops and then factorization (unitarity) and duality would lead to basically unique answers (see Kikkawa, Sakita and Virasoro [KSV69], Bardakci, Halpern and Shapiro [BHS69], Amati, Bouchiat and Gervais [ABG69], Neveu and Scherk [NS70], Frye and Susskind [FS70] and Gross, Neveu, Scherk and Schwarz [GNSS70]).

Both planar and nonplanar loops (see Figure 2.7) were needed, the latter in order to describe the peculiarities of vacuum exchange processes. However, the nonplanar loop had a big surprise up its sleeve: Lovelace [Lov71] discovered that, for $D \neq 26$, this loop gave nonsensical singularities in the vacuum channel. By contrast, for $D = 26$, it gave new poles that could be interpreted as a new set of positive norm physical states with vacuum quantum numbers. Furthermore, those new states would interact just as the (already known) states of another DRM, the one invented by Virasoro [Vir69b] and Shapiro [Sha70] (and later reinterpreted as describing closed, rather than open, strings). Thus, the magic number 26 was again making its appearance[2] in a completely independent way! For a theory of hadrons these new states were very good candidates for hadrons lying on the Pomeron

[2] Actually this observation came before the one based on imposing the absence of ghosts.

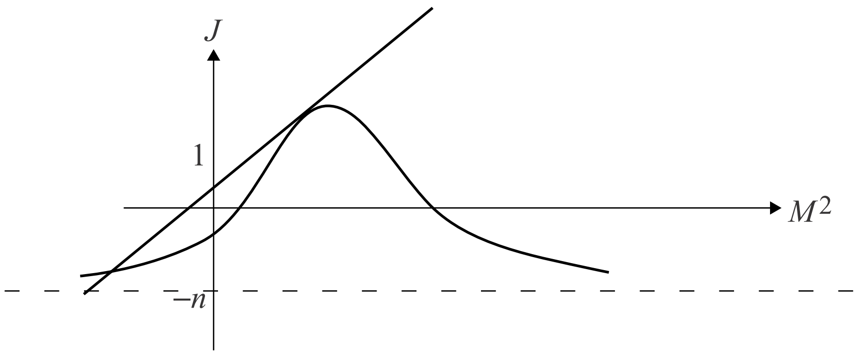

Figure 2.8 Regge trajectories in potential scattering (straight line) and in hadronic physics (curved line).

trajectory, except that the trajectory's intercept was 2, once more about a factor 2 larger than the experimental value!

2.5 Hints of a string

The (more or less vague) idea that the DRM had a physical interpretation in terms of some extended object came soon after they were invented. With hindsight we can find many (mostly missed) hints that such an underlying object had to be a string. I can mention at least five of them.

- From linear Regge trajectories. We have:

$$\alpha' = \frac{dJ}{dM^2} \sim 10^{-13} \text{ cm GeV}^{-1}. \tag{2.11}$$

  Its inverse, $T \sim 10^{13}$ GeV cm^{-1}, has dimensions of a string tension (where $c = 1$ but no $\hbar$ is needed)! One can add to this that linearly rising Regge trajectories are very different from those originally found by T. Regge in potential scattering. The latter would rise up to some point and then inevitably fall down at large M (see Figure 2.8).
- From duality and duality diagrams. The duality diagrams of Harari and Rosner can be further decorated with little springs connecting the quark lines and then they describe pictorially (see Figure 2.9) the joining and splitting of open strings. The intermediate states of the nonplanar loop would realize a DHS duality between two open strings in one channel and a single closed string in another.
- From the harmonic oscillators. This was certainly one decisive hint: indeed a string can be described as an infinite set of independent harmonic oscillators whose characteristic frequencies are a multiple of a fundamental (lowest) frequency.
- From $Q(z)$ and its correlators. These indicated the existence of one effective 'coordinate' z labelling points on a one-dimensional object; the correlators themselves, behaving logarithmically in the distance, were characteristic of a $(1 + 1)$-dimensional field theory.

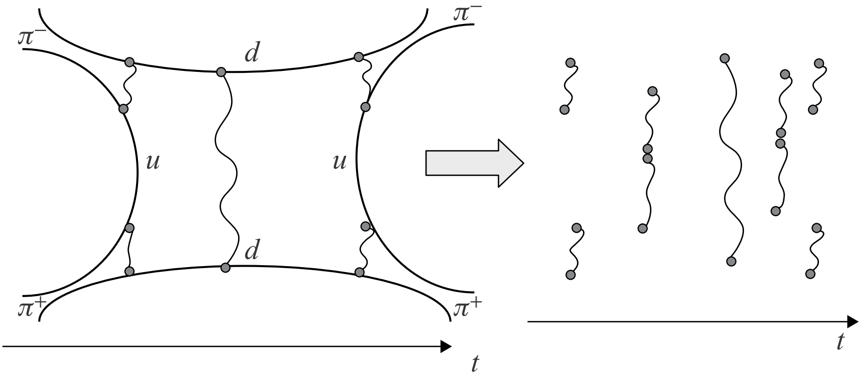

Figure 2.9 Duality diagrams interpreted in terms of the joining and splitting of strings.

