In physics, **string theory** is a theoretical framework in which the point-like particles of particle physics are replaced by one-dimensional objects called strings. It describes how these strings propagate through space and interact with each other. On distance scales larger than the string scale, a string looks just like an ordinary particle, with its mass, charge, and other properties determined by the vibrational state of the string. In string theory, one of the many vibrational states of the string corresponds to the graviton, a quantum mechanical particle that carries gravitational force. Thus, string theory is a theory of quantum gravity.

String theory is a broad and varied subject that attempts to address a number of deep questions of fundamental physics. String theory has been applied to a variety of problems in black hole physics, early universe cosmology, nuclear physics, and condensed matter physics, and it has stimulated a number of major developments in pure mathematics. Because string theory potentially provides a unified description of gravity and particle physics, it is a candidate for a theory of everything, a self-contained mathematical model that describes all fundamental forces and forms of matter. Despite much work on these problems, it is not known to what extent string theory describes the real world or how much freedom the theory allows in the choice of its details.

String theory was first studied in the late 1960s as a theory of the strong nuclear force, before being abandoned in favor of quantum chromodynamics. Subsequently, it was realized that the very properties that made string theory unsuitable as a theory of nuclear physics made it a promising candidate for a quantum theory of gravity. The earliest version of string theory, bosonic string theory, incorporated only the class of particles known as bosons. It later developed into superstring theory, which posits a connection called supersymmetry between bosons and the class of particles called fermions. Five consistent versions of superstring theory were developed before it was conjectured in the mid-1990s that they were all different limiting cases of a single theory in eleven dimensions known as M-theory. In late 1997, theorists discovered an important relationship called the AdS/CFT correspondence, which relates string theory to another type of physical theory called a quantum field theory.

One of the challenges of string theory is that the full theory does not have a satisfactory definition in all circumstances. Another issue is that the theory is thought to describe an enormous landscape of possible universes, and this has complicated efforts to develop theories of particle physics based on string theory. These issues have led some in the community to criticize these approaches to physics and question the value of continued research on string theory unification.
In the twentieth century, two theoretical frameworks emerged for formulating the laws of physics. The first is Albert Einstein's general theory of relativity, a theory that explains the force of gravity and the structure of space and time. The other is quantum mechanics which is a completely different formulation to describe physical phenomena using the known probability principles. By the late 1970s, these two frameworks had proven to be sufficient to explain most of the observed features of the universe, from elementary particles to atoms to the evolution of stars and the universe as a whole.[1]

In spite of these successes, there are still many problems that remain to be solved. One of the deepest problems in modern physics is the problem of quantum gravity.[1] The general theory of relativity is formulated within the framework of classical physics, whereas the other fundamental forces are described within the framework of quantum mechanics. A quantum theory of gravity is needed in order to reconcile general relativity with the principles of quantum mechanics, but difficulties arise when one attempts to apply the usual prescriptions of quantum theory to the force of gravity.[2] In addition to the problem of developing a consistent theory of quantum gravity, there are many other fundamental problems in the physics of atomic nuclei, black holes, and the early universe.[a]

String theory is a theoretical framework that attempts to address these questions and many others. The starting point for string theory is the idea that the point-like particles of particle physics can also be modeled as one-dimensional objects called strings. String theory describes how strings propagate through space and interact with each other. In a given version of string theory, there is only one kind of string, which may look like a small loop or segment of ordinary string, and it can vibrate in different ways. On distance scales
larger than the string scale, a string will look just like an ordinary particle, with its mass, charge, and other properties determined by the vibrational state of the string. In this way, all of the different elementary particles may be viewed as vibrating strings. In string theory, one of the vibrational states of the string gives rise to the graviton, a quantum mechanical particle that carries gravitational force. Thus string theory is a theory of quantum gravity.[3]

One of the main developments of the past several decades in string theory was the discovery of certain “dualities”, mathematical transformations that identify one physical theory with another. Physicists studying string theory have discovered a number of these dualities between different versions of string theory, and this has led to the conjecture that all consistent versions of string theory are subsumed in a single framework known as M-theory.[4]

Studies of string theory have also yielded a number of results on the nature of black holes and the gravitational interaction. There are certain paradoxes that arise when one attempts to understand the quantum aspects of black holes, and work on string theory has attempted to clarify these issues. In late 1997 this line of work culminated in the discovery of the anti-de Sitter/conformal field theory correspondence or AdS/CFT.[5] This is a theoretical result which relates string theory to other physical theories which are better understood theoretically. The AdS/CFT correspondence has implications for the study of black holes and quantum gravity, and it has been applied to other subjects, including nuclear[6] and condensed matter physics.[7][8]

Since string theory incorporates all of the fundamental interactions, including gravity, many physicists hope that it will eventually[9] fully describe our universe, making it a theory of everything. One of the goals of current research in string theory is to find a solution of the theory that reproduces the observed spectrum of elementary particles, with a small cosmological constant, containing dark matter and a plausible mechanism for cosmic inflation. While there has been progress toward these goals, it is not known to what extent string theory describes the real world or how much freedom the theory allows in the choice of details.[9]

One of the challenges of string theory is that the full theory does not have a satisfactory definition in all circumstances. The scattering of strings is most straightforwardly defined using the techniques of perturbation theory, but it is not known in general how to define string theory nonperturbatively.[10] It is also not clear whether there is any principle by which string theory selects its vacuum state, the physical state that determines the properties of our universe.[11] These problems have led some in the community to criticize these approaches to the unification of physics and question the value of continued research on these problems.[12]

### Strings

The application of quantum mechanics to physical objects such as the electromagnetic field, which are extended in space and time, is known as quantum field theory. In particle physics, quantum field theories form the basis for our understanding of elementary particles, which are modeled as excitations in the fundamental fields.[13]

In quantum field theory, one typically computes the probabilities of various physical events using the techniques of perturbation theory. Developed by Richard Feynman and others in the first half of the twentieth century, perturbative quantum field theory uses special diagrams called Feynman diagrams to organize computations. One imagines that these diagrams depict the paths of point-like particles and their interactions.[13]

The starting point for string theory is the idea that the point-like particles of quantum field theory can also be modeled as one-dimensional objects called strings.[14] The interaction of strings is most straightforwardly defined by generalizing the perturbation theory used in ordinary quantum field theory. At the level of Feynman diagrams, this means replacing the one-dimensional diagram representing the path of a point particle by a two-dimensional surface representing the motion of a string.[15] Unlike in quantum field theory, string theory does not have a full non-perturbative definition, so many of the theoretical questions that physicists would like to answer remain out of reach.[6]
In theories of particle physics based on string theory, the characteristic length scale of strings is assumed to be on the order of the Planck length, or $10^{-35}$ meters, the scale at which the effects of quantum gravity are believed to become significant.[15] On much larger length scales, such as the scales visible in physics laboratories, such objects would be indistinguishable from zero-dimensional point particles, and the vibrational state of the string would determine the type of particle. One of the vibrational states of a string corresponds to the graviton, a quantum mechanical particle that carries the gravitational force.[3]

The original version of string theory was bosonic string theory, but this version described only bosons, a class of particles which transmit forces between the matter particles, or fermions. Bosonic string theory was eventually superseded by theories called superstring theories. These theories describe both bosons and fermions, and they incorporate a theoretical idea called supersymmetry. This is a mathematical relation that exists in certain physical theories between the bosons and fermions. In theories with supersymmetry each boson has a counterpart which is a fermion, and vice versa.[17]

There are several versions of superstring theory: type I, type IIA, type IIB, and two flavors of heterotic string theory (SO(32) and $E_8 \times E_8$). The different theories allow different types of strings, and the particles that arise at low energies exhibit different symmetries. For example, the type I theory includes both open strings (which are segments with endpoints) and closed strings (which form closed loops), while types IIA, IIB and heterotic include only closed strings.[18]

Extra dimensions

In everyday life, there are three familiar dimensions of space: height, width and length. Einstein’s general theory of relativity treats time as a dimension on par with the three spatial dimensions; in general relativity, space and time are not modeled as separate entities but are instead unified to a four-dimensional spacetime. In this framework, the phenomenon of gravity is viewed as a consequence of the geometry of spacetime.[19]

In spite of the fact that the universe is well described by four-dimensional spacetime, there are several reasons why physicists consider theories in other dimensions. In some cases, by modeling spacetime in a different number of dimensions, a theory becomes more mathematically tractable, and one can perform calculations and gain general insights more easily.[b] There are also situations where theories in two or three spacetime dimensions are useful for describing phenomena in condensed matter physics.[20] Finally, there exist scenarios in which there could actually be more than four dimensions of spacetime which have nonetheless managed to escape detection.[21]

One notable feature of string theories is that these theories require extra dimensions of spacetime for their mathematical consistency. In bosonic string theory, spacetime is 26-dimensional, while in superstring theory it is 10-dimensional, and in M-theory it is 11-dimensional. In order to describe real physical phenomena using string theory, one must therefore imagine scenarios in which these extra dimensions would not be observed in experiments.[22]

Compactification is one way of modifying the number of dimensions in a physical theory. In compactification, some of the extra dimensions are assumed to "close up" on themselves to form circles.[23] In the limit where these curled up dimensions become very small, one obtains a theory in which spacetime has effectively a lower number of dimensions. A standard analogy for this is to consider a multidimensional object such as a garden hose. If the hose is viewed from a sufficient distance, it appears to have only one dimension, its length. However, as one approaches the hose, one discovers that it contains a second dimension, its circumference. Thus, an ant crawling on the surface of the hose would move in two dimensions.[4]

Compactification can be used to construct models in which spacetime is effectively four-dimensional. However, not every way of compactifying the extra dimensions produces a model with the right properties to describe nature. In a viable model of particle physics, the compact extra dimensions must be shaped like a Calabi–Yau manifold.[23] A Calabi–Yau manifold is a special space which is typically taken to be six-dimensional in applications to string theory. It is named after mathematicians Eugenio Calabi and Shing-Tung Yau.[25]
Another approach to reducing the number of dimensions is the so-called brane-world scenario. In this approach, physicists assume that the observable universe is a four-dimensional subspace of a higher dimensional space. In such models, the force-carrying bosons of particle physics arise from open strings with endpoints attached to the four-dimensional subspace, while gravity arises from closed strings propagating through the larger ambient space. This idea plays an important role in attempts to develop models of real world physics based on string theory, and it provides a natural explanation for the weakness of gravity compared to the other fundamental forces.[26]

### Dualities

One notable fact about string theory is that the different versions of the theory all turn out to be related in highly nontrivial ways. One of the relationships that can exist between different string theories is called S-duality. This is a relationship which says that a collection of strongly interacting particles in one theory can, in some cases, be viewed as a collection of weakly interacting particles in a completely different theory. Roughly speaking, a collection of particles is said to be strongly interacting if they combine and decay often and weakly interacting if they do so infrequently. Type I string theory turns out to be equivalent by S-duality to the $SO(32)$ heterotic string theory. Similarly, type IIB string theory is related to itself in a nontrivial way by S-duality.[27]

Another relationship between different string theories is T-duality. Here one considers strings propagating around a circular extra dimension. T-duality states that a string propagating around a circle of radius $R$ is equivalent to a string propagating around a circle of radius $1/R$ in the sense that all observable quantities in one description are identified with quantities in the dual description. For example, a string has momentum as it propagates around a circle, and it can also wind around the circle one or more times. The number of times the string winds around a circle is called the winding number. If a string has momentum $p$ and winding number $n$ in one description, it will have momentum $n$ and winding number $p$ in the dual description. For example, type IIA string theory is equivalent to type IIB string theory via T-duality, and the two versions of heterotic string theory are also related by T-duality.[27]

In general, the term duality refers to a situation where two seemingly different physical systems turn out to be equivalent in a nontrivial way. Two theories related by a duality need not be string theories. For example, Montonen–Olive duality is example of an S-duality relationship between quantum field theories. The AdS/CFT correspondence is example of a duality which relates string theory to a quantum field theory. If two theories are related by a duality, it means that one theory can be transformed in some way so that it ends up looking just like the other theory. The two theories are then said to be dual to one another under the transformation. Put differently, the two theories are mathematically different descriptions of the same phenomena.[28]

### Branes

In string theory and other related theories, a brane is a physical object that generalizes the notion of a point particle to higher dimensions. For instance, a point particle can be viewed as a brane of dimension zero, while a string can be viewed as a brane of dimension one. It is also possible to consider higher-dimensional branes. In dimension $p$, these are called $p$-branes. The word brane
comes from the word “membrane” which refers to a two-dimensional brane.\[29\]

Branes are dynamical objects which can propagate through spacetime according to the rules of quantum mechanics. They have mass and can have other attributes such as charge. A p-brane sweeps out a \((p+1)\)-dimensional volume in spacetime called its worldvolume. Physicists often study fields analogous to the electromagnetic field which live on the worldvolume of a brane.\[29\]

In string theory, D-branes are an important class of branes that arise when one considers open strings. As an open string propagates through spacetime, its endpoints are required to lie on a D-brane. The letter “D” in D-brane refers to a certain mathematical condition on the system known as the Dirichlet boundary condition. The study of D-branes in string theory has led to important results such as the AdS/CFT correspondence, which has shed light on many problems in quantum field theory.\[30\]

Branes are frequently studied from a purely mathematical point of view, and they are described as objects of certain categories, such as the derived category of coherent sheaves on a complex algebraic variety or the Fukaya category of a symplectic manifold.\[31\] The connection between the physical notion of a brane and the mathematical notion of a category has led to important mathematical insights in the fields of algebraic and symplectic geometry and representation theory.\[32\][33]

**M-theory**

Prior to 1995, theorists believed that there were five consistent versions of superstring theory (type I, type IIA, type IIB, and two versions of heterotic string theory). This understanding changed in 1995 when Edward Witten suggested that the five theories were just special limiting cases of an eleven-dimensional theory called M-theory. Witten’s conjecture was based on the work of a number of other physicists, including Ashoke Sen, Chris Hull, Paul Townsend, and Michael Duff. His announcement led to a flurry of research activity now known as the second superstring revolution.\[34\]

**Unification of superstring theories**

In the 1970s, many physicists became interested in supergravity theories, which combine general relativity with supersymmetry. Whereas general relativity makes sense in any number of dimensions, supergravity places an upper limit on the number of dimensions.\[35\] In 1978, work by Werner Nahm showed that the maximum spacetime dimension in which one can formulate a consistent supersymmetric theory is eleven.\[36\] In the same year, Eugene Cremmer, Bernard Julia, and Joel Scherk of the École Normale Supérieure showed that supergravity not only permits up to eleven dimensions but is in fact most elegant in this maximal number of dimensions.\[37\][38]

Initially, many physicists hoped that by compactifying eleven-dimensional supergravity, it might be possible to construct realistic models of our four-dimensional world. The hope was that such models would provide a unified description of the four fundamental forces of nature: electromagnetism, the strong and weak nuclear forces, and gravity. Interest in eleven-dimensional supergravity soon waned as various flaws in this scheme were discovered.

