STRING THEORY

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OUTLINE

I) Early History and Basic Concepts

II) String Theory for Unification

III) Superstrings

IV) Conclusion

I) Early History and Basic Concepts

String theory arose in the late 1960s in an attempt to understand the strong nuclear force. This is the force that holds protons and neutrons together inside the nucleus of an atom.

The strong nuclear force also hold quarks and gluons together inside the neutron and proton. Strongly interacting particles, such as the proton and neutron, are called hadrons.

A correct theory must incorporate the well-established principles of special relativity and quantum mechanics. A theory of this type, based on point-like particles, is called a quantum field theory.

In addition to the strong nuclear force, the other known fundamental forces are electromagnetism, the weak nuclear force, and gravity.

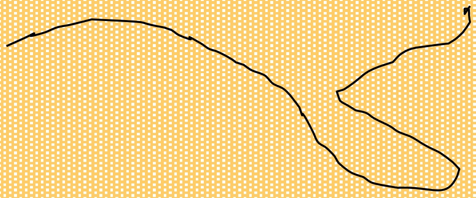
Strings are physical objects that are curves in space. They have energy density or tension, just as point particles have mass.

A theory based on strings can account for various features of the strong nuclear force such as the rich spectrum of hadrons and the high-energy behavior of interactions.

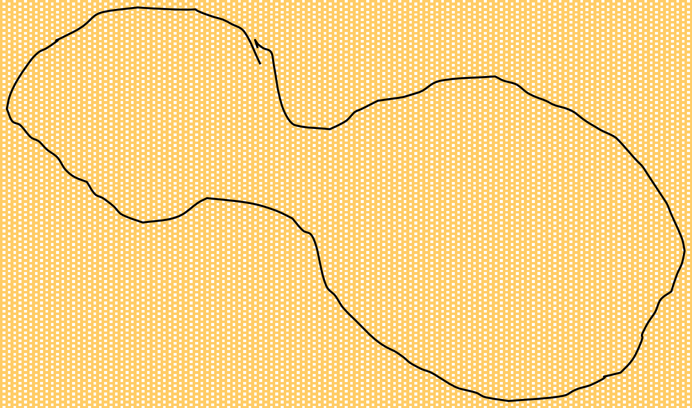
The first string theory was developed in the period 1968-70 by Gabriele Veneziano and hundreds of others.

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 dream was that this could give a unified understanding of the complicated spectrum of hadrons that was discovered in the 1960s.

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.

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 new type of symmetry that relates bosons and fermions. 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 every hadron has a positive mass. We tried for years to modify the string theories to describe 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.

QCD STRINGS?

There probably exists another string theory (not yet discovered) that is equivalent to QCD. It is expected to contain a strongly curved 4^{th} dimension of space that encodes the energy scale.

Such a reformulation of QCD would be very useful for computing properties of hadrons, so this is still an active research subject.

Summary of Part I

- String theory was developed to describe the strong nuclear force. This was unsuccessful because the string theories that were discovered require unrealistic extra dimensions of space and massless particles.

- The correct theory of the strong nuclear force (QCD) was discovered, so string theory was abandoned by all but a few diehards (including myself).

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 a spin 0 Higgs particle.
- 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).

Joël Scherk (1946-1980)

The Size of Strings

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

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

To account for the observed strength of gravity the natural size is the Planck length

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

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 ultraviolet finite.

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. Experiments at the LHC look for signs of 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 Partners

- The spin ½ quarks and leptons have spin 0 superpartners called squarks and sleptons.
- The spin 1 gauge particles and spin 0 Higgs particles have spin ½ superpartners called gauginos and Higgsinos. These consist of gluinos, neutralinos, and charginos.
- There is a good chance that the superpartner masses are low enough that some of them may be discovered at the LHC. There is no sign of them yet, however.


Large Hadron Collider
CMS
Large Hadron Collider
• Beams circulate 11,245 times/sec
• 100's of millions of collisions/second
• Collisions are a billion times hotter than the centre of the sun
• Create new particles (E = mc²)
CERN Computer Centre
CMS Centre @ CERN
Lucas Taylor, 2012
3

