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From the standard model to M-theory: The development of string theory

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Abstract. String theory is now the most competitive theory of quantum gravity, and it takes an important role in theoretical physics. In this article, we introduced why we need string theory and how string theory is formed. The importance of string theory is described through general relativity and the Standard Model of particle physics. String theory is originally discovered to describe strong interaction. While a better model for strong interaction was developed, string theory was found to be a candidate for a theory about quantum gravity. The first version of string theory is the bosonic string theory, which was constructed in 26-dimensional space and used to describe bosons. After supersymmetry was introduced, the dimensions were reduced to 10, and the theory is hence called the superstring theory. In the first superstring revolution, 5 different superstring theories were constructed and compactified on the 6-dimensional Calabi-Yau manifold. In the second superstring revolution, the idea of different dualities was introduced in string, as well as D-branes. Hence, it was found that the 5 different superstrings can be unified to get the 11-dimensional M-theory.

Keywords: String Theory, Dual Models, Supersymmetry, M-Theory.

1. Introduction

String theory is very different from many other theories in physics. Usually, any formation of physical theories needs observations and experiments. We then find and build a model for our observations. This idea originated in the 16th century, followed by Galileo Galilei who is called the father of classical physics. This method was involved in every step of classical physics before the 19th century, the creation of general relativity. To find such a model, we need to find trends through different experiments. It usually takes dozens of years to complete a theory from any observations. However, the development of general relativity did not contain much experiment. It was built on mathematical models instead. Many predictions of general relativity have been proven. Such as the existence of black holes, which was predicted by a particular solution of Einstein field equations, the Schwarzschild singularity initially. Other predictions like the bending of light and gravitational redshift were also proven. The theory of general relativity is almost perfect in that it predicts everything from gravity. However, the theory cannot be quantized, which is another main topic in modern physics.

The development of general relativity helps the development of cosmology. Around the 1980s, the theory of cosmic inflation was proposed, and evidence of quantum fluctuation was found. However, the research on fluctuations might involve Planck scales. Hence it is needed to combine general relativity and quantum field theory. However, the theory of quantum gravity was not developed much in this

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period. The next topic in cosmology is black holes. The existence of black holes was predicted by general relativity. However, the study of black holes also needs statistical mechanics, which needs quantum mechanics. It was found that a black hole has a non-zero entropy that proportional to the area of the black hole horizon. That is, to study black hole entropy, a theory of quantum gravity is needed.

Known that quantum field theory is considered as a combination of quantum mechanics and field theory. Hence some proposed that we can combine quantum mechanics and gravitational fields since the theory of general relativity is also based on field theory. Which should be called the quantum gravitational field theory. However, when we are looking at quantum electrodynamics, the exchanging particles, photons, are not interacting with each other. This means that the electromagnetic forces are linear simply. However, for gravitational fields, gravitons will interact with each other which rejects this linearity and forms a closed loop that is difficult to calculate. Another version of quantum gravity is needed; hence string theory was founded to be a candidate of a theory of quantum gravity.

2. Before string theory

As we talk about string theory, we need to know the Standard Model of particles first. Before the Standard Model, we only understood electromagnetism through the finding of Maxwell's equations. One of the important findings in electrodynamics is that the total charge in a closed system is conserved. By Noether's Theorem, each conserved quantity corresponds to a symmetry. Hence, gauge symmetry was introduced here. After that, Pauli finds out that from the local gauge symmetry of the unitary group U (1), we can get Maxwell's equations directly. After this, the conservation of isotopic spin was found to correspond to the isotopic gauge invariance, that is the non-abelian gauge theory (Yang-Mills Theory), the fundamental theory of the Standard Model. After quarks were introduced, the SU (3) color symmetry of quarks was found to build a strong interaction. For weak interactions, the symmetry was found to be weak isospin SU (2) × hypercharge U (1) symmetry. Finally, color confinement and asymptotic freedom were introduced, and the Higgs mechanism was proposed to finalize the Standard Model. Higgs bosons were found in the Large Hadron Collider, which shows the success of the Standard Model.