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One of the problems was that the laws of physics appear to distinguish between clockwise and counterclockwise, a phenomenon known as chirality. Edward Witten and others observed this chirality property cannot be readily derived by compactifying from eleven dimensions.[38]

In the first superstring revolution in 1984, many physicists turned to string theory as a unified theory of particle physics and quantum gravity. Unlike supergravity theory, string theory was able to accommodate the chirality of the standard model, and it provided a theory of gravity consistent with quantum effects.[38] Another feature of string theory that many physicists were drawn to in the 1980s and 1990s was its high degree of uniqueness. In ordinary particle theories, one can consider any collection of elementary particles whose classical behavior is described by an arbitrary Lagrangian. In string theory, the possibilities are much more constrained: by the 1990s, physicists had agreed that there were only five consistent supersymmetric versions of the theory.[38]

Although there were only a handful of consistent superstring theories, it remained a mystery why there was not just one consistent formulation.[38] However, as physicists began to examine string theory more closely, they realized that these theories are related in intricate and nontrivial ways. They found that a system of strongly interacting strings can, in some cases, be viewed as a system of weakly interacting strings. This phenomenon is known as S-duality. It was studied by Ashoke Sen in the context of heterotic strings in four dimensions[39][40] and by Chris Hull and Paul Townsend in the context of the type IIB theory.[41] Theorists also found that different string theories may be related by T-duality. This duality implies that strings propagating on completely different spacetime geometries may be physically equivalent.[42]

At around the same time, as many physicists were studying the properties of strings, a small group of physicists was examining the possible applications of higher dimensional objects. In 1987, Eric Bergshoeff, Ergin Sezgin, and Paul Townsend showed that eleven-dimensional supergravity includes two-dimensional branes.[43] Intuitively, these objects look like sheets or membranes propagating through the eleven-dimensional spacetime. Shortly after this discovery, Michael Duff, Paul Howe, Takeo Inami, and Kellogg Stelle considered a particular compactification of eleven-dimensional supergravity with one of the dimensions curled up into a circle.[44] In this setting, one can imagine the membrane wrapping around the circular dimension. If the radius of the circle is sufficiently small, then this membrane looks just like a string in ten-dimensional spacetime. In fact, Duff and his collaborators showed that this construction reproduces exactly the strings appearing in type IIA superstring theory.[45]

Speaking at a string theory conference in 1995, Edward Witten made the surprising suggestion that all five superstring theories were in fact just different limiting cases of a single theory in eleven spacetime dimensions. Witten’s announcement drew together all of the previous results on S- and T-duality and the appearance of higher dimensional branes in string theory.[46] In the months following Witten’s announcement, hundreds of new papers appeared on the Internet confirming different parts of his proposal.[47] Today this flurry of work is known as the second superstring revolution.[46]

Initially, some physicists suggested that the new theory was a fundamental theory of membranes, but Witten was skeptical of the role of membranes in the theory. In a paper from 1996, Hořava and Witten wrote “As it has been proposed that the eleven-dimensional theory is a supermembrane theory but there are some reasons to doubt that interpretation, we will non-committally call it the M-theory, leaving to the future the relation of M to membranes.”[49] In the absence of an understanding of the true meaning and structure of M-theory, Witten has suggested that the M should stand for “magic”, “mystery”, or “membrane” according to taste, and the true meaning of the title should be decided when a more fundamental formulation of the theory is known.[49]

**Matrix theory**

In mathematics, a matrix is a rectangular array of numbers or other data. In physics, a matrix model is a particular kind of physical theory whose mathematical formulation involves the notion of a matrix in an important way. A matrix model describes the behavior of a set of matrices within the framework of quantum mechanics.[51]

One important example of a matrix model is the BFSS matrix model proposed by Tom Banks, Willy Fischler, Stephen Shenker, and Leonard Susskind in 1997. This theory describes the behavior of a set of nine large matrices. In their original paper, these authors showed, among other things, that the low energy limit of this matrix model is described by eleven-dimensional supergravity. These
calculations led them to propose that the BFSS matrix model is exactly equivalent to M-theory. The BFSS matrix model can therefore be used as a prototype for a correct formulation of M-theory and a tool for investigating the properties of M-theory in a relatively simple setting.\[^{51}\]

The development of the matrix model formulation of M-theory has led physicists to consider various connections between string theory and a branch of mathematics called noncommutative geometry. This subject is a generalization of ordinary geometry in which mathematicians define new geometric notions using tools from noncommutative algebra.\[^{52}\] In a paper from 1998, Alain Connes, Michael R. Douglas, and Albert Schwarz showed that some aspects of matrix models and M-theory are described by a noncommutative quantum field theory, a special kind of physical theory in which spacetime is described mathematically using noncommutative geometry.\[^{53}\] This established a link between matrix models and M-theory on the one hand, and noncommutative geometry on the other hand. It quickly led to the discovery of other important links between noncommutative geometry and various physical theories.\[^{54}\][\(^{55}\)]

## Black holes

In general relativity, a black hole is defined as a region of spacetime in which the gravitational field is so strong that no particle or radiation can escape. In the currently accepted models of stellar evolution, black holes are thought to arise when massive stars undergo gravitational collapse, and many galaxies are thought to contain supermassive black holes at their centers. Black holes are also important for theoretical reasons, as they present profound challenges for theorists attempting to understand the quantum aspects of gravity. String theory has proved to be an important tool for investigating the theoretical properties of black holes because it provides a framework in which theorists can study their thermodynamics.\[^{56}\]

### Bekenstein–Hawking formula

In the branch of physics called statistical mechanics, entropy is a measure of the randomness or disorder of a physical system. This concept was studied in the 1870s by the Austrian physicist Ludwig Boltzmann who showed that the thermodynamic properties of a gas could be derived from the combined properties of its many constituent molecules. Boltzmann argued that by averaging the behaviors of all the different molecules in a gas, one can understand macroscopic properties such as volume, temperature, and pressure. In addition, this perspective led him to give a precise definition of entropy as the natural logarithm of the number of different states of the molecules (also called microstates) that give rise to the same macroscopic features.\[^{57}\]

In the twentieth century, physicists began to apply the same concepts to black holes. In most systems such as gases, the entropy scale with the volume. In the 1970s, the physicist Jacob Bekenstein suggested that the entropy of a black hole is instead proportional to the surface area of its event horizon, the boundary beyond which matter and radiation is lost to its gravitational attraction.\[^{58}\] When combined with ideas of the physicist Stephen Hawking,\[^{59}\] Bekenstein's work yielded a precise formula for the entropy of a black hole. The Bekenstein–Hawking formula expresses the entropy $S$ as

$$S = \frac{c^3 k A}{4 \hbar G}$$

where $c$ is the speed of light, $k$ is Boltzmann’s constant, $\hbar$ is the reduced Planck constant, $G$ is Newton’s constant, and $A$ is the surface area of the event horizon.\[^{60}\]

Like any physical system, a black hole has an entropy defined in terms of the number of different microstates that lead to the same macroscopic features. The Bekenstein–Hawking entropy formula gives the expected value of the entropy of a black hole, but by the 1990s, physicists still lacked a derivation of this formula by counting microstates in a theory of quantum gravity. Finding such a derivation of this formula was considered an important test of the viability of any theory of quantum gravity such as string theory.\[^{61}\]

### Derivation within string theory
In a paper from 1996, Andrew Strominger and Cumrun Vafa showed how to derive the Beckenstein–Hawking formula for certain black holes in string theory. Their calculation was based on the observation that D-branes—which look like fluctuating membranes when they are weakly interacting—become dense, massive objects with event horizons when the interactions are strong. In other words, a system of strongly interacting D-branes in string theory is indistinguishable from a black hole. Strominger and Vafa analyzed such D-brane systems and calculated the number of different ways of placing D-branes in spacetime so that their combined mass and charge is equal to a given mass and charge for the resulting black hole. Their calculation reproduced the Bekenstein–Hawking formula exactly, including the factor of $1/4$.

Their calculation was based on the observation that D-branes—which look like fluctuating membranes when they are weakly interacting—become dense, massive objects with event horizons when the interactions are strong. These are defined as black holes with the lowest possible mass compatible with a given charge. Strominger and Vafa also restricted attention to black holes in five-dimensional spacetime with unphysical supersymmetry.

Although it was originally developed in this very particular and physically unrealistic context in string theory, the entropy calculation of Strominger and Vafa has led to a qualitative understanding of how black hole entropy can be accounted for in any theory of quantum gravity. Indeed, in 1998, Strominger argued that the original result could be generalized to an arbitrary consistent theory of quantum gravity without relying on strings or supersymmetry. In collaboration with several other authors in 2010, he showed that some results on black hole entropy could be extended to non-extremal astrophysical black holes.

**AdS/CFT correspondence**

One approach to formulating string theory and studying its properties is provided by the anti-de Sitter/conformal field theory (AdS/CFT) correspondence. This is a theoretical result which implies that string theory is in some cases equivalent to a quantum field theory. In addition to providing insights into the mathematical structure of string theory, the AdS/CFT correspondence has shed light on many aspects of quantum field theory in regimes where traditional calculational techniques are ineffective. The AdS/CFT correspondence was first proposed by Juan Maldacena in late 1997. Important aspects of the correspondence were elaborated in articles by Steven Gubser, Igor Klebanov, and Alexander Markovich Polyakov, and by Edward Witten. By 2010, Maldacena's article had over 7000 citations, becoming the most highly cited article in the field of high energy physics.

**Overview of the correspondence**

In the AdS/CFT correspondence, the geometry of spacetime is described in terms of a certain vacuum solution of Einstein's equation called anti-de Sitter space. In very elementary terms, anti-de Sitter space is a mathematical model of spacetime in which the notion of distance between points (the metric) is different from the notion of distance in ordinary Euclidean geometry. It is closely related to hyperbolic space, which can be viewed as a disk as illustrated on the left. This image shows a tessellation of a disk by triangles and squares. One can define the distance between points of this disk in such a way that all the triangles and squares are the same size and the circular outer boundary is infinitely far from any point in the interior.

One can imagine a stack of hyperbolic disks where each disk represents the state of the universe at a given time. The resulting geometric object is three-dimensional anti-de Sitter space. It looks like a solid cylinder in which any cross section is a copy of the hyperbolic disk. Time runs along the vertical direction in this picture. The surface of this cylinder plays an important role in the AdS/CFT correspondence.

As with the hyperbolic plane, anti-de Sitter space is curved in such a way that any point in the interior is actually infinitely far from this boundary surface.
This construction describes a hypothetical universe with only two space dimensions and one time dimension, but it can be generalized to any number of dimensions. Indeed, hyperbolic space can have more than two dimensions and one can "stack up" copies of hyperbolic space to get higher-dimensional models of anti-de Sitter space. An important feature of anti-de Sitter space is its boundary (which looks like a cylinder in the case of three-dimensional anti-de Sitter space). One property of this boundary is that, within a small region on the surface around any given point, it looks just like Minkowski space, the model of spacetime used in nongravitational physics. One can therefore consider an auxiliary theory in which "spacetime" is given by the boundary of anti-de Sitter space. This observation is the starting point for AdS/CFT correspondence, which states that the boundary of anti-de Sitter space can be regarded as the "spacetime" for a quantum field theory. The claim is that this quantum field theory is equivalent to a gravitational theory, such as string theory, in the bulk anti-de Sitter space in the sense that there is a "dictionary" for translating entities and calculations in one theory into their counterparts in the other theory. For example, a single particle in the gravitational theory might correspond to some collection of particles in the boundary theory. In addition, the predictions in the two theories are quantitatively identical so that if two particles have a 40 percent chance of colliding in the gravitational theory, then the corresponding collections in the boundary theory would also have a 40 percent chance of colliding.

The AdS/CFT correspondence was a major advance in physicists' understanding of string theory and quantum gravity. One reason for this is that the correspondence provides a formulation of string theory in terms of quantum field theory, which is well understood by comparison. Another reason is that it provides a general framework in which physicists can study and attempt to resolve the paradoxes of black holes.

In 1975, Stephen Hawking published a calculation which suggested that black holes are not completely black but emit a dim radiation due to quantum effects near the event horizon. At first, Hawking's result posed a problem for theorists because it suggested that black holes destroy information. More precisely, Hawking's calculation seemed to conflict with one of the basic postulates of quantum mechanics which states that physical systems evolve in time according to the Schrödinger equation. This property is usually referred to as unitarity of time evolution. The apparent contradiction between Hawking's calculation and the unitarity postulate of quantum mechanics came to be known as the black hole information paradox.

The AdS/CFT correspondence resolves the black hole information paradox, at least to some extent, because it shows how a black hole can evolve in a manner consistent with quantum mechanics in some contexts. Indeed, one can consider black holes in the context of the AdS/CFT correspondence, and any such black hole corresponds to a configuration of particles on the boundary of anti-de Sitter space. These particles obey the usual rules of quantum mechanics and in particular evolve in a unitary fashion, so the black hole must also evolve in a unitary fashion, respecting the principles of quantum mechanics. In 2005, Hawking announced that the paradox had been settled in favor of information conservation by the AdS/CFT correspondence, and he suggested a concrete mechanism by which black holes might preserve information.

Applications to quantum gravity

The discovery of the AdS/CFT correspondence was a major advance in physicists' understanding of string theory and quantum gravity. One reason for this is that the correspondence provides a formulation of string theory in terms of quantum field theory, which is well understood by comparison. Another reason is that it provides a general framework in which physicists can study and attempt to resolve the paradoxes of black holes. In 1975, Stephen Hawking published a calculation which suggested that black holes are not completely black but emit a dim radiation due to quantum effects near the event horizon. At first, Hawking's result posed a problem for theorists because it suggested that black holes destroy information. More precisely, Hawking's calculation seemed to conflict with one of the basic postulates of quantum mechanics which states that physical systems evolve in time according to the Schrödinger equation. This property is usually referred to as unitarity of time evolution. The apparent contradiction between Hawking's calculation and the unitarity postulate of quantum mechanics came to be known as the black hole information paradox.