- From DDF 'transverse' states. The fact that only $D - 2$ sets of oscillators were enough corresponds to the statement that only vibrations of the string that are orthogonal to the string itself have physical meaning.

Indeed these last three hints were not missed, and the proposal that a string was lying at the basis of all those magic properties that had been found was finally made, particularly by Nambu [Nam70a], Nielsen [Nie70] and Susskind [Sus70]. The identification remained qualitative for some time until Nambu [Nam70b] and Goto [Got71] first formulated in a precise way the classical action of a relativistic string, and then the work of Goddard, Goldstone, Rebbi and Thorn [GGRT73] established the connection between the DRM spectrum and that of a quantized string. In doing so, GGRT established for the third time the necessity of the $\alpha(0) = 1$ and $D = 26$ constraints. But, paradoxically, now that the DRM had been raised to the level of a respectable theory, it became apparent that it was not the right theory for strong interactions.

2.6 Good and bad news

The good news was essentially theoretical (see also the Chapters by André Neveu, Pierre Ramond, Ferdinando Gliozzi and Michael Green, in this Volume):

- the Neveu–Schwarz [NS71] and Ramond [Ram71] fermionic extensions introducing fermions and lowering the critical dimension from $D = 26$ to $D = 10$;
- the discovery of supersymmetry in the West (found independently in Russia);
- the Gliozzi–Scherk–Olive [GSO76, GSO77] projection leading to the elimination of the tachyon and to fully consistent superstring theories;
- the Scherk–Schwarz proposal [SS74] that string theory should be reinterpreted as a theory of quantum gravity;

- the Green–Schwarz [GS84] anomaly cancellation, showing that consistent and realistic superstring theories unifying all interactions may exist.

The bad news (for the hadronic string) was instead phenomenological, i.e. related to experimental data:

- $D \neq 4$, i.e. the dimensionality of spacetime required by string theory is not the one we observe;
- massless states with $J = 0, 1/2, \ldots, 2$ were a big embarrassment for any theory of strong interactions;
- the softness of string theory did not allow for sizeable cross-sections for events with large momentum transfers, whereas
  - scaling in $R = \sigma(e^+ e^- \to \text{hadrons})/\sigma(e^+ e^- \to \mu^+ \mu^-)$,
  - Bjorken scaling in $e + p \to e + \text{hadrons}$,
  - large-p_t events at CERN's newest accelerator, the Intersecting Storage Ring (ISR),

  were all showing evidence for pointlike structure in the hadrons – alas, there was no such pointlike structure in the Nambu–Goto string!

2.7 QCD takes over

At about the same time a strong competitor to the DRM and strings came out: quantum chromodynamics (QCD). It was a consistent theory in $D = 4$. With its property of ultraviolet (asymptotic) freedom it could account for those hard events that string theory had difficulties dealing with. Also, the (at the time just conjectured) property of infrared slavery could explain why quarks (and also gluons) could not be seen directly in experiments, as well as the existence of a mass gap (no massless states).

Clearly, it was not the kind of QFT we had discarded early on. Less revolutionary than string theory, it had just the right amount of novelty to be right. Did we need more to be convinced and abandon (reluctantly) our strings? Personally, I still kept trying some phenomenology with string theory using its topological structure, apparently very unlike that of any QFT.

I gave up around 1974, when 't Hooft [tHo74] showed that even the topology of duality diagrams comes out of QCD, provided one considers a $1/N_c$ expansion, where N_c is the number of colours ($N_c = 3$ in real life). Indeed:

- in large-N_c QCD duality diagrams take up a precise meaning, they are planar Feynman diagrams bounded by quark propagators and filled with a 'fishnet' of gluon propagators and vertices (see Figure 2.10);
- they provide naturally a justification for the narrow-resonance approximation[3] that we had been using all the time;

[3] The fact that in the limit $N_c \to \infty$ mesons become stable and not interacting had been pointed out before the advent of QCD by Lipkin [Lip68].