The greatest problem encountered now is that gravity is not included in this model. It only contains three other forces in the 4 fundamental forces. Gravity was described by General Relativity, which is a theory at a very large scale. While the Standard Model describes objects on a very small scale. The inconsistency makes it hard to combine the 2 theories, hence physicists started to find a theory for quantum gravity.

To find the creation of string theory, we need to trace back to the 1970s, Italian physicist Gabriele Veneziano found that the Euler beta function describes the duality of a particle and its scattering amplitude like a string [1]. That is the creation of string theory. It was used to describe strong interactions at first but, was substituted by Quantum Chromodynamics at the end. However, during the research on quantum gravity, Japanese physicist Tamiaki Yoneya suggested that string theory can be used for quantum gravity, where the interaction of strings and be described using gauge symmetry [2].

3. Bosonic String Theory

After Veneziano, in 1969, Jack E. Paton and Hong-Mo Chan incorporate isospin into the model. That is to incorporate charges at endpoints of open strings, which enable gauge field to be added into string theory [3]. In 1971, Pierre Ramond, and John H. Schwarz introduced fermi fields to the theory [4]. In 1974, Tamiaki Yoneya, John H. Schwarz, and Joël Scherk found that the zero-slope limit is contained in the model as the graviton [5] [6]. Which is the beginning of bosonic string theory.

The bosonic string theory is the very first version of string theory, which is also the simplest version of strings within the framework of string theory. Why it is called the bosonic string theory is that it can only describe bosons, the force particles. The fermions, matter particles are inconsistent with the bosonic string theory. Bosonic string theory suggests that bosons are made of one-dimensional oscillating strings instead of particles. The strings are in Planck's length and Planck's mass. The oscillation of strings in spacetime gives a world sheet. We may quantize the string and find the area functional of the world sheet and its Nambu-Goto action. The strings have 2 basic topologies, open strings and closed strings. The endpoints of an open string are located on something called D-branes, and it can move freely on the plane. The close strings do not attach to the D-brane since they are like oscillating loops in free space. The central feature of bosonic strings is that they vibrate in various modes, much like the strings of a musical instrument. These vibrational patterns determine the mass and properties of the particles that the string represents. Different vibrational modes correspond to different particles, and the lowest energy modes of bosonic strings are interpreted as the gravitons (the particle for gravitation).

4. Supersymmetry and superstrings

In 1970, Ferdinando Gliozzi, Joël Scherk, and David I. Olive introduced GSO projection that gives supersymmetry to the model and reduced the dimension of the spacetime to 10 [7]. In 1980, Michael Green and John Schwarz defined the Lorentz-covariant superstring action with D=10 supersymmetry [8]. Hence, superstring theory was first introduced, which incorporated fermions and supersymmetry. Superstring theory is considered more promising as it includes more realistic descriptions of the universe and has been a major focus of research ever since. Supersymmetry suggests that every particle, either bosons or fermions, has an associated particle in the other class, which is called the superpartners. For example, an electron, which is a fermion, has a bosonic pair named selectron. They have the same mass but different spin numbers. In the simplest version of supersymmetry, every particle has its superpartner. While this symmetry might be broken from some complex version.

5. First superstring revolution

Here the first superstring revolution came. In 1984, Michael Green and John Schwarz discovered the anomaly cancelation in type I string theory with gauge group SO (32) [9]. In 1985, the Princeton string quartet (David Gross, Jeffrey Harvey, Emil Martinec, and Ryan Rohm) constructed the theory of heterotic strings [10]. In the same year, Philip Candelas, Gary Horowitz, Andrew Strominger, and Edward Witten published a paper about Calabi-Yau compactification [11]. Those are the three main events in the first superstring revolution. Anomaly is the breaking of a symmetry from the quantization of a classical theory which reduces the validity of the theory. Green-Schwarz found that in type I superstring theory, different anomalies would cancel with each other under the gauge group SO (32) by the Green-Schwarz mechanism. They also noticed that this anomaly cancelation also holds under gauge group E8 × E8, but they did not construct the theory. This discovery shows the existence of self-consistent superstring theory that is compatible with the Standard Model. The second event, the discovery of heterotic string theory, hybridized the bosonic strings and superstrings. It is found that with gauge groups SO (32) and E8 × E8, the theory is self-consistent. The third event talks about Calabi-Yau compactification. That is, we obtain a N=1, D=4 supersymmetry when the extra dimensions of type 1 superstrings and heterotic strings are compactified on a 6-dimensional Calabi-Yau manifold. Hence, the 10-dimensional superstring theory is reduced to a normal 4-dimensional spacetime and 6 compact dimensions. During this time, 5 self-consistent superstring theories were founded, which are type I, type IIA, type IIB, heterotic SO (32), and heterotic E8×E8. The unmentioned type II A and type II B superstring theory was developed from left-handed and right-handed GSO projections.