The AdS/CFT correspondence resolves the black hole information paradox, at least to some extent, because it shows how a black hole can evolve in a manner consistent with quantum mechanics in some contexts. Indeed, one can consider black holes in the context of the AdS/CFT correspondence, and any such black hole corresponds to a configuration of particles on the boundary of anti-de Sitter space. These particles obey the usual rules of quantum mechanics and in particular evolve in a unitary fashion, so the black hole must also evolve in a unitary fashion, respecting the principles of quantum mechanics. In 2005, Hawking announced that the paradox had been settled in favor of information conservation by the AdS/CFT correspondence, and he suggested a concrete mechanism by which black holes might preserve information.
In addition to its applications to theoretical problems in quantum gravity, the AdS/CFT correspondence has been applied to a variety of problems in quantum field theory. One physical system that has been studied using the AdS/CFT correspondence is the quark–gluon plasma, an exotic state of matter produced in particle accelerators. This state of matter arises for brief instants when heavy ions such as gold or lead nuclei are collided at high energies. Such collisions cause the quarks that make up atomic nuclei to deconfine at temperatures of approximately two trillion kelvins, conditions similar to those present at around $10^{-11}$ seconds after the Big Bang.\[^{[83]}\]

The physics of the quark–gluon plasma is governed by a theory called quantum chromodynamics, but this theory is mathematically intractable in problems involving the quark–gluon plasma.\[^{[d]}\] In an article appearing in 2005, Đam Thanh Sơn and his collaborators showed that the AdS/CFT correspondence could be used to understand some aspects of the quark–gluon plasma by describing it in the language of string theory.\[^{[84]}\] By applying the AdS/CFT correspondence, Sơn and his collaborators were able to describe the quark–gluon plasma in terms of black holes in five-dimensional spacetime. The calculation showed that the ratio of two quantities associated with the quark–gluon plasma, the shear viscosity and volume density of entropy, should be approximately equal to a certain universal constant. In 2008, the predicted value of this ratio for the quark–gluon plasma was confirmed at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory.\[^{[85] [86]}\]

**Applications to condensed matter physics**

The AdS/CFT correspondence has also been used to study aspects of condensed matter physics. Over the decades, experimental condensed matter physicists have discovered a number of exotic states of matter, including superconductors and superfluids. These states are described using the formalism of quantum field theory, but some phenomena are difficult to explain using standard field theoretic techniques. Some condensed matter theorists including Subir Sachdev hope that the AdS/CFT correspondence will make it possible to describe these systems in the language of string theory and learn more about their behavior.\[^{[85]}\]

So far some success has been achieved in using string theory methods to describe the transition of a superfluid to an insulator. A superfluid is a system of electrically neutral atoms that flows without any friction. Such systems are often produced in the laboratory using liquid helium, but recently experimentalists have developed new ways of producing artificial superfluids by pouring trillions of cold atoms into a lattice of criss-crossing lasers. These atoms initially behave as a superfluid, but as experimentalists increase the intensity of the lasers, they become less mobile and then suddenly transition to an insulating state. During the transition, the atoms behave in an unusual way. For example, the atoms slow to a halt at a rate that depends on the temperature and on Planck’s constant, the fundamental parameter of quantum mechanics, which does not enter into the description of the other phases. This behavior has recently been understood by considering a dual description where properties of the fluid are described in terms of a higher dimensional black hole.\[^{[87]}\]

**Phenomenology**

In addition to being an idea of considerable theoretical interest, string theory provides a framework for constructing models of real world physics that combine general relativity and particle physics. Phenomenology is the branch of theoretical physics in which physicists construct realistic models of nature from more abstract theoretical ideas. String phenomenology is the part of string theory that attempts to construct realistic or semi-realistic models based on string theory.

Partly because of theoretical and mathematical difficulties and partly because of the extremely high energies needed to test these theories experimentally, there is so far no experimental evidence that would unambiguously point to any of these models being a correct fundamental description of nature. This has led some in the community to criticize these approaches to unification and...
question the value of continued research on these problems.\[12\]

Particle physics

The currently accepted theory describing elementary particles and their interactions is known as the standard model of particle physics. This theory provides a unified description of three of the fundamental forces of nature: electromagnetism and the strong and weak nuclear forces. Despite its remarkable success in explaining a wide range of physical phenomena, the standard model cannot be a complete description of reality. This is because the standard model fails to incorporate the force of gravity and because of problems such as the hierarchy problem and the inability to explain the structure of fermion masses or dark matter.

String theory has been used to construct a variety of models of particle physics going beyond the standard model. Typically, such models are based on the idea of compactification. Starting with the ten- or eleven-dimensional spacetime of string or M-theory, physicists postulate a shape for the extra dimensions. By choosing this shape appropriately, they can construct models roughly similar to the standard model of particle physics, together with additional undiscovered particles.\[88\] One popular way of deriving realistic physics from string theory is to start with the heterotic theory in ten dimensions and assume that the six extra dimensions of spacetime are shaped like a six-dimensional Calabi–Yau manifold. Such compactifications offer many ways of extracting realistic physics from string theory. Other similar methods can be used to construct realistic or semi-realistic models of our four-dimensional world based on M-theory.\[89\]

Cosmology

The Big Bang theory is the prevailing cosmological model for the universe from the earliest known periods through its subsequent large-scale evolution. Despite its success in explaining many observed features of the universe including galactic redshifts, the relative abundance of light elements such as hydrogen and helium, and the existence of a cosmic microwave background, there are several questions that remain unanswered. For example, the standard Big Bang model does not explain why the universe appears to be same in all directions, why it appears flat on very large distance scales, or why certain hypothesized particles such as magnetic monopoles are not observed in experiments.\[90\]

Currently, the leading candidate for a theory going beyond the Big Bang is the theory of cosmic inflation. Developed by Alan Guth and others in the 1980s, inflation postulates a period of extremely rapid accelerated expansion of the universe prior to the expansion described by the standard Big Bang theory. The theory of cosmic inflation preserves the successes of the Big Bang while providing a natural explanation for some of the mysterious features of the universe.\[91\] The theory has also received striking support from observations of the cosmic microwave background, the radiation that has filled the sky since around 380,000 years after the Big Bang.\[92\]

In the theory of inflation, the rapid initial expansion of the universe is caused by a hypothetical particle called the inflaton. The exact properties of this particle are not fixed by the theory but should ultimately be derived from a more fundamental theory such as string theory.\[93\] Indeed, there have been a number of attempts to identify an inflaton within the spectrum of particles described by string theory, and to study inflation using string theory. While these approaches might eventually find support in observational data such as measurements of the cosmic microwave background, the application of string theory to cosmology is still in its early stages.\[94\]

Connections to mathematics

In addition to influencing research in theoretical physics, string theory has stimulated a number of major developments in pure mathematics. Like many developing ideas in theoretical physics, string theory does not at present have a mathematically rigorous formulation in which all of its concepts can be defined precisely. As a result, physicists who study string theory are often guided by
physical intuition to conjecture relationships between the seemingly different mathematical structures that are used to formalize different parts of the theory. These conjectures are later proved by mathematicians, and in this way, string theory serves as a source of new ideas in pure mathematics.\[^{95}\]

**Mirror symmetry**

After Calabi–Yau manifolds had entered physics as a way to compactify extra dimensions in string theory, many physicists began studying these manifolds. In the late 1980s, several physicists noticed that given such a compactification of string theory, it is not possible to reconstruct uniquely a corresponding Calabi–Yau manifold.\[^{96}\] Instead, two different versions of string theory, type IIA and type IIB, can be compactified on completely different Calabi–Yau manifolds giving rise to the same physics. In this situation, the manifolds are called mirror manifolds, and the relationship between the two physical theories is called mirror symmetry.\[^{97}\]

Regardless of whether Calabi–Yau compactifications of string theory provide a correct description of nature, the existence of the mirror duality between different string theories has significant mathematical consequences. The Calabi–Yau manifolds used in string theory are of interest in pure mathematics, and mirror symmetry allows mathematicians to solve problems in enumerative geometry, a branch of mathematics concerned with counting the numbers of solutions to geometric questions.\[^{31}\][\(^{98}\)]

Enumerative geometry studies a class of geometric objects called algebraic varieties which are defined by the vanishing of polynomials. For example, the Clebsch cubic illustrated on the right is an algebraic variety defined using a certain polynomial of degree three in four variables. A celebrated result of nineteenth-century mathematicians Arthur Cayley and George Salmon states that there are exactly 27 straight lines that lie entirely on such a surface.\[^{99}\]

Generalizing this problem, one can ask how many lines can be drawn on a quintic Calabi–Yau manifold, such as the one illustrated above, which is defined by a polynomial of degree five. This problem was solved by the nineteenth-century German mathematician Hermann Schubert, who found that there are exactly 2,875 such lines. In 1986, geometer Sheldon Katz proved that the number of curves, such as circles, that are defined by polynomials of degree two and lie entirely in the quintic is 609,250.\[^{100}\]

By the year 1991, most of the classical problems of enumerative geometry had been solved and interest in enumerative geometry had begun to diminish.\[^{101}\] The field was reinvigorated in May 1991 when physicists Philip Candelas, Xenia de la Ossa, Paul Green, and Linda Parks showed that mirror symmetry could be used to translate difficult mathematical questions about one Calabi–Yau manifold into easier questions about its mirror.\[^{102}\] In particular, they used mirror symmetry to show that a six-dimensional Calabi–Yau manifold can contain exactly 317,206,375 curves of degree three.\[^{101}\] In addition to counting degree-three curves, Candelas and his collaborators obtained a number of more general results for counting rational curves which went far beyond the results obtained by mathematicians.\[^{103}\]

Originally, these results of Candelas were justified on physical grounds. However, mathematicians generally prefer rigorous proofs that do not require an appeal to physical intuition. Inspired by physicists’ work on mirror symmetry, mathematicians have therefore constructed their own arguments proving the enumerative predictions of mirror symmetry\[^{e}\]. Today mirror symmetry is an active area of research in mathematics, and mathematicians are working to develop a more complete mathematical understanding of mirror symmetry based on physicists’ intuition.\[^{104}\] Major approaches to mirror symmetry include the homological mirror symmetry program of Maxim Kontsevich\[^{32}\] and the SYZ conjecture of Andrew Strominger Shing-Tung Yau, and Eric Zaslow.\[^{105}\]

**Monstrous moonshine**
Group theory is the branch of mathematics that studies the concept of symmetry. For example, one can consider a geometric shape such as an equilateral triangle. There are various operations that one can perform on this triangle without changing its shape. One can rotate it through 120°, 240°, or 360°, or one can reflect in any of the lines labeled $S_0$, $S_1$, or $S_2$ in the picture. Each of these operations is called a symmetry, and the collection of these symmetries satisfies certain technical properties making it into what mathematicians call a group. In this particular example, the group is known as the dihedral group of order 6 because it has six elements. A general group may describe finitely many or infinitely many symmetries; if there are only finitely many symmetries, it is called a finite group.\(^{[106]}\)

Mathematicians often strive for a classification (or list) of all mathematical objects of a given type. It is generally believed that finite groups are too diverse to admit a useful classification. A more modest but still challenging problem is to classify all finite simple groups. These are finite groups which may be used as building blocks for constructing arbitrary finite groups in the same way that prime numbers can be used to construct arbitrary whole numbers by taking products.\(^{[f]}\) One of the major achievements of contemporary group theory is the classification of finite simple groups, a mathematical theorem which provides a list of all possible finite simple groups.\(^{[107]}\)

A seemingly unrelated construction is the $j$-function of number theory. This object belongs to a special class of functions called modular functions, whose graphs form a certain kind of repeating pattern.\(^{[109]}\) Although this function appears in a branch of mathematics which seems very different from the theory of finite groups, the two subjects turn out to be intimately related. In the late 1970s, mathematicians John McKay and John Thompson noticed that certain numbers arising in the analysis of the monster group (namely, the dimensions of its irreducible representations) are related to numbers that appear in a formula for the $j$-function (namely, the coefficients of its Fourier series).\(^{[110]}\) This relationship was further developed by John Horton Conway and Simon Norton, who called it monstrous moonshine because it seemed so far fetched.\(^{[112]}\)

In 1992, Richard Borcherds constructed a bridge between the theory of modular functions and finite groups and, in the process, explained the observations of McKay and Thompson.\(^{[113][114]}\) Borcherds' work used ideas from string theory in an essential way, extending earlier results of Igor Frenkel, James Lepowsky, and Arne Meurman, who had realized the monster group as the symmetries of a particular version of string theory.\(^{[115]}\) In 1998, Borcherds was awarded the Fields medal for his work.\(^{[116]}\)

Since the 1990s, the connection between string theory and moonshine has led to further results in mathematics and physics.\(^{[108]}\) In 2010, physicists Tohru Eguchi, Hirosi Ooguri, and Yuji Tachikawa discovered connections between a different sporadic group, the Mathieu group $M_{24}$, and a certain version of string theory.\(^{[117]}\) Miranda Cheng, John Duncan, and Jeffrey A. Harvey proposed a generalization of this moonshine phenomenon called umbral moonshine\(^{[118]}\) and their conjecture was proved mathematically by Duncan, Michael Griffin, and Ken Ono.\(^{[119]}\) Witten has also speculated that the version of string theory appearing in monstrous moonshine might be related to a certain simplified model of gravity in three spacetime dimensions.\(^{[120]}\)

**History**
Some of the structures reintroduced by string theory arose for the first time much earlier as part of the program of classical unification started by Albert Einstein. The first person to add a fifth dimension to a theory of gravity was Gunnar Nordström in 1914, who noted that gravity in five dimensions describes both gravity and electromagnetism in four. Nordström attempted to unify electromagnetism with his theory of gravitation, which was however superseded by Einstein's general relativity in 1919. Thereafter, German mathematician Theodor Kaluza combined the fifth dimension with general relativity, and only Kaluza is usually credited with the idea. In 1926, the Swedish physicist Oskar Klein gave a physical interpretation of the unobservable extra dimension—it is wrapped into a small circle. Einstein introduced a non-symmetric metric tensor, while much later Brans and Dicke added a scalar component to gravity. These ideas would be revived within string theory where they are demanded by consistency conditions.

String theory was originally developed during the late 1960s and early 1970s as a never completely successful theory of hadrons, the subatomic particles like the proton and neutron that feel the strong interaction. In the 1960s, Geoffrey Chew and Steven Frautschi discovered that the mesons make families called Regge trajectories with masses related to spins in a way that was later understood by Yoichiro Nambu, Holger Bech Nielsen and Leonard Susskind to be the relationship expected from rotating strings. Chew advocated making a theory for the interactions of these trajectories that did not presume that they were composed of any fundamental particles, but would construct their interactions from self-consistency conditions on the S-matrix. The S-matrix approach was started by Werner Heisenberg in the 1940s as a way of constructing a theory that did not rely on the local notions of space and time, which Heisenberg believed break down at the nuclear scale. While the scale was off by many orders of magnitude, the approach he advocated was ideally suited for a theory of quantum gravity.

Working with experimental data, R. Dolen, D. Horn and C. Schmid developed some sum rules for hadron exchange. When a particle and antiparticle scatter, virtual particles can be exchanged in two qualitatively different ways. In the s-channel, the two particles annihilate to make temporary intermediate states that fall apart into the final state particles. In the t-channel, the particles exchange intermediate states by emission and absorption. In field theory, the two contributions add together, one giving a continuous background contribution, the other giving peaks at certain energies. In the data, it was clear that the peaks were stealing from the background—the authors interpreted this as saying that the t-channel contribution was dual to the s-channel one, meaning both described the whole amplitude and included the other.