Summary of Part II

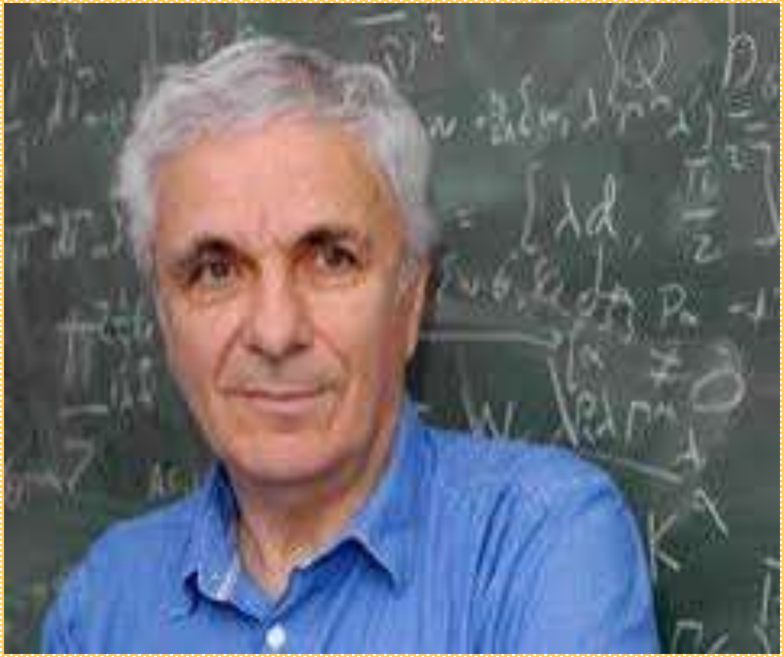
The goal of string theory was changed from describing the strong nuclear force to constructing a unified quantum theory combining the Standard Model and General Relativity. This converted the ``shortcomings'' of string theory (extra dimensions and massless particles) into major advantages.

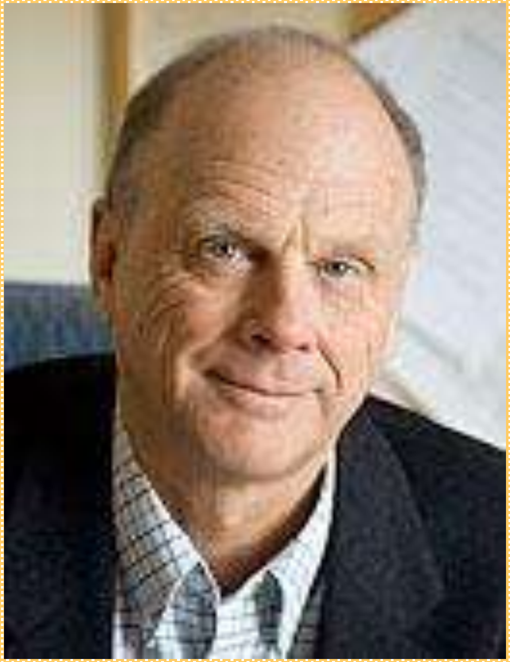
This was proposed in 1974, but it took ten more years to gain widespread acceptance.

III) Superstrings

- In 1979 I began a fruitful 6-year collaboration with Michael Green (then at the University of London). Michael is now the Lucasian Professor at the University of Cambridge.
- We spent each summer at the Aspen Center for Physics. At other times we worked together at Caltech or London.
- In some of our work we were joined by Lars Brink from Gothenburg, Sweden.

Michael Green and Lars Brink





Parity Violation and Anomalies

An important property of the weak nuclear force is parity violation, which is asymmetry under mirror reflection. Parity violation is difficult to reconcile with quantum mechanics, since it typically gives inconsistencies, called anomalies.

For a long time it was unclear whether parity violation is possible in string theory. Green and I struggled with this problem for a couple of years before we found the solution.

Anomaly Cancellation

In August 1984 (at the ACP) Green and I discovered an anomaly cancellation mechanism that makes parity violation possible in superstring theory. For a correct choice of symmetry the gravity and matter contributions to the anomalies cancel.

Out of the infinity of possible symmetries (classified by Lie groups) only two give the required cancellation:

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

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 five theories requires supersymmetry and ten dimensions and has no arbitrary dimensionless 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 equations and gives a parity-violating supersymmetric theory in the ordinary 4d spacetime.

Starting with the *E8 x E8* Heterotic theory, and choosing the right CY space, one can obtain a supersymmetric extension of the Standard Model containing gravity with many realistic features.

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.

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.