The first superstring revolution lasted 1 year, and many new concepts have been introduced. However, when the research got saturated, the development of string theory was stacked for a few years until the second superstring revolution.

6. Second superstring revolution

In 1984. Keiji Kikkawa and Masami Yamasaki found that there is a target space duality (or T-duality) in superstring theory [12]. This means the concept of space in string theory is not definite. Under T-duality, type II A superstring theory is equivalent to type II B superstring theory, and heterotic SO (32) is equivalent to heterotic E8×E8. S-duality (strong-weak duality) was also introduced in string theory by Ashoke Sen between open strings and closed strings [13]. In 1994, Seiberg and Witten published 2 papers about N=2 super Yang-Mills theory, which is now called the Seiberg-Witten theory [14] [15]. In 1995, Witten argued that 11-dimensional supergravity is the low energy limit of Type II superstring theory [16]. In the same year, Petr Hořava and Witten found the S-duality between SO (32) heterotic and Type I superstring theory, as well as the relation between E8 × E8 heterotic 11-dimensional theory [17]. Joseph Polchinski found that Dirichlet-branes (D-branes) play an important role in string theory [18]. Combine with the research from Andrew Strominger that different Calabi-Yau manifolds can be connected using D-3 branes, it was found that in strong coupling limit, the 5 different superstring theories can be unified as an 11-dimensional theory, that is the M-theory [19]. When M-theory was proposed, the properties behind it were not strictly defined, and hence it became a major topic in that year. Until the year 1997, it was founded by Juan Maldacena that the large N limit of certain conformal field theories describes supergravity on the product of Anti-de Sitter space with a compact manifold [20]. Such a theory is now called the AdS/CFT correspondence, which is still a major topic in string theory today. Anti-de Sitter space (AdS) is the solution space of the Einstein field equations that are equipped with negative constant curvature (hyperbolic), while Minkowski space is the solution space with zero curvature (Euclidean), and de Sitter space is the solution space with positive constant curvature (spherical). Conformal Field Theory (CFT) is a special type of quantum field theory that is invariant under scale transformations (dilations) or conformal transformations. Scale invariance means that the theory does not change no matter what scale we use and is included under conformal invariance. Conformal transformations are the transformations that preserve angles, which include scale transformations, Poincaré transformations, and special conformal transformations. Such correspondence originates from the observation that the boundary of AdS behaves the same as Minkowski space locally, which is a holographic duality between a n+1-dimensional space with gravity and a n-dimensional space without gravity.

7. Conclusion

In conclusion, string theory is a self-consistent theory that tries to describe QFT and general relativity in the same framework. A theory like this is necessary because we want to discuss some topic that involves gravity in Planck scales. For example, the information paradox for black holes, quantum fluctuations, and when we trace back to the Big Bang. String theory stands out to be the most competitive theory of quantum gravity. String theory began as a theory that was used to describe strong interaction but was substituted by field theory. When the need for a quantum gravity theory showed up, string theory was again founded as a candidate. The first version of string theory is called bosonic string theory since supersymmetry was not introduced at that time. It was built in a 26-dimensional space since the theory is only self-consistent in 26 dimensions for Lorentzian symmetry. When supersymmetry was found, superstrings were defined to be in 10-dimensional space, while the extra dimensions were eliminated by the supersymmetry. In the first superstring revolution, 5 independent, self-consistent theory was built. All these theories are anomaly free and can be compactified on a 6-dimensional Calabi-Yau manifold, which leaves a 4-dimensional spacetime. In the second superstring revolution, the idea of duality was founded in string theory. The 5 different superstring theories dual with each other in some pattern and can be unified into the 11-dimensional M-theory.

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