The result was widely advertised by Murray Gell-Mann, leading Gabriele Veneziano to construct a scattering amplitude that had the property of Dolen–Horn–Schmid duality, later renamed world-sheet duality. The amplitude needed poles where the particles appear, on straight line trajectories, and there is a special mathematical function whose poles are evenly spaced on half the real line—the gamma function—which was widely used in Regge theory. By manipulating combinations of gamma functions, Veneziano was able to find a consistent scattering amplitude with poles on straight lines, with mostly positive residues, which obeyed duality and had the appropriate Regge scaling at high energy. The amplitude could fit near-beam scattering data as well as other Regge type fits, and had a suggestive integral representation that could be used for generalization.

Over the next years, hundreds of physicists worked to complete the bootstrap program for this model, with many surprises. Veneziano himself discovered that for the scattering amplitude to describe the scattering of a particle that appears in the theory, an obvious self-consistency condition, the lightest particle must be a tachyon. Miguel Virasoro and Joel Shapiro found a different amplitude now understood to be that of closed strings, while Ziro Koba and Holger Nielsen generalized Veneziano's integral representation to multiparticle scattering. Veneziano and Sergio Fubini introduced an operator formalism for computing the scattering amplitudes that was a forerunner of world-sheet conformal theory while Virasoro understood how to remove the poles with wrong-sign residues using a constraint on the
states. Claud Lovelace calculated a loop amplitude, and noted that there is an inconsistency unless the dimension of the theory is 26. Charles Thorn, Peter Goddard and Richard Brower went on to prove that there are no wrong-sign propagating states in dimensions less than or equal to 26.

In 1969–70, Yoichiro Nambu, Holger Bech Nielsen and Leonard Susskind recognized that the theory could be given a description in space and time in terms of strings. The scattering amplitudes were derived systematically from the action principle by Peter Goddard, Jeffrey Goldstone, Claudio Rebbi, and Charles Thorn, giving a space-time picture to the vertex operators introduced by Veneziano and Fubini and a geometrical interpretation to the Virasoro conditions.

In 1971, Pierre Ramond added fermions to the model, which led him to formulate a two-dimensional supersymmetry to cancel the wrong-sign states. John Schwarz and André Neveu added another sector to the fermion theory a short time later. In the fermion theories, the critical dimension was 10. Stanley Mandelstam formulated a world sheet conformal theory for both the boson and fermion case, giving a two-dimensional field theoretic path-integral to generate the operator formalism. Michio Kaku and Keiji Kikkawa gave a different formulation of the bosonic string, as a string field theory, with infinitely many particle types and with fields taking values not on points, but on loops and curves.

In 1974, Tamiaki Yoneya discovered that all the known string theories included a massless spin-two particle that obeyed the correct Ward identities to be a graviton. John Schwarz and Joel Scherk came to the same conclusion and made the bold leap to suggest that string theory was a theory of gravity, not a theory of hadrons. They reintroduced Kaluza–Klein theory as a way of making sense of the extra dimensions. At the same time, quantum chromodynamics was recognized as the correct theory of hadrons, shifting the attention of physicists and apparently leaving the bootstrap program in the dustbin of history.

String theory eventually made it out of the dustbin, but for the following decade all work on the theory was completely ignored. Still, the theory continued to develop at a steady pace thanks to the work of a handful of devotees. Ferdinando Gliozzi, Joel Scherk, and David Olive realized in 1977 that the original Ramond and Neveu Schwarz-strings were separately inconsistent and needed to be combined. The resulting theory did not have a tachyon, and was proven to have space-time supersymmetry by John Schwarz and Michael Green in 1984. The same year, Alexander Polyakov gave the theory a modern path integral formulation, and went on to develop conformal field theory extensively. In 1979, Daniel Friedan showed that the equations of motions of string theory, which are generalizations of the Einstein equations of general relativity, emerge from the renormalization group equations for the two-dimensional field theory. Schwarz and Green discovered T-duality, and constructed two superstring theories—IIA and IIB related by T-duality, and type I theories with open strings. The consistency conditions had been so strong, that the entire theory was nearly uniquely determined, with only a few discrete choices.

**First superstring revolution**

In the early 1980s, Edward Witten discovered that most theories of quantum gravity could not accommodate chiral fermions like the neutrino. This led him, in collaboration with Luis Álvarez-Gaumé, to study violations of the conservation laws in gravity theories with anomalies, concluding that type I string theories were inconsistent. Green and Schwarz discovered a contribution to the anomaly that Witten and Álvarez-Gaumé had missed, which restricted the gauge group of the type I string theory to be $SO(32)$. In coming to understand this calculation, Edward Witten became convinced that string theory was truly a consistent theory of gravity, and he became a high-profile advocate. Following Witten's lead, between 1984 and 1986, hundreds of physicists started to work in this field, and this is sometimes called the first superstring revolution.

During this period, David Gross, Jeffrey Harvey, Emil Martinec, and Ryan Rohm discovered heterotic strings. The gauge group of these closed strings was two copies of $E_8$, and either copy could easily and naturally include the standard model. Philip Candelas, Gary Horowitz, Andrew Strominger and Edward Witten found that the Calabi–Yau manifolds are the compactifications that preserve a realistic amount of supersymmetry, while Lance Dixon and others worked out the physical properties of orbifolds, distinctive geometrical singularities allowed in string theory. Cumrun Vafa generalized T-duality from circles.
to arbitrary manifolds, creating the mathematical field of mirror symmetry. Daniel Friedan, Emil Martinec and Stephen Shenker further developed the covariant quantization of the superstring using conformal field theory techniques. David Gross and Vipul Periwal discovered that string perturbation theory was divergent. Stephen Shenker showed it diverged much faster than in field theory suggesting that new non-perturbative objects were missing.

In the 1990s, Joseph Polchinski discovered that the theory requires higher-dimensional objects, called D-branes and identified these with the black-hole solutions of supergravity. These were understood to be the new objects suggested by the perturbative divergences, and they opened up a new field with rich mathematical structure. It quickly became clear that D-branes and other p-branes, not just strings, formed the matter content of the string theories, and the physical interpretation of the strings and branes was revealed—they are a type of black hole. Leonard Susskind had incorporated the holographic principle of Gerardus ’t Hooft into string theory, identifying the long highly excited string states with ordinary thermal black hole states. As suggested by ’t Hooft, the fluctuations of the black hole horizon, the worldsheet or world-volume theory, describes not only the degrees of freedom of the black hole, but all nearby objects too.

In 1995, at the annual conference of string theorists at the University of Southern California (USC), Edward Witten gave a speech on string theory that in essence united the five string theories that existed at the time, and giving birth to a new 11-dimensional theory called M-theory. M-theory was also foreshadowed in the work of Paul Townsend at approximately the same time. The flurry of activity that began at this time is sometimes called the second superstring revolution.[34]

During this period, Tom Banks, Willy Fischler, Stephen Shenker and Leonard Susskind formulated matrix theory, a full holographic description of M-theory using IIA D0 branes.[51] This was the first definition of string theory that was fully non-perturbative and a concrete mathematical realization of the holographic principle. It is an example of a gauge-gravity duality and is now understood to be a special case of the AdS/CFT correspondence. Andrew Strominger and Cumrun Vafa calculated the entropy of certain configurations of D-branes and found agreement with the semi-classical answer for extreme charged black holes.[62] Petr Hořava and Witten found the eleven-dimensional formulation of the heterotic string theories, showing that orbifolds solve the chirality problem. Witten noted that the effective description of the physics of D-branes at low energies is by a supersymmetric gauge theory, and found geometrical interpretations of mathematical structures in gauge theory that he and Nathan Seiberg had earlier discovered in terms of the location of the branes.

In 1997, Juan Maldacena noted that the low energy excitations of a theory near a black hole consist of objects close to the horizon, which for extreme charged black holes looks like an anti-de Sitter space.[71] He noted that in this limit the gauge theory describes the string excitations near the branes. So he hypothesized that string theory on a near-horizon extreme-charged black-hole geometry, an anti-de Sitter space times a sphere with flux, is equally well described by the low-energy limiting gauge theory, the N = 4 supersymmetric Yang–Mills theory. This hypothesis, which is called the AdS/CFT correspondence, was further developed by Steven Gubser, Igor Klebanov and Alexander Polyakov[72] and by Edward Witten,[73] and it is now well-accepted. It is a concrete realization of the holographic principle, which has far-reaching implications for black holes, locality and information in physics, as well as the nature of the gravitational interaction.[56] Through this relationship, string theory has been shown to be related to gauge theories like quantum chromodynamics and this has led to more quantitative understanding of the behavior of hadrons, bringing string theory back to its roots.

**Criticism**
Number of solutions

To construct models of particle physics based on string theory, physicists typically begin by specifying a shape for the extra dimensions of spacetime. Each of these different shapes corresponds to a different possible universe, or "vacuum state", with a different collection of particles and forces. String theory as it is currently understood has an enormous number of vacuum states, typically estimated to be around $10^{500}$, and these might be sufficiently diverse to accommodate almost any phenomena that might be observed at low energies.\[121\]

Many critics of string theory have expressed concerns about the large number of possible universes described by string theory. In his book *Not Even Wrong*, Peter Woit, a lecturer in the mathematics department at Columbia University, has argued that the large number of different physical scenarios renders string theory vacuous as a framework for constructing models of particle physics. According to Woit,

> The possible existence of, say, $10^{500}$ consistent different vacuum states for superstring theory probably destroys the hope of using the theory to predict anything. If one picks among this large set just those states whose properties agree with present experimental observations, it is likely there still will be such a large number of these that one can get just about whatever value one wants for the results of any new observation.\[122\]

Some physicists believe this large number of solutions is actually a virtue because it may allow a natural anthropic explanation of the observed values of physical constants, in particular the small value of the cosmological constant.\[122\] The anthropic principle is the idea that some of the numbers appearing in the laws of physics are not fixed by any fundamental principle but must be compatible with the evolution of intelligent life. In 1987, Steven Weinberg published an article in which he argued that the cosmological constant could not have been too large, or else galaxies and intelligent life would not have been able to develop.\[123\] Weinberg suggested that there might be a huge number of possible consistent universes, each with a different value of the cosmological constant, and observations indicate a small value of the cosmological constant only because humans happen to live in a universe that has allowed intelligent life, and hence observers, to exist.\[124\]

String theorist Leonard Susskind has argued that string theory provides a natural anthropic explanation of the small value of the cosmological constant.\[125\] According to Susskind, the different vacuum states of string theory might be realized as different universes within a larger multiverse. The fact that the observed universe has a small cosmological constant is just a tautological consequence of the fact that a small value is required for life to exist.\[126\] Many prominent theorists and critics have disagreed with Susskind's conclusions.\[127\] According to Woit, "in this case [anthropic reasoning] is nothing more than an excuse for failure. Speculative scientific ideas fail not just when they make incorrect predictions, but also when they turn out to be vacuous and incapable of predicting anything."\[128\]

Background independence

One of the fundamental properties of Einstein's general theory of relativity is that it is background independent, meaning that the formulation of the theory does not in any way privilege a particular spacetime geometry.\[129\]

One of the main criticisms of string theory from early on is that it is not manifestly background independent. In string theory, one must typically specify a fixed reference geometry for spacetime, and all other possible geometries are described as perturbations of this fixed one. In his book *The Trouble With Physics*, physicist Lee Smolin of the Perimeter Institute for Theoretical Physics claims that this is the principal weakness of string theory as a theory of quantum gravity, saying that string theory has failed to incorporate this important insight from general relativity.\[130\]

Others have disagreed with Smolin's characterization of string theory. In a review of Smolin's book, string theorist Joseph Polchinski writes
[Smolin] is mistaking an aspect of the mathematical language being used for one of the physics being described. New physical theories are often discovered using a mathematical language that is not the most suitable for them… In string theory it has always been clear that the physics is background-independent even if the language being used is not, and the search for more suitable language continues. Indeed, as Smolin belatedly notes, [AdS/CFT] provides a solution to this problem, one that is unexpected and powerful.[131]

Polchinski notes that an important open problem in quantum gravity is to develop holographic descriptions of gravity which do not require the gravitational field to be asymptotically anti-de Sitter.[131] Smolin has responded by saying that the AdS/CFT correspondence, as it is currently understood, may not be strong enough to resolve all concerns about background independence.

**Sociology of science**

Since the superstring revolutions of the 1980s and 1990s, string theory has become the dominant paradigm of high energy theoretical physics.[132] Some string theorists have expressed the view that there does not exist an equally successful alternative theory addressing the deep questions of fundamental physics. In an interview from 1987, Nobel laureate David Gross made the following controversial comments about the reasons for the popularity of string theory:

> The most important [reason] is that there are no other good ideas around. That's what gets most people into it. When people started to get interested in string theory they didn't know anything about it. In fact, the first reaction of most people is that the theory is extremely ugly and unpleasant, at least that was the case a few years ago when the understanding of string theory was much less developed. It was difficult for people to learn about it and to be turned on. So I think the real reason why people have got attracted by it is because there is no other game in town. All other approaches of constructing grand unified theories, which were more conservative to begin with, and only gradually became more and more radical, have failed, and this game hasn't failed yet.[133]

Several other high-profile theorists and commentators have expressed similar views, suggesting that there are no viable alternatives to string theory.[134]

Many critics of string theory have commented on this state of affairs. In his book criticizing string theory, Peter Woit views the status of string theory research as unhealthy and detrimental to the future of fundamental physics. He argues that the extreme popularity of string theory among theoretical physicists is partly a consequence of the financial structure of academia and the fierce competition for scarce resources.[135] In his book *The Road to Reality*, mathematical physicist Roger Penrose expresses similar views, stating "The often frantic competitiveness that this ease of communication engenders leads to bandwagon effects, where researchers fear to be left behind if they do not join in."[136] Penrose also claims that the technical difficulty of modern physics forces young scientists to rely on the preferences of established researchers, rather than forging new paths of their own.[137] Lee Smolin expresses a slightly different position in his critique, claiming that string theory grew out of a tradition of particle physics which discourages speculation about the foundations of physics, while his preferred approach, loop quantum gravity, encourages more radical thinking. According to Smolin,

> String theory is a powerful, well-motivated idea and deserves much of the work that has been devoted to it. If it has so far failed, the principal reason is that its intrinsic flaws are closely tied to its strengths—and, of course, the story is unfinished, since string theory may well turn out to be part of the truth. The real question is not why we have expended so much energy on string theory but why we haven't expended nearly enough on alternative approaches.[138]

Smolin goes on to offer a number of prescriptions for how scientists might encourage a greater diversity of approaches to quantum gravity research.[139]
Notes and references

Notes

a. For example, physicists are still working to understand the phenomenon of quark confinement, the paradoxes of black holes, and the origin of dark energy.

b. For example, in the context of the AdS/CFT correspondence theorists often formulate and study theories of gravity in unphysical numbers of spacetime dimensions.


d. More precisely, one cannot apply the methods of perturbative quantum field theory.


f. More precisely a nontrivial group is called simple if its only normal subgroups are the trivial group and the group itself. The Jordan–Hölder theorem exhibits finite simple groups as the building blocks for all finite groups.