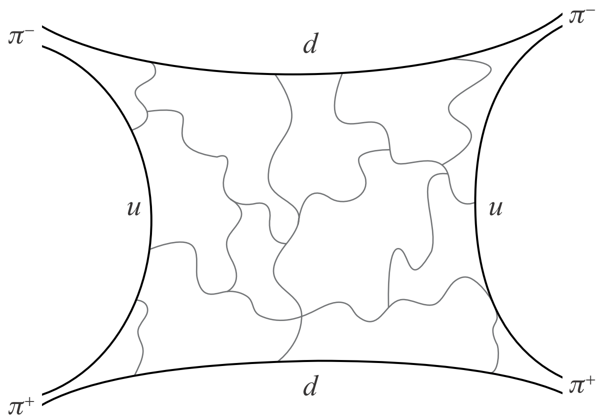

Figure 2.10 Large-N QCD interpretation of duality diagrams.

- at sub-leading order the nonplanar diagrams give new bound states, the glueballs, and presumably the Pomeron as the Regge trajectory these new states lie on;
- the Hagedorn temperature is reinterpreted as a deconfining temperature for quarks and gluons.

It all seems to fall beautifully into place . . .

And finally the property of confinement (for which there is by now overwhelming numerical evidence and even a compelling theoretical picture based on an analogy with superconductivity) explains why string-like objects (such as chromoelectric flux tubes) and excitations do really exist in the hadronic world. This is no doubt the reason why, by trying to put some order in the complicated world of strong interactions, we did end up with a theory of strings, albeit with the wrong one. After 40 years we still do not know which is the correct string theory description of hadrons (a subject that has become fashionable once more in the modern string community), a kind of mirage employed by Nature to deceive many of us, but which led to the premature discovery of a framework that could one day answer even greater questions.

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Gabriele Veneziano was born in Florence in 1942. He received his 'Laurea' in physics at the University of Florence in 1965, and his PhD at the Weizmann Institute in 1967. He has been Research Associate, and then visiting scientist, at MIT (1968–1972), full Professor at the Weizmann Institute (1972–1977), and staff member in the Theory Division at CERN (1977–2007). He is currently Professor at the Collège de France, Paris. Honours received include the Pomeranchuk Prize (Moscow), Heineman Prize (APS), Einstein Medal (Bern), Fermi Medal (Italy), Oskar Klein Medal (Stockholm), James Joyce award (Dublin), and others.

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3

Gravity, unification, and the superstring

JOHN H. SCHWARZ

Abstract

This Chapter surveys some of the highlights in the development of string theory through to the first superstring revolution in 1984. The emphasis is on topics in which the author was involved, especially the observation that critical string theories provide consistent quantum theories of gravity and the proposal to use string theory to construct a unified theory of all fundamental particles and forces.

3.1 Introduction

I am happy to have this opportunity to reminisce about the origins and development of string theory from 1962 (when I entered graduate school) through to the first superstring revolution in 1984. Some of the topics were discussed previously in three papers that were written for various special events in 2000 [Sch00a, Sch00b, Sch01]. Also, some of this material was reviewed in the 1985 reprint volumes [Sch85], as well as string theory textbooks (Green, Schwarz and Witten [GSW87] and Becker, Becker and Schwarz [BBS07]). In presenting my experiences and impressions of this period, it is inevitable that my own contributions are emphasized.

Some of the other early contributors to string theory present their recollections elsewhere in this Volume. Taken together, these contributions should convey a fairly accurate account of the origins of this remarkable subject. Since the history of science community has shown little interest in string theory, it is important to get this material on the record. There have been popular books about string theory and related topics, which serve a useful purpose, but there remains a need for a more scholarly study of the origins and history of string theory.

The remainder of this Chapter is divided into the following Sections:

- 1960–1968: the analytic S-matrix,
- 1968–1970: the Dual Resonance Model,

The Birth of String Theory, ed. Andrea Cappelli, Elena Castellani, Filippo Colomo and Paolo Di Vecchia.
Published by Cambridge University Press.

- 1971–1973: the Ramond–Neveu–Schwarz model,
- 1974–1975: gravity and unification,
- 1975–1979: supersymmetry and supergravity,
- 1979–1984: superstrings and anomalies.

For each topic, I will give a brief account of the evolution of the research in the corresponding subject. For most of them, more detailed accounts will be provided by other contributors to this Volume. The main focus in this contribution will therefore be on one of the above topics (gravity and unification).

3.2 1960–1968: the analytic S-matrix

In the early Sixties there existed a successful quantum theory of the electromagnetic force (QED), which was completed in the late Forties, but the theories of the weak and strong nuclear forces were not yet known. In UC Berkeley, where I was a graduate student during the period 1962–1966, the emphasis was on developing a theory of the strong nuclear force.

I felt that UC Berkeley was the centre of the Universe for high energy theory at the time. Geoffrey Chew (my thesis advisor) and Stanley Mandelstam were highly influential leaders. Also, Steve Weinberg and Shelly Glashow were impressive younger faculty members. David Gross was a contemporaneous Chew student with whom I shared an office.

