The Birth and Development of Superstring Theory

John H. Schwarz

IIT Roorkee Institute Lecture

OCTOBER 17, 2020

OUTLINE

I) Early History and Basic Concepts

II) String Theory for Unification

III) Superstring Revolutions

IV) Concluding Remarks

I) Early History and Basic Concepts

String theory arose in the late 1960s in an attempt to construct a theory of the strong nuclear force. This is the force that holds neutrons and protons together inside atomic nuclei.

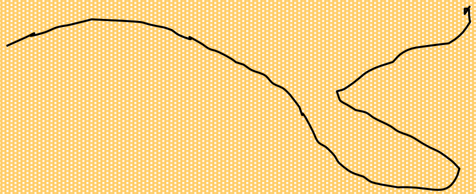
Many other (unstable) strongly interacting particles (generically called hadrons) were discovered at accelerators during this period. We needed a theory to account for them.

In Berkeley, where I was graduate student in the mid 1960s, Geoffrey Chew (who was my advisor) advocated an approach called S-matrix theory, which was very popular at the time.

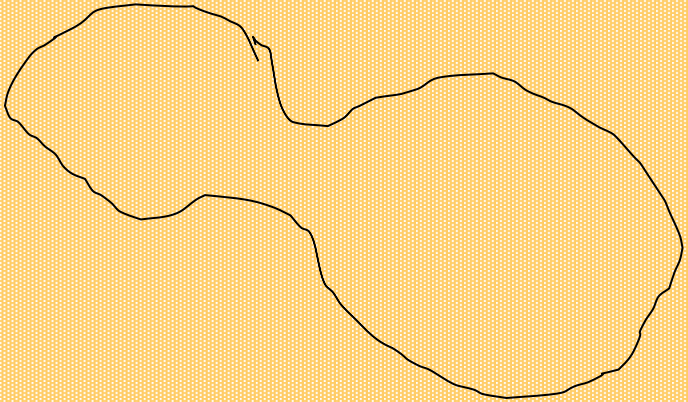
In 1968, Gabriele Veneziano proposed a simple formula that satisfies many of the S-matrix principles. After two years of study and generalization, it became clear that this formula arises from a theory based on strings, which are one-dimensional, (instead of point-like particles).

Two possible topologies for strings

Open strings have two ends:



Closed strings are loops without any ends:



The Basic Idea

Different modes of oscillation (or quantum states) of the string behave as different particles.

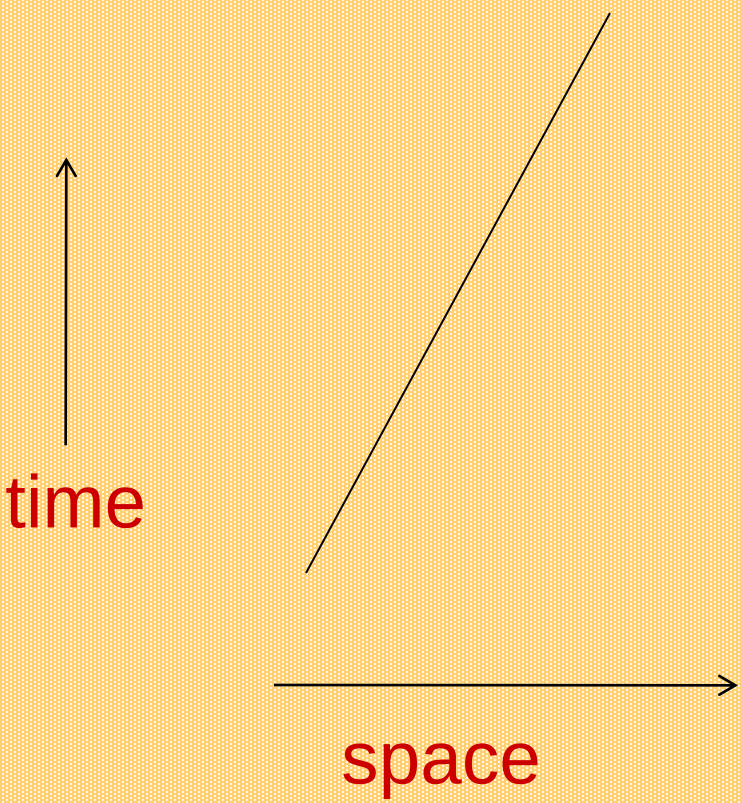
So, in this sense, there is a unique object (namely, the string). The original dream was that this could give a unified understanding of the complicated spectrum of hadrons that was discovered in the 1960s.