1. As it does not currently fully describe our universe.

Citations

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Further reading

Popularizations

General

Critical

Textbooks

For physicists

For mathematicians

External links
- *The Elegant Universe*—A three-hour miniseries with Brian Greene by NOVA (original PBS Broadcast Dates: October 28, 8–10 p.m. and November 4, 8–9 p.m., 2003). Various images, texts, videos and animations explaining string theory.
- *Not Even Wrong*—A blog critical of string theory
- The Official String Theory Web Site
- *Why String Theory*—An introduction to string theory


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In string theory, a domain wall is a theoretical (d-1)-dimensional singularity. A domain wall is meant to represent an object of codimension one embedded into space (a defect in space localized in one spatial dimension). For example, D8-branes are domain walls in type II string theory. In M-theory, the existence of Horava–Witten domain walls, "ends of the world" that carry an E8 gauge theory, is important for various relations between superstring theory and M-theory.

If domain walls exist, their interactions are hypothesized to emit gravitational waves that would be detectable by LIGO and similar experiments.¹

See also

- Topological defect
- Cosmic string
- Membrane (M-theory)
- Gravitational singularity

References


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Non-critical string theory

The non-critical string theory describes the relativistic string without enforcing the critical dimension. Although this allows the construction of a string theory in 4 spacetime dimensions, such a theory usually does not describe a Lorentz invariant background. However, there are recent developments which make possible Lorentz invariant quantization of string theory in 4-dimensional Minkowski space-time.

There are several applications of the non-critical string. Through the AdS/CFT correspondence it provides a holographic description of gauge theories which are asymptotically free. It may then have applications to the study of the QCD, the theory of strong interactions between quarks. Another area of much research is two-dimensional string theory which provides simple toy models of string theory. There also exists a duality to the 3-dimensional Ising model.

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The critical dimension and central charge

In order for a string theory to be consistent, the worldsheet theory must be conformally invariant. The obstruction to conformal symmetry is known as the Weyl anomaly and is proportional to the central charge of the worldsheet theory. In order to preserve conformal symmetry the Weyl anomaly, and thus the central charge, must vanish. For the bosonic string this can be accomplished by a worldsheet theory consisting of 26 free bosons. Since each boson is interpreted as a flat spacetime dimension, the critical dimension of the bosonic string is 26. A similar logic for the superstring results in 10 free bosons (and 10 free fermions as required by worldsheet supersymmetry). The bosons are again interpreted as spacetime dimensions and so the critical dimension for the superstring is 10. A string theory which is formulated in the critical dimension is called critical string.

The non-critical string is not formulated with the critical dimension, but nonetheless has vanishing Weyl anomaly. A worldsheet theory with the correct central charge can be constructed by introducing a non-trivial target space, commonly by giving an expectation value to the dilaton which varies linearly along some spacetime direction. For this reason non-critical string theory is sometimes called the linear dilaton theory. Since the dilaton is related to the string coupling constant, this theory contains a region where the coupling is weak (and so perturbation theory is valid) and another region where the theory is strongly coupled. For dilaton varying along a spacelike direction, the dimension of the theory is less than the critical dimension and so the theory is termed subcritical. For dilaton varying along a timelike direction, the dimension is greater than the critical dimension and the theory is termed supercritical. The dilaton can also vary along a lightlike direction, in which case the dimension is equal to the critical dimension and the theory is a critical string theory.

Two-dimensional string theory

Perhaps the most studied example of non-critical string theory is that with two-dimensional target space. While clearly not of phenomenological interest, string theories in two dimensions serve as important toy models. They allow one to probe interesting concepts which would be computationally intractable in a more realistic scenario.
These models often have fully non-perturbative descriptions in the form of the quantum mechanics of large matrices. Such a description known as the $c=1$ matrix model captures the dynamics of bosonic string theory in two dimensions. Of much recent interest are matrix models of the two-dimensional Type 0 string theories. These "matrix models" are understood as describing the dynamics of open strings lying on D-branes in these theories. Degrees of freedom associated with closed strings and spacetime itself, appear as emergent phenomena, providing an important example of open string tachyon condensation in string theory.

See also

- String theory, for general information about critical superstrings
- Weyl anomaly
- Central charge
- Liouville gravity

References

Relationship between string theory and quantum field theory

Many first principles in quantum field theory are explained, or get further insight, in string theory.

From quantum field theory to string theory

- Emission and absorption: one of the most basic building blocks of quantum field theory is the notion that particles (such as electrons) can emit and absorb other particles (such as photons). Thus, an electron may just "split" into an electron plus a photon, with a certain probability (which is roughly the coupling constant). This is described in string theory as one string splitting into two. This process is an integral part of the theory. The mode on the original string also "splits" between its two parts, resulting in two strings which possibly have different modes, representing two different particles.

- Coupling constant in quantum field theory this is, roughly, the probability for one particle to emit or absorb another particle, the latter typically being a gauge boson (a particle carrying a force). In string theory the coupling constant is no longer a constant, but is rather determined by the abundance of strings in a particular mode, dilaton. Strings in this mode couple to the worldsheet curvature of other strings, so their abundance through space-time determines the measure by which an average string worldsheet will be curved. This determines its probability to split or connect to other strings: the more a worldsheet is curved, it has a higher chance of splitting and reconnecting.

- Spin: each particle in quantum field theory has a particular spin, which is an internal angular momentum. Classically, the particle rotates in a fixed frequency, but this cannot be understood if particles are point-like. In string theory, spin is understood by the rotation of the string. For example, a photon with well-defined spin follows (i.e. in circular polarization) looks like a tiny straight line revolving around its center.

- Gauge symmetry: in quantum field theory the mathematical description of physical fields include non-physical states. In order to omit these states from the description of every physical process, a mechanism called gauge symmetry is used. This is true for string theory as well, but in string theory it is often more intuitive to understand why the non-physical states should be disposed of. The simplest example is the photon: a photon is a vector particle (it has an inner "arrow" which points to some direction, its polarization). Mathematically, it can point towards any direction in space-time. Suppose the photon is moving in the z direction; then it may either point towards the x, y or r spatial directions, or towards the t (time) direction (or any diagonal direction). Physically, however, the photon may not point towards the z or t directions (longitudinal polarization), but only in the x-y plane (transverse polarization). A gauge symmetry is used to dispose of the non-physical states. In string theory photons are described by a tiny oscillating line, with the axis of the line being the direction of the polarization (i.e. the inner direction of the photon is the axis of the string which the photon is made of). If we look at the worldsheet, the photon will look like a long strip which stretches along the time direction with an angle towards the z-direction (because it is moving along the z-direction as time goes by); its short dimension is therefore in the x-y plane. The short dimension of this strip is precisely the direction of the photon (its polarization) in a certain moment in time. Thus the photon cannot point towards the z or t directions, and its polarization must be transverse.

Note: formally, gauge symmetries in string theory are (at least in most cases) a result of the existence of a global symmetry together with the profound gauge symmetry of string theory, which is the symmetry of the worldsheet under a local change of coordinates and scales.

- Renormalization: in particle physics the behaviour of particles in the smallest scales is largely unknown. In order to avoid this difficulty, the particles are treated as fields behaving according to an "effective field theory" at low energy scales, and a mathematical tool known as renormalization is used to describe the unknown aspects of this effective theory using only a few parameters. These parameters can be adjusted so that calculations give adequate results. In string theory, this is unnecessary since the behaviour of the strings is presumed to be known to every scale.

- Fermions: in the bosonic string, a string can be described as an elastic one-dimensional object (i.e. a line) "living" in spacetime. In superstring theory every point of the string is not only located at some point in spacetime, but it may also have a small arrow "drawn" on it, pointing at some direction in spacetime. These arrows are described by an internal field "living" on the string. This is an internal field, because at each point of the string there is only one arrow; thus one cannot bring two arrows to the same point. This fermionic field (which is a field on the worldsheet) is ultimately responsible for the appearance of fermions in spacetime; roughly, two strings with arrows drawn on them cannot coexist at the same point in spacetime, because then one would effectively have one string with two sets of arrows at the same point, which is not allowed, as explained above. Therefore two such strings are fermions in spacetime.

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[1]
1. This argument uses the zero picture representation, in which states of the Neveu–Schwarz sector have an even number of excited fermionic oscillators, and are therefore commuting among themselves (i.e. have the statistics of bosons). States of the Ramond sector are anticommuting among themselves (i.e. have the statistics of fermions), ultimately due to the fermionic fields “living” on them. The spacetime statistics of states in scattering amplitudes is a consequence of their worldsheet statistics.
Topological string theory

In theoretical physics, topological string theory is a version of string theory. Topological string theory was established and is studied by physicists such as Edward Witten and Cumrun Vafa.

Overview

There are two main versions of topological string theory: the topological A-model and the topological B-model. The results of the calculations in topological string theory generically encode all holomorphic quantities within the full string theory whose values are protected by spacetime supersymmetry. Various calculations in topological string theory are closely related to Chern–Simons theory, Gromov–Witten invariants, mirror symmetry, geometric Langlands Program and many other topics.

The operators in topological string theory represent the algebra of operators in the full string theory that preserve a certain amount of supersymmetry. Topological string theory is obtained by a topological twist of the worldsheet description of ordinary string theory: the operators are given different spins. The operation is fully analogous to the construction of topological field theory which is a related concept. Consequently there are no local degrees of freedom in topological string theory.

Admissible spacetimes

The fundamental strings of string theory are two-dimensional surfaces. A quantum field theory known as the \( N = (1,1) \) sigma model is defined on each surface. This theory consist of maps from the surface to a supermanifold. Physically the supermanifold is interpreted as spacetime and each map is interpreted as the embedding of the string in spacetime.
Only special spacetimes admit topological strings. Classically, one must choose a spacetime such that the theory respects an additional pair of supersymmetries making the spacetime an $N = (2,2)$ sigma model. A particular case of this is if the spacetime is a Kähler manifold and the H-flux is identically equal to zero. Generalized Kähler manifolds can have a nontrivial H-flux.

**Topological twist**

Ordinary strings on special backgrounds are never topological. To make these strings topological, one needs to modify the sigma model via a procedure called a topological twist which was invented by Edward Witten in 1988. The central observation is that these theories have two U(1) symmetries known as R-symmetries, and the Lorentz symmetry may be modified by mixing rotations and R-symmetries. One may use either of the two R-symmetries, leading to two different theories, called the A model and the B model. After this twist, the action of the theory is BRST exact, and as a result the theory has no dynamics. Instead, all observables depend on the topology of a configuration. Such theories are known as topological theories.

Classically this procedure is always possible.

Quantum mechanically, the U(1) symmetries may be anomalous, making the twist impossible. For example, in the Kähler case with $H = 0$ the twist leading to the A-model is always possible but that leading to the B-model is only possible when the first Chern class of the spacetime vanishes, implying that the spacetime is Calabi-Yau. More generally (2,2) theories have two complex structures and the B model exists when the first Chern classes of associated bundles sum to zero whereas the A model exists when the difference of the Chern classes is zero. In the Kähler case the two complex structures are the same and so the difference is always zero, which is why the A model always exists.

There is no restriction on the number of dimensions of spacetime, other than that it must be even because spacetime is generalized Kähler. However, all correlation functions with worldsheets that are not spheres vanish unless the complex dimension of the spacetime is three, and so spacetimes with complex dimension three are the most interesting. This is fortunate for phenomenology, as phenomenological models often use a physical string theory compactified on a 3 complex-dimensional space. The topological string theory is not equivalent to the physical string theory, even on the same space, but certain supersymmetric quantities agree in the two theories.

**Objects**

**A-model**

The topological A-model comes with a target space which is a 6 real-dimensional generalized Kähler spacetime. In the case in which the spacetime is Kähler, the theory describes two objects. There are fundamental strings, which wrap two real-dimensional holomorphic curves. Amplitudes for the scattering of these strings depend only on the Kähler form of the spacetime, and not on the complex structure. Classically these correlation functions are determined by the cohomology ring. There are quantum mechanical instanton effects which correct these and yield Gromov–Witten invariants, which measure the cup product in a deformed cohomology ring called the quantum cohomology. The string field theory of the A-model closed strings is known as Kähler gravity, and was introduced by Michael Bershadsky and Vladimir Sadov in Theory of Kähler Gravity.

In addition, there are D2-branes which wrap Lagrangian submanifolds of spacetime. These are submanifolds whose dimensions are one half that of space time, and such that the pullback of the Kähler form to the submanifold vanishes. The worldvolume theory on a stack of N D2-branes is the string field theory of the open strings of the A-model, which is a U(N) Chern–Simons theory.

The fundamental topological strings may end on the D2-branes. While the embedding of a string depends only on the Kähler form, the embeddings of the branes depends entirely on the complex structure. In particular, when a string ends on a brane the intersection will always be orthogonal, as the wedge product of the Kähler form and the holomorphic 3-form is zero. In the physical string this is necessary for the stability of the configuration, but here it is a property of Lagrangian and holomorphic cycles on a Kahler manifold.
There may also be coisotropic branes in various dimensions other than half dimensions of Lagrangian submanifolds. These were first introduced by Anton Kapustin and Dmitri Orlov in Remarks on A-Branes, Mirror Symmetry and the Fukaya Category.

**B-model**

The B-model also contains fundamental strings, but their scattering amplitudes depend entirely upon the complex structure and are independent of the Kähler structure. In particular, they are insensitive to worldsheet instanton effects and so can often be calculated exactly. Mirror symmetry then relates them to A model amplitudes, allowing one to compute Gromov–Witten invariants. The string field theory of the closed strings of the B-model is known as the Kodaira–Spencer theory of gravity and was developed by Michael Bershadsky, Sergio Cecotti, Hirosi Ooguri and Cumrun Vafa in Kodaira–Spencer Theory of Gravity and Exact Results for Quantum String Amplitudes.

The B-model also comes with D(-1), D1, D3 and D5-branes, which wrap holomorphic 0, 2, 4 and 6-submanifolds respectively. The 6-submanifold is a connected component of the spacetime. The theory on a D5-brane is known as holomorphic Chern–Simons theory. The Lagrangian density is the wedge product of that of ordinary Chern–Simons theory with the holomorphic (3,0)-form, which exists in the Calabi-Yau case. The Lagrangian densities of the theories on the lower-dimensional branes may be obtained from holomorphic Chern–Simons theory by dimensional reductions.

**Topological M-theory**

Topological M-theory, which enjoys a seven-dimensional spacetime, is not a topological string theory, as it contains no topological strings. However, topological M-theory on a circle bundle over a 6-manifold has been conjectured to be equivalent to the topological A-model on that 6-manifold.