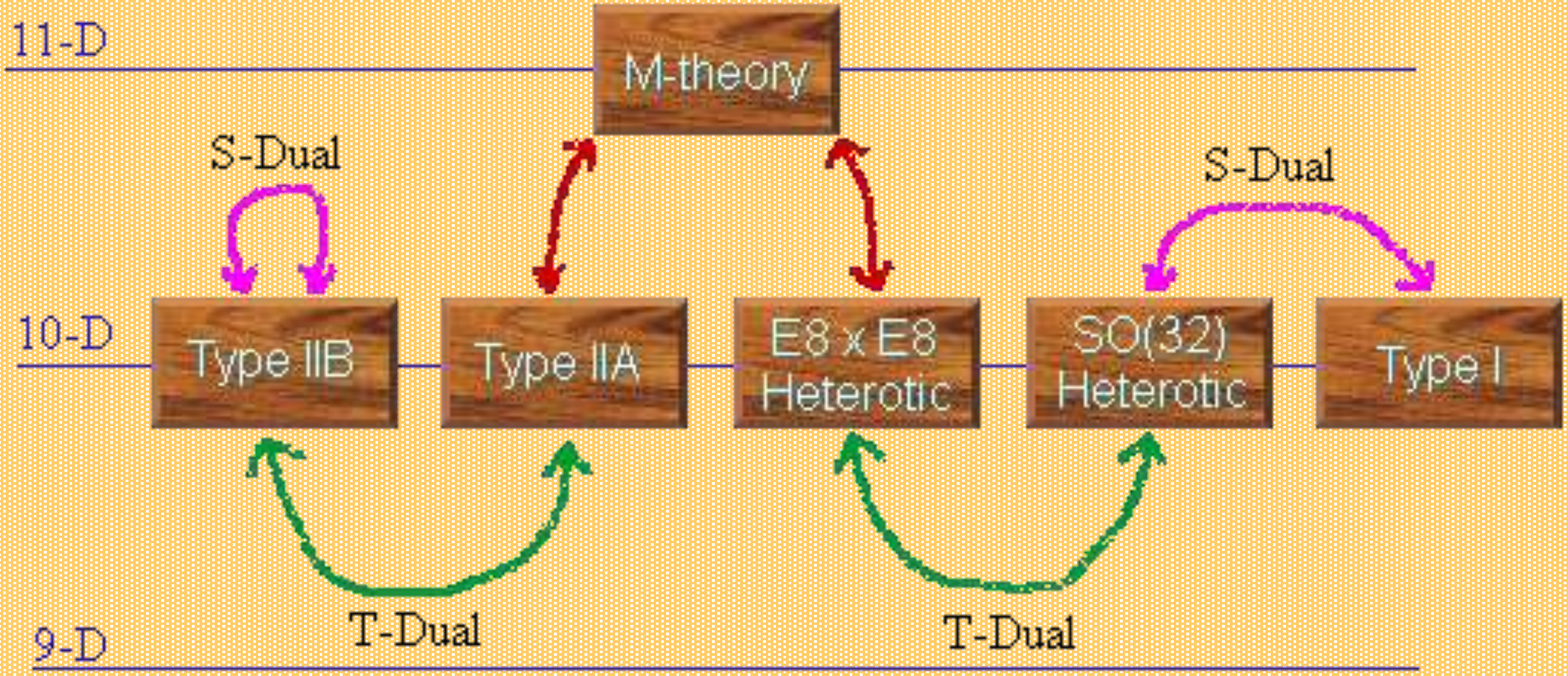
M-Theory

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

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 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.

Status of String Theory

For many years string theory was regarded as a radical and speculative alternative to QFT for describing quantum gravity and unification.

Following the discovery of AdS/CFT, it has become clear to me (and many others) that string theory is not radical at all. Rather, it is the inevitable framework for the logical completion of QFT. Of course, we remain eager to see more direct experimental evidence.

Many Challenges Remain

1. Develop the necessary mathematical techniques and concepts

2. Find a complete and compelling formulation of the theory

3. Understand empty space (including dark energy)

4. Explain elementary particle physics

5. Understand spacetime and quantum mechanics

6. Understand the origin and evolution of the Universe

7. Understand how the theory reconciles black holes with quantum mechanics

8. Apply string theory methods to other branches of physics

IV) Conclusion

String theory has evolved remarkably over the past 45 years. There is much current work applying its results and techniques to pure mathematics as well as to other areas of physics. These include black-hole physics, cosmology, nuclear physics, condensed matter physics, fluid dynamics, etc.

Thus, it is now unifying disciplines as well as forces and particles.

It will take very long to answer all of our remaining questions. Moreover, guided by experiment, new questions will arise. The good news is that the string theory community is making impressive progress.

THE END

A ``Theory of Everything''?

- The best we can hope for is a complete understanding of the microscopic laws of nature.
- This would probably be insufficient to explain the origin of the Universe.
- It would certainly not explain the innumerable quantum accidents that are responsible for the specific complex reality that we experience.

Thus, ``theory of everything'' is misleading. Moreover, many scientists find it offensive.