Formulating Theories

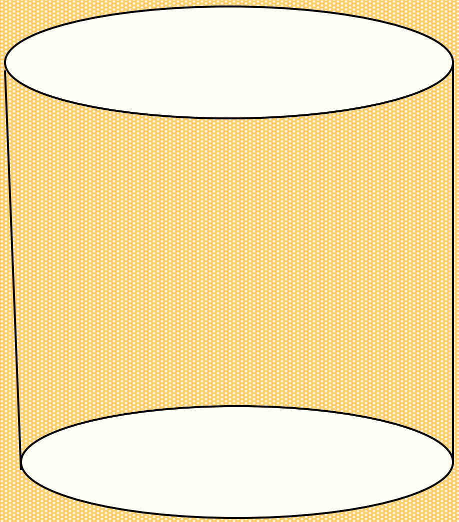
The next few slides attempt to give you a rough idea of how to formulate relativistic theories of point particles and of strings. I will discuss classical theories first and then quantum theories. These are the most technical slides in the talk. This will enable me to explain how string theories are better.

Crucial concepts for this purpose are the world-line of a point particle and the world-sheet of a string.

Point particle world-line



Closed string world-sheet



Classical Particle Dynamics

What is the trajectory that a point particle actually follows from a specified initial position to a specified final position?

Answer: the correct point-particle world-line for a particle of mass m is the one whose invariant length is a minimum. This is the principle of least action, where the action is

$$S = m\int ds$$

Classical String Dynamics

A string is characterized by a tension T rather than a mass m. For a specified initial string position and a specified final string position, what is the correct trajectory of the string?

Answer: the correct classical string world-sheet is the one for which the invariant area of the world-sheet is a minimum. The action is

$$S = T \int dA$$

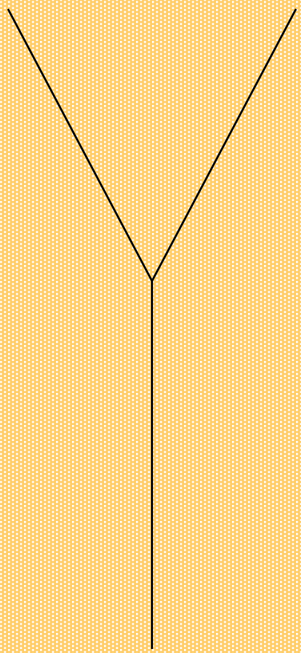
Quantum Dynamics

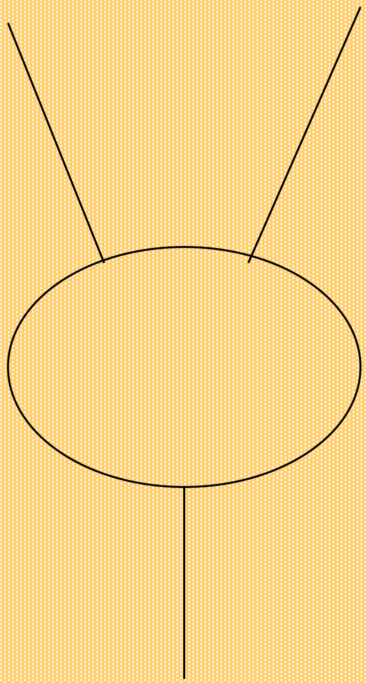
The quantum amplitude for a transition from a specified initial configuration to a specified final one is given by the sum of

$$\exp (i S/\hbar)$$

over all possible world lines (or world sheets) that connect them. Each distinct topology is characterized by a Feynman diagram. The contribution of each one is given by a finite-dimensional integral.