In particular, the D2-branes of the A-model lift to points at which the circle bundle degenerates, or more precisely Kaluza–Klein monopoles. The fundamental strings of the A-model lift to membranes named M2-branes in topological M-theory.

One special case that has attracted much interest is topological M-theory on a space with G\(_2\) holonomy and the A-model on a Calabi-Yau. In this case, the M2-branes wrap associative 3-cycles. Strictly speaking, the topological M-theory conjecture has only been made in this context, as in this case functions introduced by Nigel Hitchin in The Geometry of Three-Forms in Six and Seven Dimensions and Stable Forms and Special Metrics provide a candidate low energy effective action.

These functions are called “Hitchin functional” and Topological string is closely related to Hitchin’s ideas on generalized complex structure, Hitchin system, and ADHM construction etc.

**Observables**

**The topological twist**

The 2-dimensional worldsheet theory is an \(\mathcal{N} = (2,2)\) supersymmetric sigma model, the \(\mathcal{N} = (2,2)\) supersymmetry means that the fermionic generators of the supersymmetry algebra, called supercharges, may be assembled into a single Dirac spinor, which consists of two Majorana–Weyl spinors of each chirality. This sigma model is topologically twisted, which means that the Lorentz symmetry generators that appear in the supersymmetry algebra simultaneously rotate the physical spacetime and also rotate the fermionic directions via the action of one of the R-symmetries. The R-symmetry group of a 2-dimensional \(\mathcal{N} = (2,2)\) field theory is \(U(1) \times U(1)\), twists by the two different factors lead to the A and B models respectively. The topological twisted construction of topological string theories was introduced by Edward Witten in his 1988 paper\(^1\).

**What do the correlators depend on?**
The topological twist leads to a topological theory because the stress–energy tensor may be written as an anticommutator of a supercharge and another field. As the stress–energy tensor measures the dependence of the action on the metric tensor, this implies that all correlation functions of Q-invariant operators are independent of the metric. In this sense, the theory is topological.

More generally, any D-term in the action, which is any term which may be expressed as an integral over all of superspace, is an anticommutator of a supercharge and so does not affect the topological observables. Yet more generally, in the B model any term which may be written as an integral over the fermionic $\tilde{\theta}^\pm$ coordinates does not contribute, whereas in the A-model any term which is an integral over $\theta^-$ or over $\bar{\theta}^+$ does not contribute. This implies that A model observables are independent of the superpotential (as it may be written as an integral over just $\bar{\theta}^\pm$) but depend holomorphically on the twisted superpotential and vice versa for the B model.

**Dualities**

### Dualities between TSTs

A number of dualities relate the above theories. The A-model and B-model on two mirror manifolds are related by mirror symmetry, which has been described as a T-duality on a three-torus. The A-model and B-model on the same manifold are conjectured to be related by S-duality, which implies the existence of several new branes, called NS branes by analogy with the NS5-brane, which wrap the same cycles as the original branes but in the opposite theory. Also a combination of the A-model and a sum of the B-model and its conjugate are related to topological M-theory by a kind of dimensional reduction. Here the degrees of freedom of the A-model and the B-models appear to not be simultaneously observable, but rather to have a relation similar to that between position and momentum in quantum mechanics.

**The holomorphic anomaly**

The sum of the B-model and its conjugate appears in the above duality because it is the theory whose low energy effective action is expected to be described by Hitchin's formalism. This is because the B-model suffers from a holomorphic anomaly, which states that the dependence on complex quantities, while classically holomorphic, receives nonholomorphic quantum corrections. In Quantum Background Independence in String Theory, Edward Witten argued that this structure is analogous to a structure that one finds geometrically quantizing the space of complex structures. Once this space has been quantized, only half of the dimensions simultaneously commute and so the number of degrees of freedom has been halved. This halving depends on an arbitrary choice, called a polarization. The conjugate model contains the missing degrees of freedom, and so by tensoring the B-model and its conjugate one reobtains all of the missing degrees of freedom and also eliminates the dependence on the arbitrary choice of polarization.

**Geometric transitions**

There are also a number of dualities that relate configurations with D-branes, which are described by open strings, to those with branes the branes replaced by flux and with the geometry described by the near-horizon geometry of the lost branes. The latter are described by closed strings.

Perhaps the first such duality is the Gopakumar-Vafa duality, which was introduced by Rajesh Gopakumar and Cumrun Vafa in On the Gauge Theory/Geometry Correspondence. This relates a stack of N D6-branes on a 3-sphere in the A-model on the deformed conifold to the closed string theory of the A-model on a resolved conifold with a B field equal to N times the string coupling constant. The open strings in the A model are described by a U(N) Chern–Simons theory, while the closed string theory on the A-model is described by the Kähler gravity.

Although the conifold is said to be resolved, the area of the blown up two-sphere is zero, it is only the B-field, which is often considered to be the complex part of the area, which is nonvanishing. In fact, as the Chern–Simons theory is topological, one may shrink the volume of the deformed three-sphere to zero and so arrive at the same geometry as in the dual theory.
The mirror dual of this duality is another duality, which relates open strings in the B model on a brane wrapping the 2-cycle in the resolved conifold to closed strings in the B model on the deformed conifold. Open strings in the B-model are described by dimensional reductions of homolomorphic Chern–Simons theory on the branes on which they end, while closed strings in the B model are described by Kodaira–Spencer gravity.

**Dualities with other theories**

**Crystal melting, quantum foam and U(1) gauge theory**

In the paper *Quantum Calabi-Yau and Classical Crystals*, Andrei Okounkov, Nicolai Reshetikhin and Cumrun Vafa conjectured that the quantum A-model is dual to a classical melting crystal at a temperature equal to the inverse of the string coupling constant. This conjecture was interpreted in *Quantum Foam and Topological Strings*, by Amer Iqbal, Nikita Nekrasov, Andrei Okounkov and Cumrun Vafa. They claim that the statistical sum over melting crystal configurations is equivalent to a path integral over changes in spacetime topology supported in small regions with area of order the product of the string coupling constant and \( \alpha' \).

Such configurations, with spacetime full of many small bubbles, dates back to John Archibald Wheeler in 1964, but has rarely appeared in string theory as it is notoriously difficult to make precise. However in this duality the authors are able to cast the dynamics of the quantum foam in the familiar language of a topologically twisted U(1) gauge theory, whose field strength is linearly related to the Kähler form of the A-model. In particular this suggests that the A-model Kähler form should be quantized.

**Applications**

A-model topological string theory amplitudes are used to compute prepotentials in N=2 supersymmetric gauge theories in four and five dimensions. The amplitudes of the topological B-model, with fluxes and or branes, are used to compute superpotentials in N=1 supersymmetric gauge theories in four dimensions. Perturbative A model calculations also count BPS states of spinning black holes in five dimensions.

**See also**

- Quantum topology
- Topological defect
- Topological entropy in physics
- Topological order
- Topological quantum field theory
- Topological quantum number
- Introduction to M-theory

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In non-technical terms, **M-theory** presents an idea about the basic substance of the universe. As of 2019 science has produced no experimental evidence to support the concept that M-theory is a description of the real world. Although a complete mathematical formulation of M-theory is not known, the general approach is the leading contender for a universal "Theory of Everything" that unifies gravity with other forces such as electromagnetism. M-theory aims to unify quantum mechanics with general relativity's gravitational force in a mathematically consistent way. In comparison, other theories such as loop quantum gravity are considered less elegant because they posit gravity to be completely different from forces such as the electromagnetic force.\(^1\)\(^2\)\(^3\)

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**Background**

In the early years of the 20th century, the atom – long believed to be the smallest building-block of matter – was proven to consist of even smaller components called protons, neutrons and electrons, which are known as subatomic particles. Starting in the 1960’s, other subatomic particles were discovered. In the 1970s, it was discovered that protons and neutrons (and other hadrons) are themselves made up of smaller particles called quarks. The **Standard Model** is the set of rules that describes the interactions of these particles.

In the 1980s, a new mathematical model of theoretical physics, called string theory, emerged. It showed how all the different subatomic particles known to science could be constructed by hypothetical one-dimensional "strings", infinitesimal building-blocks that have only the dimension of length, but not height or width.

However, for string theory to be mathematically consistent, the strings must be in a universe of ten dimensions. This contradicts the experience that our real universe has four dimensions: three space dimensions (height, width, and length) and one time dimension. To "save" their theory, string theorists therefore added the explanation that the additional six dimensions exist but cannot be detected directly; this was explained by sophisticated mathematical objects called **Calabi–Yau manifolds**. The number of dimensions was later increased to 11 based on various interpretations of the 10-dimensional theory that led to five partial theories, as described below.

**Supergravity** theory also played a significant part in establishing the necessity of the 11th dimension.

These "strings" vibrate in multiple dimensions and, depending on how they vibrate, they might be seen in three-dimensional space as matter, light or gravity. It is the vibration of the string that determines whether it appears to be matter or energy, and every form of matter or energy is the result of the vibration of strings.

String theory as described above ran into a problem: another version of the equations was discovered, then another, and then another. Eventually, five major string theories were developed. The main differences between the theories were principally the number of dimensions in which the strings developed, and their characteristics (some were open loops, some were closed loops, etc.). Furthermore, all these theories appeared to be workable. Scientists were not comfortable with five seemingly contradictory sets of equations to describe the same thing.
Speaking at the string theory conference at the University of Southern California in 1995, Edward Witten of the Institute for Advanced Study suggested that the five different versions of string theory might be describing the same thing seen from different perspectives.\[4\] He proposed a unifying theory called "M-theory", in which the "M" is not specifically defined but is generally understood to stand for "membrane". The words "matrix", "master", "mother", "monster", "mystery" and "magic" have also been claimed. M-theory brought all of the string theories together. It did this by asserting that strings are really one-dimensional slices of a two-dimensional membrane vibrating in 1-dimensional spacetime. Vibrations of higher-dimensional objects (as in three-dimensional vibrating blob or sphere or even more possible dimensions) are certainly a part of M-theory\[5\] but the basic theory of branes is still in progress. Higher-dimensional objects are much harder to mathematically calculate than a point in classical physics or a one-dimensional string in string theory or two-dimensional membranes in M-theory.

## Status

M-theory is not complete, but the mathematics of the approach has been explored in great detail. However, so far no experimental support of the M-theory exists.\[1\] Some physicists are skeptical that this approach will ever lead to a physical theory describing our real world, due to fundamental issues.\[6\]

Nevertheless, some cosmologists are drawn to M-theory because of its mathematical elegance and relative simplicity, triggering the hope that the simplicity is a reason why it may describe our world.

One feature of M-theory that has drawn great interest is that naturally predicts the existence of the graviton, a spin-2 particle hypothesized to mediate the gravitational force; furthermore, M-theory naturally predicts a phenomenon that resembles black hole evaporation. Competing unification theories such as asymptotically safe gravity, E8 theory, noncommutative geometry, and causal fermion systems have not demonstrated any level of mathematical consistency. M-theory's chief rival is loop quantum gravity, a non-unifying theory; many physicists consider loop quantum gravity to be less elegant than M-theory because it posits gravity to be completely different from the other fundamental forces.\[1][2]

## See also

- History of string theory

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## Further reading


**External links**

- The *Elegant Universe* - A Three-Hour miniseries with Brian Greene by NOVA (original PBS Broadcast Dates: October 28, 8-10 p.m. and November 4, 8-9 p.m., 2003). Various images, texts, videos and animations explaining string theory and M-theory

- Superstringtheory.com - The "Official String Theory Web Site", created by Patricia Schwarz. Excellent references on string theory and M-theory for the layperson and expert.


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Cosmic string

Cosmic strings are hypothetical 1-dimensional topological defects which may have formed during a symmetry breaking phase transition in the early universe when the topology of the vacuum manifold associated to this symmetry breaking was not simply connected. It is expected that at least one string per Hubble volume is formed. Their existence was first contemplated by the theoretical physicist Tom Kibble in the 1970s.

The formation of cosmic strings is somewhat analogous to the imperfections that form between crystal grains in solidifying liquids, or the cracks that form when water freezes into ice. The phase transitions leading to the production of cosmic strings are likely to have occurred during the earliest moments of the universe's evolution, just after cosmological inflation, and are a fairly generic prediction in both quantum field theory and string theory models of the early universe.

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Theories containing cosmic strings

In string theory, the role of cosmic strings can be played by the fundamental strings (or F-strings) themselves that define the theory perturbatively, by D-strings which are related to the F-strings by weak-strong or so called S-duality, or higher-dimensional D-, NS- or M-branes that are partially wrapped on compact cycles associated to extra spacetime dimensions so that only one non-compact dimension remains.[1]

The prototypical example of a quantum field theory with cosmic strings is the Abelian Higgs model. The quantum field theory and string theory cosmic strings are expected to have many properties in common, but more research is needed to determine the precise distinguishing features. The F-strings for instance are fully quantum-mechanical and do not have a classical definition, whereas the field theory cosmic strings are almost exclusively treated classically.

Dimensions

Cosmic strings, if they exist, would be extremely thin with diameters of the same order of magnitude as that of a proton, i.e. ~ 1 fm, or smaller. Given that this scale is much smaller than any cosmological scale these strings are often studied in the zero-width, or Nambu–Goto approximation. Under this assumption strings behave as one-dimensional objects and obey the Nambu–Goto action, which is classically equivalent to the Polyakov action that defines the bosonic sector of superstring theory.
In field theory, the string width is set by the scale of the symmetry breaking phase transition. In string theory, the string width is set (in the simplest cases) by the fundamental string scale, warp factors (associated to the spacetime curvature of an internal six-dimensional spacetime manifold) and/or the size of internal compact dimensions. (In string theory, the universe is either 10- or 11-dimensional, depending on the strength of interactions and the curvature of spacetime.)

**Gravitation**

A string is a geometrical deviation from Euclidean geometry in spacetime characterized by an angular deficit: a circle around the outside of a string would comprise a total angle less than 360°. From the general theory of relativity such a geometrical defect must be in tension, and would be manifested by mass. Even though cosmic strings are thought to be extremely thin, they would have immense density, and so would represent significant gravitational wave sources. A cosmic string about a kilometer in length may be more massive than the Earth.

However general relativity predicts that the gravitational potential of a straight string vanishes: there is no gravitational force on static surrounding matter. The only gravitational effect of a straight cosmic string is a relative deflection of matter (or light) passing the string on opposite sides (a purely topological effect). A closed cosmic string gravitates in a more conventional way.

During the expansion of the universe, cosmic strings would form a network of loops, and in the past it was thought that their gravity could have been responsible for the original clumping of matter into galactic superclusters. It is now calculated that their contribution to the structure formation in the universe is less than 10%.