Geoffrey Chew's approach to understanding the strong interactions was based on several general principles [Che62, Che66]. He was very persuasive in advocating them, and I was strongly influenced by him. The first principle was that quantum field theory, which was so successful in describing QED, was inappropriate for describing a strongly interacting theory, where a weak-coupling perturbation expansion would not be useful. A compelling reason for holding this view was that none of the hadrons (particles that have strong interactions) seemed to be more fundamental than any of the others. Therefore a field theory that singled out some subset of the hadrons did not seem sensible. Also, it was clearly not possible to formulate a quantum field theory with a fundamental field for every hadron. One spoke of 'nuclear democracy' to describe this situation. The quark concept arose during this period, but the prevailing opinion was that quarks were just mathematical constructs. The SLAC deep inelastic scattering experiments in the late Sixties made it clear that quarks and gluons are physical (confined) particles. It was then natural to try to base a quantum field theory on them, and QCD was developed a few years later with the discovery of asymptotic freedom.

For these reasons, Chew argued that field theory was inappropriate for describing strong nuclear forces. Instead, he advocated focussing attention on physical quantities, especially the S-matrix, which describes on-mass-shell scattering amplitudes. The goal was therefore to develop a theory that would determine the S-matrix. Some of the ingredients that went into this were properties deduced from quantum field theory, such as unitarity and maximal analyticity of the S-matrix. These basically encode the requirements of causality and nonnegative probabilities.

Another important proposal, due to Chew and Frautschi, whose necessity was less obvious, was maximal analyticity in angular momentum [CF61, CF62]. The idea is that partial wave amplitudes $a_l(s)$, which are defined in the first instance for angular momenta $l = 0, 1, \ldots$, can be uniquely extended to an analytic function of l, $a(l, s)$, with isolated poles called Regge poles. The Mandelstam invariant s is the square of the invariant energy of the scattering reaction. The position of a Regge pole is given by a Regge trajectory $l = \alpha(s)$. The values of s for which l takes a physical value correspond to physical hadron states. The necessity of branch points in the l plane, with associated Regge cuts, was established by Mandelstam. Their role in phenomenology was less clear.

The theoretical work in this period was strongly influenced by experimental results. Many new hadrons were discovered in experiments at the Bevatron in Berkeley, the Alternating Gradient Synchrotron in Brookhaven, and the Proton Synchrotron at CERN. Plotting masses squared versus angular momentum (for fixed values of other quantum numbers), it was noticed that the Regge trajectories are approximately linear with a common slope:

$$\alpha(s) = \alpha(0) + \alpha' s, \qquad \alpha' \sim 1.0\,(\mathrm{GeV})^{-2}. \tag{3.1}$$

Using the crossing-symmetry properties of analytically continued scattering amplitudes, one argued that exchange of Regge poles (in the t-channel) controlled the high energy, fixed momentum transfer, asymptotic behaviour of physical amplitudes:

$$A(s, t) \sim \beta(t)(s/s_0)^{\alpha(t)}, \qquad s \to \infty, \quad t < 0. \tag{3.2}$$

In this way one deduced from data that the intercept of the trajectory of the ρ-meson, for example, was $\alpha_\rho(0) \sim 0.5$. This is consistent with the measured mass $m_\rho = 0.76\,\mathrm{GeV}$ and the Regge slope $\alpha' \sim 1.0\,(\mathrm{GeV})^{-2}$.

The ingredients discussed above are not sufficient to determine the S-matrix, so one needed more. Therefore, Chew advocated another principle called the 'bootstrap'. The idea was that the exchange of hadrons in crossed channels provides forces that are responsible for causing hadrons to form bound states. Thus, one has a self-consistent structure in which the entire collection of hadrons provides the forces that makes their own existence possible. It was unclear for some time how to formulate this intriguing property in a mathematically precise way. As an outgrowth of studies of 'finite energy sum rules' in 1967 (Dolen, Horn and Schmid [DHS67, DHS68], Igi and Matsuda [IM67a, IM67b], Logunov, Soloviev and Tavkhelidze [LST67]) this was achieved in a certain limit in 1968 (Freund [Fre68], Harari [Har69] and Rosner [Ros69]). The limit, called the 'narrow resonance approximation' was one in which the inverse lifetimes of the resonances are negligible compared to their masses. The observed linearity of Regge trajectories suggested this approximation, since otherwise pole positions would have significant imaginary parts. In this approximation branch cuts in scattering amplitudes, whose branch points correspond to multiparticle thresholds, are approximated by a sequence of resonance poles.

The bootstrap idea had a precise formulation in the narrow resonance approximation, which was called 'duality'. This is the statement that a scattering amplitude can be expanded in an infinite series of s-channel poles, and this gives the same result as its expansion in an