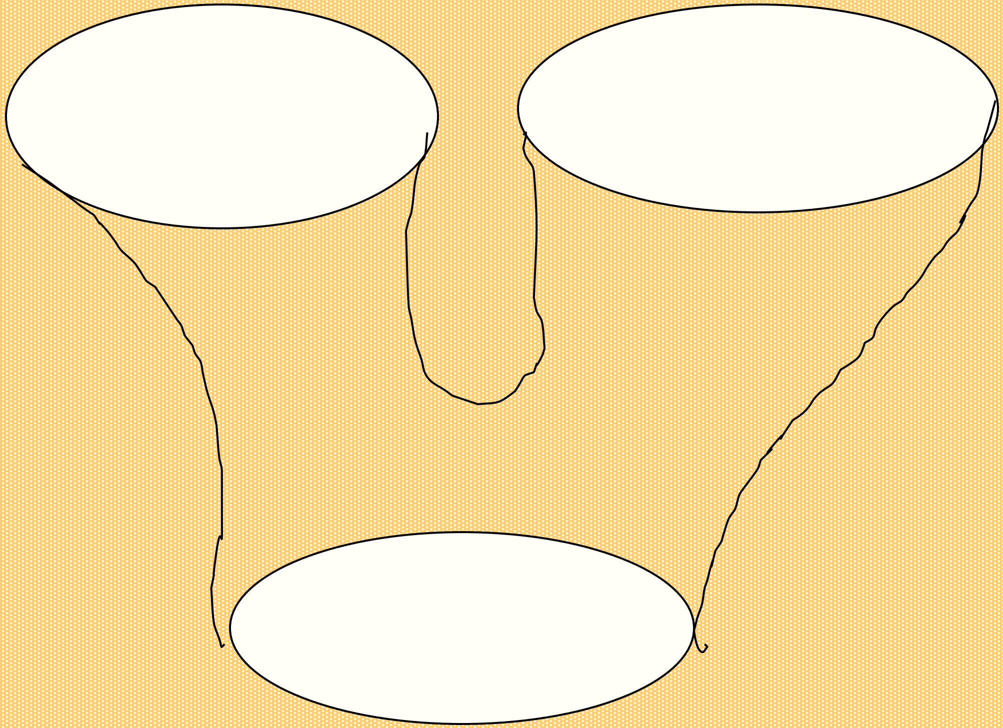
Quantum Particle Interactions





Feynman diagrams

Closed String Interaction



Upside-down pants diagram

Remarkable Facts

- Unlike point-particle Feynman diagrams, string world-sheets are smooth.
- As a consequence, string theories have no short-distance (UV) divergences.
- String interactions are uniquely determined by the topology of the world-sheet and the structure of the noninteracting string theory.

Problems of the Original String Theory

- Quantum mechanical consistency of the original string theory requires 26 dimensions (25 are spatial and 1 is time). This was completely unexpected – and certainly not what we wanted.
- This theory only describes bosons, whereas realistic physical theories always involve fermions as well.
- It also has an unstable vacuum.

Superstrings

A second string theory, containing fermions as well as bosons, was constructed in 1971 by Pierre Ramond, André Neveu, and me. It requires 10 dimensions (9 space and 1 time).

The development of this string theory led to the discovery of supersymmetry, a symmetry that relates bosons and fermions to one another. Strings in theories that have supersymmetry are usually called superstrings.

Both string theories – the 26d bosonic string theory and the 10d superstring theory -- have oscillation modes that correspond to massless particles.

This was another disturbing fact, since it was known that there are no massless hadrons. We tried for a few years to construct a string theory that describes only massive particles in 4d spacetime. All such attempts led to inconsistencies.

The Death of String Theory

In 1973 a theory of the strong nuclear force, called QCD (or quantum chromodynamics), was developed. It is a quantum field theory based on point particles (quarks and gluons).