**Negative mass cosmic string**

The standard model of a cosmic string is a geometrical structure with an angle deficit, which thus is in tension and hence has positive mass. In 1995, Visser et al. proposed that cosmic strings could theoretically also exist with angle excesses, and thus negative tension and hence negative mass. The stability of such exotic matter strings is problematic; however, they suggested that if a negative mass string were to be wrapped around a wormhole in the early universe, such a wormhole could be stabilized sufficiently to exist in the present day.[2][3]

**Super-critical cosmic string**

The exterior geometry of a (straight) cosmic string can be visualized in an embedding diagram as follows: Focusing on the two-dimensional surface perpendicular to the string, its geometry is that of a cone which is obtained by cutting out a wedge of angle δ and gluing together the edges. The angular deficit δ is linearly related to the string tension (= mass per unit length), i.e. the larger the tension, the steeper the cone. Therefore, δ reaches 2π for a certain critical value of the tension, and the cone degenerates to a cylinder. (In visualizing this setup one has to think of a string with a finite thickness.) For even larger, “super-critical” values, δ exceeds 2π and the (two-dimensional) exterior geometry closes up (it becomes compact), ending in a conical singularity.

However, this static geometry is unstable in the super-critical case (unlike for sub-critical tensions): Small perturbations lead to a dynamical spacetime which expands in axial direction at a constant rate. The 2D exterior is still compact, but the conical singularity can be avoided, and the embedding picture is that of a growing cigar. For even larger tensions (exceeding the critical value by approximately a factor of 1.6), the string cannot be stabilized in radial direction anymore.

Realistic cosmic strings are expected to have tensions around 6 orders of magnitude below the critical value, and are thus always sub-critical. However, the inflating cosmic string solutions might be relevant in the context of brane cosmology, where the string is promoted to a 3-brane (corresponding to our universe) in a six-dimensional bulk.

**Observational evidence**
It was once thought that the gravitational influence of cosmic strings might contribute to the large-scale clumping of matter in the universe, but all that is known today through galaxy surveys and precision measurements of the cosmic microwave background (CMB) fits an evolution out of random, gaussian fluctuations. These precise observations therefore tend to rule out a significant role for cosmic strings and currently it is known that the contribution of cosmic strings to the CMB cannot be more than 10%.

The violent oscillations of cosmic strings generically lead to the formation of cusps and kinks. These in turn cause parts of the string to pinch off into isolated loops. These loops have a finite lifespan and decay (primarily) via gravitational radiation. This radiation which leads to the strongest signal from cosmic strings may in turn be detectable in gravitational wave experiments, such as LIGO and LISA. An important open question is to what extent do the pinched off loops backreact or change the initial state of the emitting cosmic string—such backreaction effects are almost always neglected in computations and are known to be important, even for order of magnitude estimates.

Gravitational lensing of a galaxy by a straight section of a cosmic string would produce two identical, undistorted images of the galaxy. In 2003 a group led by Mikhail Sazhin reported the accidental discovery of two seemingly identical galaxies very close together in the sky, leading to speculation that a cosmic string had been found. However, observations by the Hubble Space Telescope in January 2005 showed them to be a pair of similar galaxies, not two images of the same galaxy. A cosmic string would produce a similar duplicate image of fluctuations in the cosmic microwave background which it was thought might have been detectable by the Planck Surveyor mission. However, a 2013 analysis of data from the Planck mission failed to find any evidence of cosmic strings.

A piece of evidence supporting cosmic string theory is a phenomenon noticed in observations of the "double quasar" called Q0957+561A,B. Originally discovered by Dennis Walsh, Bob Carswell, and Ray Weymann in 1979, the double image of this quasar is caused by a galaxy positioned between it and the Earth. The gravitational lens effect of this intermediate galaxy bends the quasar's light so that it follows two paths of different lengths to Earth. The result is that we see two images of the same quasar, one arriving a short time after the other (about 417.1 days later). However, a team of astronomers at the Harvard-Smithsonian Center for Astrophysics led by Rudolph Schild studied the quasar and found that during the period between September 1994 and July 1995 the two images appeared to have no time delay; changes in the brightness of the two images occurred simultaneously on four separate occasions. Schild and his team believe that the only explanation for this observation is that a cosmic string passed between the Earth and the quasar during that time period traveling at very high speed and oscillating with a period of about 100 days.

Currently the most sensitive bounds on cosmic string parameters come from the non-detection of gravitational waves by Pulsar timing array data. The earthbound Laser Interferometer Gravitational-Wave Observatory (LIGO) and especially the space-based gravitational wave detector Laser Interferometer Space Antenna (LISA) will search for gravitational waves and are likely to be sensitive enough to detect signals from cosmic strings, provided the relevant cosmic string tensions are not too small.

### String theory and cosmic strings

During the early days of string theory both string theorists and cosmic string theorists believed that there was no direct connection between superstrings and cosmic strings (the names were chosen independently by analogy with ordinary string). The possibility of cosmic strings being produced in the early universe was first envisioned by quantum field theorist Tom Kibble in 1976, and this sprouted the first flurry of interest in the field. In 1985, during the first superstring revolution, Edward Witten contemplated on the possibility of fundamental superstrings having been produced in the early universe and stretched to macroscopic scales, in which case (following the nomenclature of Tom Kibble) they would then be referred to as cosmic superstrings. He concluded that had they been produced they would have either disintegrated into smaller strings before ever reaching macroscopic scales (in the case of Type I superstring theory), they would always appear as boundaries of domain walls whose tension would force the strings to collapse rather than grow to cosmic scales (in the context of heterotic superstring theory), or having a characteristic energy scale close to the Planck energy they would be produced before cosmological inflation and hence be diluted away with the expansion of the universe and not be observable.
Much has changed since these early days, primarily due to the second superstring revolution. It is now known that string theory in addition to the fundamental strings which define the theory perturbatively also contains other one-dimensional objects, such as D-strings, and higher-dimensional objects such as D-branes, NS-branes and M-branes partially wrapped on compact internal spacetime dimensions, while being spatially extended in one non-compact dimension. The possibility of large compact dimensions and large warp factors allows strings with tension much lower than the Planck scale. Furthermore, various dualities that have been discovered point to the conclusion that actually all these apparently different types of string are just the same object as it appears in different regions of parameter space. These new developments have largely revived interest in cosmic strings, starting in the early 2000s.

In 2002, Henry Tye and collaborators predicted the production of cosmic superstrings during the last stages of brane inflation[12] a string theory construction of the early universe that gives leads to an expanding universe and cosmological inflation. It was subsequently realized by string theorist Joseph Polchinski that the expanding Universe could have stretched a "fundamental" string (the sort which superstring theory considers) until it was of intergalactic size. Such a stretched string would exhibit many of the properties of the old "cosmic" string variety, making the older calculations useful again. As theorist Tom Kibble remarks, "string theory cosmologists have discovered cosmic strings lurking everywhere in the undergrowth". Older proposals for detecting cosmic strings could now be used to investigate superstring theory.

Superstrings, D-strings or the other stringy objects mentioned above stretched to intergalactic scales would radiate gravitational waves, which could be detected using experiments like LIGO and especially the space-based gravitational wave experiment LISA. They might also cause slight irregularities in the cosmic microwave background, too subtle to have been detected yet but possibly within the realm of future observability.

Note that most of these proposals depend, however, on the appropriate cosmological fundamentals (strings, branes, etc.), and no convincing experimental verification of these has been confirmed to date. Cosmic strings nevertheless provide a window into string theory. If cosmic strings are observed which is a real possibility for a wide range of cosmological string models this would provide the first experimental evidence of a string theory model underlying the structure of spacetime.

**Detection of Cosmic Strings network**

There are many attempts to detect the footprint of cosmic strings network[13][14][15]

### See also

- 0-dimensional topological defect: magnetic monopole
- 2-dimensional topological defect: domain wall
  (e.g. of 1-dimensional topological defect: a cosmic string)
- cosmic string loop stabilised by a fermionic supercurrent: vorton

### References


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External links

- An artistic perspective of Cosmic Strings
- A simulation of cosmic string
- http://www.damtp.cam.ac.uk/user/gr/public/cs_interact.html
- Dr. Kip Thorne, ITP & Caltech. Spacetime Warps and the Quantum: A Glimpse of the Future. Lecture slides and audio
- Cosmic strings and superstrings on arxiv.org

Little string theory

In theoretical physics, little string theory is a non-gravitational non-local theory in six spacetime dimensions that can be obtained as an effective theory of NS5-branes in the limit in which gravity decouples. Little string theories exhibit T-duality, much like the full string theory.

References

Matrix string theory

In physics, matrix string theory is a set of equations that describe superstring theory in a non-perturbative framework. Type IIA string theory can be shown to be equivalent to a maximally supersymmetric two-dimensional gauge theory, the gauge group of which is U(N) for a large value of N. This matrix string theory was first proposed by Luboš Motl in 1997[1] and later independently in a more complete paper by Robbert Dijkgraaf, Erik Verlinde, and Herman Verlinde.[2] Another matrix string theory equivalent to Type IIB string theory was constructed in 1996 by Ishibashi, Kawai, Kitazawa and Tsuchiya.[3] This version is known as the IKKT matrix model.

See also

- Matrix theory (physics)

References


In theoretical physics type I string theory is one of five consistent supersymmetric string theories in ten dimensions. It is the only one whose strings are unoriented (both orientations of a string are equivalent) and which contains not only closed strings, but also open strings.

Overview

The classic 1976 work of Ferdinando Gliozzi, Joel Scherk and David Olive\(^1\) paved the way to a systematic understanding of the rules behind string spectra in cases where only closed strings are present via modular invariance. It did not lead to similar progress for models with open strings, despite the fact that the original discussion was based on the type I string theory.

As first proposed by Augusto Sagnotti in 1988\(^2\) the type I string theory can be obtained as an orientifold of type IIB string theory, with 32 half-D9-branes added in the vacuum to cancel various anomalies.

At low energies, type I string theory is described by the N=1 supergravity (type I supergravity) in ten dimensions coupled to the SO(32) supersymmetric Yang–Mills theory. The discovery in 1984 by Michael Green and John H. Schwarz that anomalies in type I string theory cancel sparked the first superstring revolution. However, a key property of these models, shown by A. Sagnotti in 1992, is that in general the Green-Schwarz mechanism takes a more general form, and involves several two forms in the cancellation mechanism.

The relation between the type-IIB string theory and the type-I string theory has a large number of surprising consequences, both in ten and in lower dimensions, that were first displayed by the String Theory Group at the University of Rome Tor Vergata in the early 1990s. It opened the way to the construction of entire new classes of string spectra with or without supersymmetry. Joseph Polchinski's work on D-branes provided a geometrical interpretation for these results in terms of extended objects (D-brane, orientifold).

In the 1990s it was first argued by Edward Witten that type I string theory with the string coupling constant \(g\) is equivalent to the SO(32) heterotic string with the coupling \(1/g\). This equivalence is known as S-duality.

Notes


References


String theory landscape

The string theory landscape refers to the collection of possible false vacua in string theory,\textsuperscript{[1]} together comprising a collective "landscape" of choices of parameters governing compactifications.

The term "landscape" comes from the notion of a fitness landscape in evolutionary biology. It was first applied to cosmology by Lee Smolin in his book *The Life of the Cosmos* (1997), and was first used in the context of string theory by Leonard Susskind\textsuperscript{[2]}

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### Compactified Calabi–Yau manifolds

In string theory the number of false vacua is thought to be at least $10^{272,000}$\textsuperscript{[3]} The large number of possibilities arises from choices of Calabi–Yau manifolds and choices of generalized magnetic fluxes over various homology cycles, found in F-theory.

If there is no structure in the space of vacua, the problem of finding one with a sufficiently small cosmological constant is NP complete\textsuperscript{[4]}

This is a version of the subset sum problem

### Fine-tuning by anthropics

Fine-tuning of constants like the cosmological constant or the Higgs boson mass are usually assumed to occur for precise physical reasons as opposed to taking their particular values at random. That is, these values should be uniquely consistent with underlying physical laws.

The number of theoretically allowed configurations has prompted suggestions that this is not the case, and that many different vacua are physically realized\textsuperscript{[5]} The anthropic principle proposes that fundamental constants may have the values they have because such values are necessary for life (and hence intelligent observers to measure the constants). The anthropic landscape thus refers to the collection of those portions of the landscape that are suitable for supporting intelligent life.

In order to implement this idea in a concrete physical theory, it is necessary to postulate a multiverse in which fundamental physical parameters can take different values. This has been realized in the context of eternal inflation

Weinberg model
In 1987, Steven Weinberg proposed that the observed value of the cosmological constant was so small because it is impossible for life to occur in a universe with a much larger cosmological constant.

Weinberg attempted to predict the magnitude of the cosmological constant based on probabilistic arguments. Other attempts have been made to apply similar reasoning to models of particle physics.

Such attempts are based in the general ideas of Bayesian probability interpreting probability in a context where it is only possible to draw one sample from a distribution is problematic in frequentist probability but not in Bayesian probability, which is not defined in terms of the frequency of repeated events.

In such a framework, the probability $P(x)$ of observing some fundamental parameters $x$ is given by:

$$P(x) = P_{\text{prior}}(x) \times P_{\text{selection}}(x),$$

where $P_{\text{prior}}$ is the prior probability from fundamental theory of the parameters $x$ and $P_{\text{selection}}$ is the "anthropic selection function", determined by the number of "observers" that would occur in the universe with parameters $x$.

These probabilistic arguments are the most controversial aspect of the landscape. Technical criticisms of these proposals have pointed out that:

- The function $P_{\text{prior}}$ is completely unknown in string theory and may be impossible to define or interpret in any sensible probabilistic way
- The function $P_{\text{selection}}$ is completely unknown, since so little is known about the origin of life. Simplified criteria (such as the number of galaxies) must be used as a proxy for the number of observers. Moreover, it may never be possible to compute it for parameters radically different from those of the observable universe.

**Simplified approaches**

Tegmark et al. have recently considered these objections and proposed a simplified anthropic scenario for axion dark matter in which they argue that the first two of these problems do not apply.

Vilenkin and collaborators have proposed a consistent way to define the probabilities for a given vacuum.

A problem with many of the simplified approaches people have tried is that they "predict" a cosmological constant that is too large by a factor of 10–1000 orders of magnitude (depending on one's assumptions) and hence suggest that the cosmic acceleration should be much more rapid than is observed.

**Interpretation**

Few dispute the large number of metastable vacua. The existence, meaning, and scientific relevance of the anthropic landscape, however, remain controversial.

**Cosmological constant problem**

Andrei Linde, Sir Martin Rees and Leonard Susskind advocate it as a solution to the cosmological constant problem.

**Scientific relevance**

David Gross suggests that the idea is inherently unscientific, unfalsifiable or premature. A famous debate on the anthropic landscape of string theory is the Smolin–Susskind debate on the merits of the landscape.

