The Birth of String Theory

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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 in which they were all brought together again 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 a true 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 providing an historical account of the early stages of string theory by gathering 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 the 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 moved 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 specifically devoted 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 at filling 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 intents and criteria that are explained below.

Beside the historical record, this book could be of interest for several reasons. First, by showing the dynamics of ideas, concepts and methods involved, it offers a 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, both from 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, as e.g. two-dimensional conformal symmetry, found important physical applications in various directions outside the original domain. 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 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 string history, 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 on 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 philosophers, who have a background on quantum mechanics and quantum field theory, but need the specific vocabulary to fully appreciate 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.

The detailed content of the Editors' Chapters is reported below for better reference.

For a broader audience, we suggest to begin with the first, non-technical paragraph in each Introduction, and then approach the Authors that are less technical and more comprehensive, whose Chapters are located first of every Part. The final Chapter of the book by Cappelli and Colomo provides a non-technical overview of string theory from 1984 till the present times, that complement the historical and scientific perspective. Furthermore, the rich material presented in the Authors' Chapters, together with the original literature, can be the starting point of in-depth historical studies of the many events that took place in the development of string theory.

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

The book has associated the web page:

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

that 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 have accepted to contribute their reminiscences to the book. Many thanks also to all those who gave us precious comments and suggestions during the preparation of the Volume; in particular, Leonardo Castellani, Camillo Imbimbo, Yuri Makeenko, Raffaele Marotta, Igor Pesando, Giulio Peruzzi, 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 S. De Sanctis for helping with the bibliography. Finally, we are grateful to our collaborators and to our families for their patience and support.

Contents of Editors' Chapters

1

Introduction and synopsis

String theory describes one-dimensional systems, like thin rubber bands, that move in spacetime in accordance with relativity theory. These objects supersede the point-like particles as the elementary entities supporting the microscopic phenomena and the 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 theory, the theory of point particles.

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

This book will not directly address such kind of question: its aim is to document what the theory *was* in the beginning, about forty years ago, and follow the threads connecting its developments from 1968 to 1984. Over this period of time, the theory grew out of a set of phenomenological rules into a consistent quantum mechanical theory, while the concepts, physical pictures and goals considerably evolved and changed.

The development of the theory is 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 general properties of scattering amplitudes and some experimental inputs; it then developed 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 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 the general opinion. Among them, let us mention: D. Amati (CERN), S. Fubini (MIT and CERN), M. Gell-Mann (Caltech), S. Mandelstam (Berkeley) and Y. 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 scopes 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, that are awaiting experimental test 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 in there, that 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. Chapter 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, devoted to highlight some 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 be all 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 used since they relied on the existence of only a few, weakly-interacting, elementary particles.

The dominant approach was the S-matrix (scattering matrix) theory, that only involved first-principle quantum mechanics and empirical data, as originally advocated by Heisenberg. Approximated solutions to the scattering matrix were searched for by first assuming some phenomenological input 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.

The impact of Veneziano's result was enormous, 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 ones. The operator formalism was introduced and first loop corrections were computed in open and closed string theories, at the time called Dual Resonance Model (DRM) and 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 reaching 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 to 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 spin one and two in the open and closed string, 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 contradiction with hadron phenomenology, requiring $d = 4$ dimensions and at most massless spin-zero particles.

Part IV, 'The string', illustrates how the DRM was eventually shown to correspond to the quantum theory of a relativistic string. The analogy of the DRM spectrum with 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 introduced 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, upon 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 contributions 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 definitely 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 was 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 gravity, described by Einstein's general relativity theory. This remarkable idea was much ahead of time and could not be immediately appreciated: most of the theoretical physics community was busy developing the gauge theories that form the so-called 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, seemingly 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 was brought up with strength 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 higher consistency and extra dimensions. Although low-energy limits of superstring theories, they were developed and analyzed independently.

The abrupt change of attitude that brought back superstring theories on 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 particle, requiring chiral fermions in four dimensions as well as the cancellation of the associated chiral anomalies, as remarkably shown by Green and Schwarz. Moreover, it provided a consistent quantum theory of gravity. On the other hand, supergravity theories, in particular the most fundamental one in eleven dimensions, could not provide a finite quantum theory of gravity.

These developments led to a new booming period of string theory from 1984 onwards, that continued with highs and lows till the present time. Recent findings show that string theory contains further degrees of freedom besides 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 features of the Veneziano amplitude, the full quantization of the bosonic string action, supersymmetry and the field-theory limit.

Here below 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.

Part II - The prehistory: the analytic S-matrix

Developments till 1968

- The S-matrix approach to strong interactions is pursued [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] [Ros69] [Har69]; 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 1969-73

- The Veneziano amplitude is generalized to the scattering of N particles [GS69] [Cha69] [CT69]; in particular, the string world-sheet first appears in Koba-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 constructed for restoring perturbative unitarity [KSV69] [BHS69] [ABG69]; Lovelace shows that the nonplanar loop diagram complies with unitarity only for 26 spacetime dimensions [Lov71].
- The 3-Reggeon vertex is constructed [Sci69] [CSV69] and is generalized to N external particles [Lov70a]; the N-Reggeon vertex is used for computing multiloop diagrams [Lov70b] [Ale71] [AA71] [KY70].
- Vertex operators for excited states of the string are constructed [CFNS71] [CR71].
- Brink and Olive construct 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.
- The experiment of deep inelastic scattering shows the existence of point-like constituents inside hadrons.

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Part IV - The string

Developments during 1970-73

- Nambu, Nielsen and Susskind independently suggest that the dynamics underlying the dual model is that of a relativistic string [Nam70a] [Nam70b] [Nie69] [Nie70] [Sus69] [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 for computing dual amplitudes [FN70] [FS70].
- The string action is quantized in the light-cone gauge and 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 1970-74

- 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 [SW73] [CGOS73] formalisms.
- The one-loop [GW71] and multiloop [Mon74] amplitudes of the Ramond-Neveu-Schwarz model are computed.
- The RNS model is found to possess 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.
- 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 1974-77

- 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 [SS74] [Yon73]; therefore, string theory provides a framework for unifying all fundamental interactions [SS74] [SS75].
- Extending the world-sheet supersymmetry of the Ramond-Neveu-Schwarz model to four-dimensional field theory, the Wess-Zumino model is constructed [WZ74]; supersymmetric extensions of all known quantum field theories are found.
- 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 [FNF76] [DZ76a].
- The supersymmetric action for the Ramond-Neveu-Schwarz string is obtained [BDH76] [DZ76b].

Other developments in theoretical physics

- Quantum Chromodynamics is shown to be weakly interacting at high energy (asymptotic freedom); it 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 electroweak 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 [Fri82] [Alv83] [DOP82] [Fuj82].
- 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 a $SO(8)$ 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 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 1976-84

- 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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