It quickly became clear that QCD is correct, so string theory was abandoned by almost all of its practitioners. A community of several hundred was reduced to a handful of diehards.

II) String Theory for Unification

Before describing why string theory is good for unification, I will first describe briefly what we want to unify. These are

1) The Standard Model, which is a quantum field theory that combines QCD with the weak nuclear and electromagnetic forces.

and

2) General Relativity, which is Einstein's theory of gravity. It is a classical (not quantum) theory.

Standard Model of Particle Physics

- The Standard Model is a relativistic quantum field theory that combines QCD with a unified theory of the weak nuclear and electromagnetic forces. It is incredibly successful.
- The Standard Model describes properties and interactions of spin ½ quarks and leptons, spin 1 gauge particles, and spin 0 Higgs particles.
- Its main shortcoming is that it does not contain gravity. Also, it has many arbitrary features, for which we would like to find a deeper explanation.

Gravity

- General Relativity is a very successful and beautiful classical theory that describes gravity in terms of the geometry of spacetime. The geometry is characterized by a Riemannian metric, which is a symmetric matrix.

- When the metric is quantized, one learns that the gravitational force is mediated by a massless spin two particle, called a graviton.

Gravity in String Theory

- One of the massless particles in string theory, which is a mode of a closed string, has precisely the right properties (zero mass and spin two) to be the graviton, the particle that is responsible for the gravitational force.
- At low energies, the interactions of the string theory graviton agree with those of the graviton in General Relativity.
- One could say that ``String theory predicts the existence of gravity.''

Unification

The massless modes of open strings are spin one particles. At low energies they behave like the gauge particles that are responsible for the forces described by the Standard Model (electromagnetic, weak nuclear, strong nuclear).

In 1974 Joël Scherk and I proposed to use string theory for the unification of all forces (including gravity). Thus we stumbled upon a possible realization of "Einstein's dream."

The Size of Strings

When strings were supposed to describe hadrons their typical size needed to be

$$L \sim 10^{-13}\ \mathrm{cm}$$

To account for the observed strength of gravity the typical size should be the Planck length

$$L \sim [\ hG/c^3\ ]^{1/2} \sim 10^{-33}\ \mathrm{cm}$$

Smaller by 20 orders of magnitude!

Advantages of String Unification

1) Prior attempts to construct a quantum version of General Relativity had assumed point particles (quantum field theory). They all gave rise to infinite results that do not make sense (nonrenormalizable ultraviolet divergences).

By contrast, string theory is UV finite for the reasons that were explained earlier.

2) In a theory of gravity, such as General Relativity or string theory, the geometry of spacetime is determined by the dynamics.

When string theory is used to describe gravity, rather than the strong interactions, it makes sense to consider solutions of the string theory equations in which the extra dimensions form a compact space, such as a sphere or a torus or something more complicated.

Implications of Extra Dimensions

If the compact space is small enough, it is not observable at low energies. So space can appear to be three-dimensional. LHC experiments are searching for extra dimensions. My guess is that the LHC energy is insufficient.

Remarkably, the geometry of the invisible compact dimensions determines the types of particles and forces that occur in ordinary 4d spacetime – even at very low energies. So understanding this geometry is essential.

Supersymmetry

- It is the unique possibility for a nontrivial extension of the symmetry of spacetime implied by special relativity (the Poincaré group).
- It predicts that every particle has a supersymmetry partner. The partner of a boson is a fermion and vice versa.
- No partners of known particles have yet been discovered. The symmetry must be broken: in other words, a property of the equations but not of the solution.

The Case for Supersymmetry

- General feature of consistent string theories.
- Helps to explain the very small ratio between the energy scale of the weak force (100 GeV) and the Planck scale (10^{19} GeV).
- Allows for unification of forces at high energy.
- The lightest supersymmetry particle (LSP) provides a good candidate for dark matter, which is most of the mass in the Universe.

III) Superstring Revolutions

An important property of the Standard Model is parity violation (i.e., asymmetry under mirror reflection). Parity violation is difficult to reconcile with quantum mechanics, since inconsistencies, called anomalies, can arise.

For a long time it was unclear whether parity-violation is possible in string theory. In 1984 Michael Green and I discovered an anomaly cancellation mechanism that makes parity violation possible in superstring theory.

MBG and JHS – Aspen 1984

Superstring Resurrection

After more than a decade in the doldrums, string theory became a hot subject in the mid-1980s. The anomaly cancellation result convinced many theorists that superstring theory could give a deeper understanding of the Standard Model as part of a consistent quantum theory containing gravity.

A group of four Princeton theorists quickly discovered two new superstring theories. (Green and I had formulated three of them.)

Five Superstring Theories

Type I, Type IIA, Type IIB

***SO*(32) Heterotic** and ***E*8 x *E*8 Heterotic**

Each of these theories requires supersymmetry and ten dimensions and has no arbitrary parameters.

Calabi-Yau Compactification

Another group of four authors considered attaching a tiny 6d Calabi-Yau space, to every point in 4d spacetime. This solves the 10d equations and gives a parity-violating supersymmetric theory in ordinary 4d spacetime.

Starting with the *E8 x E8* Heterotic theory, and choosing the right CY space, one can obtain a 4d theory that is a supersymmetric extension of the Standard Model.

Dualities

Various remarkable equivalences, called dualities, were discovered in the 1980s and 1990s. They relate seemingly different theories, implying that they are actually the same theory!

For example, if a compact extra dimension is a circle of radius R, it can be equivalent to a circle of radius L^2/R, where L is the string length scale. This T duality relates the two Type II theories and the two Heterotic theories.

Stringy Geometry

T duality implies that strings “see’’ spacetime differently from point particles. A related duality, called mirror symmetry, identifies pairs of CY spaces in a similar way. Even the topologies of the mirror CY spaces are different in this case.

Strings see certain spacetime singularities and certain topology changing transitions of space as smooth and well-defined. This is a significant improvement on General Relativity.

Electric – Magnetic Symmetry

Maxwell's equations are symmetric under interchange of electric and magnetic charges and fields. This symmetry has a dramatic generalization in string theory called S duality. It relates a theory with interaction strength *g* to one with interaction strength $g' = 1/g$.

S duality relates the Type IIB theory to itself. It also relates the Type I theory and the SO(32) Heterotic theory. Thus, we understand the large g behavior of these three superstring theories.

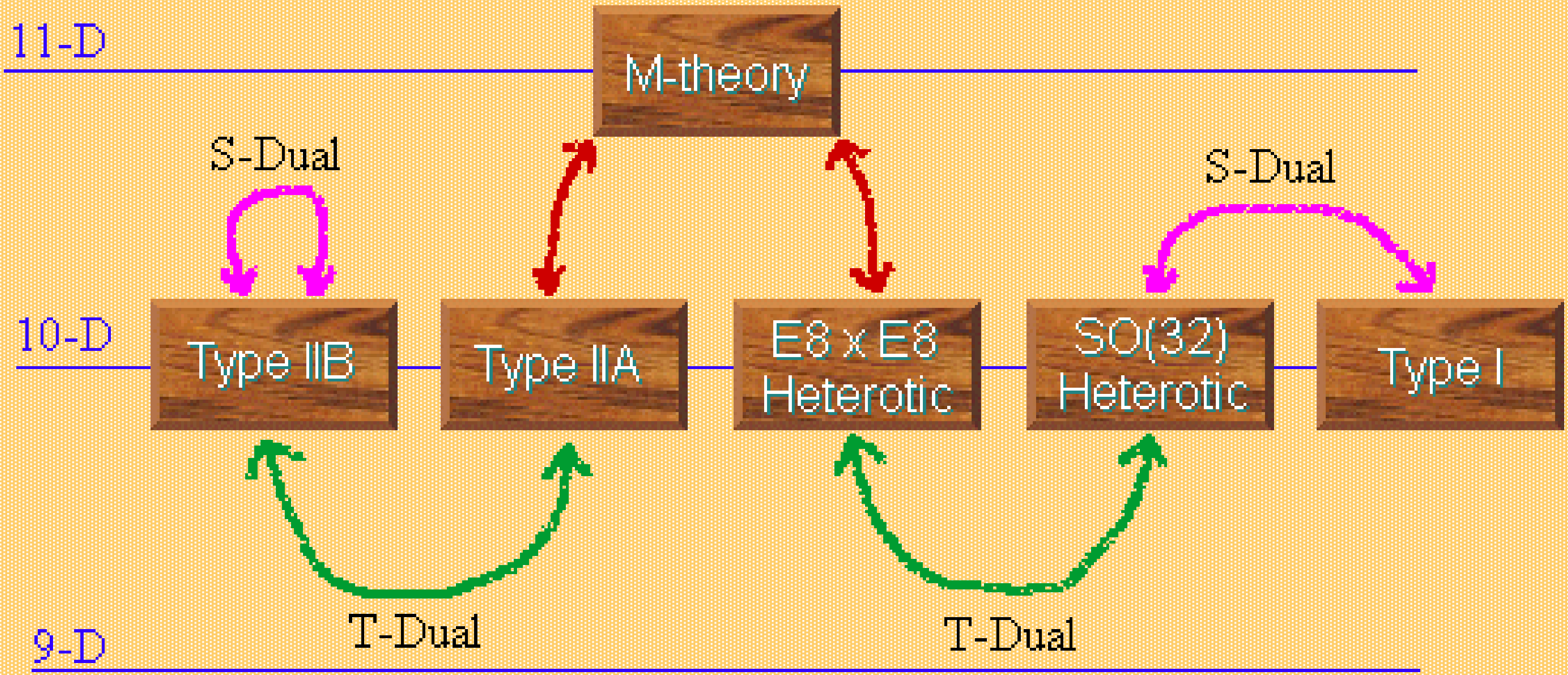
M-Theory

What happens to the Type IIA theory and the *E8 x E8* Heterotic theory when *g* becomes large? The answer was another big surprise:

They grow an eleventh dimension of size *gL*. This new dimension is a circle in the Type IIA case and a line interval in the *E8 x E8* case.

Taken together with the S and T dualities, this implies that there is a unique underlying theory.

There's just one theory!



Courtesy of John Pierre

Branes

In addition to fundamental strings, superstring theory and M-theory predict the existence of new stable objects, called p-branes. This is a made-up word meant to generalize the notion of a membrane.

p is the number of spatial dimensions that the brane occupies. For example, a point particle is a 0-brane and a string is a 1-brane. The stable branes of M-theory are a 2-brane and 5-brane.

Modeling Particle Physics

Many new approaches are now being explored:

- CY compactification of the E8 x E8 Heterotic theory extended to account for the 11th dimension
- CY compactification of type II theories with fluxes
- Nonperturbative type IIB constructions (called F-theory)
- Intersecting brane models
- Compactification of M-theory on 7-manifolds of G2 holonomy

AdS/CFT Duality

In 1997 Juan Maldacena discovered a new class of dualities (or equivalences). These relate string theory or M-theory in certain geometries (containing an Anti de Sitter space) to quantum field theories on the boundary of the AdS space.

The string theory or M-theory is represented holographically by the QFT. Since the QFT is conformally invariant (CFT), this is called an AdS/CFT duality. This is an enormous and fascinating subject, but I can only mention it here.

IV) Concluding Remarks

It appears likely that we have identified the unique theory that incorporates dynamical gravity in a consistent quantum theory.

However, this theory has an enormous number of solutions (the landscape) and we need to figure out which one describes our specific Universe. Some features are shared by all solutions and are therefore predictions. Others are shared by none (the swampland), which is also predictive. This will be discussed by Vafa.

String theory has evolved remarkably over the past 50 years. It is now unifying disciplines as well as forces and particles.

It will probably take many generations to answer all of our questions. Guided by experiment, new questions will arise. Even though this is a very ambitious project, the string theory community includes many very talented people, and it is making good progress.

Thank you for your attention.