**Popular reception**
There are several popular books about the anthropic principle in cosmology.[13] The authors of two physics blogs are opposed to this use of the anthropic principle.[14]

See also

- Extra dimensions

References


14. Lubos Motl's blog criticized the anthropic principle and Peter Woit's blog (http://www.math.columbia.edu/~woit/blog/) frequently attacks the anthropic string landscape.
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In **physics**, a **string** is a physical entity postulated in **string theory** and related subjects. Unlike **elementary particles** which are zero-dimensional or point-like by definition, strings are one-dimensional extended entities. Researchers often have an interest in string theories because theories in which the fundamental entities are strings rather than point particles automatically have many properties that some physicists expect to hold in a fundamental theory of physics. Most notably, a theory of strings that evolve and interact according to the rules of quantum mechanics will automatically describe quantum gravity.

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**Overview**

In string theory, the strings may be open (forming a segment with two endpoints) or closed (forming a loop like a circle) and may have other special properties. Prior to 1995, there were five known versions of string theory incorporating the idea of supersymmetry, which differed in the type of strings and in other aspects. Today these different string theories are thought to arise as different limiting cases of a single theory called M-theory.

In string theories of particle physics, the strings are very tiny; much smaller than can be observed in today's particle accelerators. The characteristic length scale of strings is typically on the order of the Planck length, about $10^{-35}$ meter, the scale at which the effects of quantum gravity are believed to become significant. Therefore on much larger length scales, such as the scales visible in physics laboratories, such entities would appear to be zero-dimensional point particles. Strings are able to vibrate as harmonic oscillators and different vibrational states of the same string would appear to be a different type of particle. In string theories, strings vibrating at different frequencies constitute the multiple fundamental particles found in the current Standard Model of particle physics. Strings are also sometimes studied in nuclear physics where they are used to model flux tubes.

As it propagates through spacetime, a string sweeps out a two-dimensional surface called its worldsheet. This is analogous to the one-dimensional worldline traced out by a point particle. The physics of a string is described by means of a two-dimensional conformal field theory associated with the worldsheet. The formalism of two-dimensional conformal field theory also has many applications outside of string theory for example in condensed matter physics and parts of pure mathematics.

**Types of strings**

**Closed and open strings**

Strings can be either open or closed. A **closed string** is a string that has no end-points, and therefore is topologically equivalent to a circle. An **open string** on the other hand, has two end-points and is topologically equivalent to a line interval. Not all string theories contain open strings, but every theory must contain closed strings, as interactions between open strings can always result in closed strings.
The oldest superstring theory containing open strings was type I string theory. However, the developments in string theory in the 1990s have shown that the open strings should always be thought of as ending on a new physical degree of freedom called D-branes, and the spectrum of possibilities for open strings has increased greatly.

Open and closed strings are generally associated with characteristic vibrational modes. One of the vibration modes of a closed string can be identified as the graviton. In certain string theories the lowest-energy vibration of an open string is a tachyon and can undergo tachyon condensation Other vibrational modes of open strings exhibit the properties of photons and gluons.

**Orientation**

Strings can also possess an orientation, which can be thought of as an internal "arrow" which distinguishes the string from one with the opposite orientation. By contrast, an unoriented string is one with no such arrow on it.

**See also**

- Elementary particle
- Brane
- D-brane

**References**

- "NOVA's strings homepage"


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Mirror symmetry (string theory)

In algebraic geometry and theoretical physics, mirror symmetry is a relationship between geometric objects called Calabi–Yau manifolds. The term refers to a situation where two Calabi–Yau manifolds look very different geometrically but are nevertheless equivalent when employed as extra dimensions of string theory.

Mirror symmetry was originally discovered by physicists. Mathematicians became interested in this relationship around 1990 when Philip Candelas, Xenia de la Ossa, Paul Green, and Linda Parkes showed that it could be used as a tool in enumerative geometry, a branch of mathematics concerned with counting the number of solutions to geometric questions. Candelas and his collaborators showed that mirror symmetry could be used to count rational curves on a Calabi–Yau manifold, thus solving a longstanding problem. Although the original approach to mirror symmetry was based on physical ideas that were not understood in a mathematically precise way, some of its mathematical predictions have since been proven rigorously.

Today, mirror symmetry is a major research topic in pure mathematics and mathematicians are working to develop a mathematical understanding of the relationship based on physicists' intuition. Mirror symmetry is also a fundamental tool for doing calculations in string theory, and it has been used to understand aspects of quantum field theory, the formalism that physicists use to describe elementary particles. Major approaches to mirror symmetry include the homological mirror symmetry program of Maxim Kontsevich and the SYZ conjecture of Andrew Strominger, Shing-Tung Yau, and Eric Zaslow.

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Overview

Strings and compactification

In physics, string theory is a theoretical framework in which the point-like particles of particle physics are replaced by one-dimensional objects called strings. These strings look like small segments or loops of ordinary string. String theory describes how strings propagate through space and interact with each other. On distance scales larger than the string scale, a string will look just like an ordinary particle, with its mass, charge, and other properties determined by the vibrational state of the string. Splitting and
recombination of strings correspond to particle emission and absorption, giving rise to the interactions between particles.\[1\]

There are notable differences between the world described by string theory and the everyday world. In everyday life, there are three familiar dimensions of space (up/down, left/right, and forward/backward), and there is one dimension of time (later/earlier). Thus, in the language of modern physics, one says that spacetime is four-dimensional.\[2\] One of the peculiar features of string theory is that it requires extra dimensions of spacetime for its mathematical consistency. In superstring theory, the version of the theory that incorporates a theoretical idea called supersymmetry, there are six extra dimensions of spacetime in addition to the four that are familiar from everyday experience.\[3\]

One of the goals of current research in string theory is to develop models in which the strings represent particles observed in high energy physics experiments. For such a model to be consistent with observations, its spacetime must be four-dimensional at the relevant distance scales, so one must look for ways to restrict the extra dimensions to smaller scales. In most realistic models of physics based on string theory, this is accomplished by a process called compactification, in which the extra dimensions are assumed to "close up" on themselves to form circles.\[4\] In the limit where these curled up dimensions become very small, one obtains a theory in which spacetime has effectively a lower number of dimensions. A standard analogy for this is to consider a multidimensional object such as a garden hose. If the hose is viewed from a sufficient distance, it appears to have only one dimension, its length. However, as one approaches the hose, one discovers that it contains a second dimension, its circumference. Thus, an ant crawling on the surface of the hose would move in two dimension.\[5\]

### Calabi–Yau manifolds

Compactification can be used to construct models in which spacetime is effectively four-dimensional. However, not every way of compactifying the extra dimensions produces a model with the right properties to describe nature. In a viable model of particle physics, the compact extra dimensions must be shaped like a Calabi–Yau manifold.\[4\] A Calabi–Yau manifold is a special space which is typically taken to be six-dimensional in applications to string theory. It is named after mathematicians Eugenio Calabi and Shing-Tung Yau.\[6\]

After Calabi–Yau manifolds had entered physics as a way to compactify extra dimensions, many physicists began studying these manifolds. In the late 1980s, Lance Dixon, Wolfgang Lerche, Cumrun Vafa, and Nick Warner noticed that given such a compactification of string theory, it is not possible to reconstruct uniquely a corresponding Calabi–Yau manifold.\[7\] Instead, two different versions of string theory called type IIA string theory and type IIB can be compactified on completely different Calabi–Yau manifolds giving rise to the same physics.\[8\] In this situation, the manifolds are called mirror manifolds, and the relationship between the two physical theories is called mirror symmetry.\[8\]

The mirror symmetry relationship is a particular example of what physicists call a duality. In general, the term duality refers to a situation where two seemingly different physical theories turn out to be equivalent in a nontrivial way. If one theory can be transformed so it looks just like another theory, the two are said to be dual under that transformation. Put differently, the two theories are mathematically different descriptions of the same phenomena.\[10\] Such dualities play an important role in modern physics, especially in string theory.\[11\]

Regardless of whether Calabi–Yau compactifications of string theory provide a correct description of nature, the existence of the mirror duality between different string theories has significant mathematical consequences.\[12\] The Calabi–Yau manifolds used in string theory are of interest in pure mathematics and mirror symmetry allows mathematicians to solve problems in enumerative...
algebraic geometry, a branch of mathematics concerned with counting the numbers of solutions to geometric questions. A classical problem of enumerative geometry is to enumerate the rational curves on a Calabi–Yau manifold such as the one illustrated above. By applying mirror symmetry, mathematicians have translated this problem into an equivalent problem for the mirror Calabi–Yau, which turns out to be easier to solve[13]

In physics, mirror symmetry is justified on physical grounds.[14] However, mathematicians generally require rigorous proofs that do not require an appeal to physical intuition. From a mathematical point of view, the version of mirror symmetry described above is still only a conjecture, but there is another version of mirror symmetry in the context of topological string theory, a simplified version of string theory introduced by Edward Witten[15] which has been rigorously proven by mathematicians[16] In the context of topological string theory, mirror symmetry states that two theories called the A-model and B-model are equivalent in the sense that there is a duality relating them.[17] Today mirror symmetry is an active area of research in mathematics, and mathematicians are working to develop a more complete mathematical understanding of mirror symmetry based on physicists' intuition.[18]

History

The idea of mirror symmetry can be traced back to the mid-1980s when it was noticed that a string propagating on a circle of radius $R$ is physically equivalent to a string propagating on a circle of radius $1/R$ in appropriate units[19] This phenomenon is now known as T-duality and is understood to be closely related to mirror symmetry.[20] In a paper from 1985, Philip Candelas, Gary Horowitz, Andrew Strominger, and Edward Witten showed that by compactifying string theory on a Calabi–Yau manifold, one obtains a theory roughly similar to the standard model of particle physics that also consistently incorporates an idea called supersymmetry.[21] Following this development, many physicists began studying Calabi–Yau compactifications, hoping to construct realistic models of particle physics based on string theory. Cumrun Vafa and others noticed that given such a physical model, it is not possible to reconstruct uniquely a corresponding Calabi–Yau manifold. Instead, there are two Calabi–Yau manifolds that give rise to the same physics.[22]

By studying the relationship between Calabi–Yau manifolds and certain conformal field theories called Gepner models, Brian Greene and Ronen Plesser found nontrivial examples of the mirror relationship[23] Further evidence for this relationship came from the work of Philip Candelas, Monika Lynker, and Rolf Schimmrigk, who surveyed a large number of Calabi–Yau manifolds by computer and found that they came in mirror pairs.[24]

Mathematicians became interested in mirror symmetry around 1990 when physicists Philip Candelas, Xenia de la Ossa, Paul Green, and Linda Parkes showed that mirror symmetry could be used to solve problems in enumerative geometry[25] that had resisted solution for decades or more.[26] These results were presented to mathematicians at a conference at the Mathematical Sciences Research Institute (MSRI) in Berkeley, California in May 1991. During this conference, it was noticed that one of the numbers Candelas had computed for the counting of rational curves disagreed with the number obtained by Norwegian mathematicians Geir Ellingsrud and Stein Arild Strømme using ostensibly more rigorous techniques.[27] Many mathematicians at the conference assumed that Candelas's work contained a mistake since it was not based on rigorous mathematical arguments. However, after examining their solution, Ellingsrud and Strømme discovered an error in their computer code and, upon fixing the code, they got an answer that agreed with the one obtained by Candelas and his collaborators.[28]

In 1990, Edward Witten introduced topological string theory,[15] a simplified version of string theory, and physicists showed that there is a version of mirror symmetry for topological string theory.[29] This statement about topological string theory is usually taken as the definition of mirror symmetry in the mathematical literature.[30] In an address at the International Congress of Mathematicians in 1994, mathematician Maxim Kontsevich presented a new mathematical conjecture based on the physical idea of mirror symmetry in topological string theory. Known as homological mirror symmetry, this conjecture formalizes mirror symmetry as an equivalence of two mathematical structures: the derived category of coherent sheaves on a Calabi–Yau manifold and the Fukaya category of its mirror.[31]

Also around 1995, Kontsevich analyzed the results of Candelas, which gave a general formula for the problem of counting rational curves on a quintic threefold and he reformulated these results as a precise mathematical conjecture.[32] In 1996, Alexander Givental posted a paper that claimed to prove this conjecture of Kontsevich.[33] Initially, many mathematicians found this paper hard to
understand, so there were doubts about its correctness. Subsequently, Bong Lian, Kefeng Liu, and Shing-Tung Yau published an independent proof in a series of papers. Despite controversy over who had published the first proof, these papers are now collectively seen as providing a mathematical proof of the results originally obtained by physicists using mirror symmetry. In 2000, Kentaro Hori and Cumrun Vafa gave another physical proof of mirror symmetry based on duality.

Work on mirror symmetry continues today with major developments in the context of strings on surfaces with boundaries. In addition, mirror symmetry has been related to many active areas of mathematics research, such as the McKay correspondence, topological quantum field theory, and the theory of stability conditions. At the same time, basic questions continue to vex. For example, mathematicians still lack an understanding of how to construct examples of mirror Calabi–Yau pairs though there has been progress in understanding this issue.

Applications

Enumerative geometry

Many of the important mathematical applications of mirror symmetry belong to the branch of mathematics called enumerative geometry. In enumerative geometry, one is interested in counting the number of solutions to geometric questions, typically using the techniques of algebraic geometry. One of the earliest problems of enumerative geometry was posed around the year 200 BCE by the ancient Greek mathematician Apollonius, who asked how many circles in the plane are tangent to three given circles. In general, the solution to the problem of Apollonius is that there are eight such circles.

Enumerative problems in mathematics often concern a class of geometric objects called algebraic varieties which are defined by the vanishing of polynomials. For example, the Clebsch cubic (see the illustration) is defined using a certain polynomial of degree three in four variables. A celebrated result of nineteenth-century mathematicians Arthur Cayley and George Salmon states that there are exactly 27 straight lines that lie entirely on such a surface.

Generalizing this problem, one can ask how many lines can be drawn on a quintic Calabi–Yau manifold, such as the one illustrated above, which is defined by a polynomial of degree five. This problem was solved by the nineteenth-century German mathematician Hermann Schubert, who found that there are exactly 2,875 such lines. In 1986, geometer Sheldon Katz proved that the number of curves, such as circles, that are defined by polynomials of degree two and lie entirely in the quintic is 609,250.

By the year 1991, most of the classical problems of enumerative geometry had been solved and interest in enumerative geometry had begun to diminish. According to mathematician Mark Gross, "As the old problems had been solved, people went back to check Schubert's numbers with modern techniques, but that was getting pretty stale." The field was reinvigorated in May 1991 when physicists Philip Candelas, Xenia de la Ossa, Paul Green, and Linda Parkes showed that mirror symmetry could be used to count the number of degree three curves on a quintic Calabi–Yau. Candelas and his collaborators found that these six-dimensional Calabi–Yau manifolds can contain exactly 317,206,375 curves of degree three.

In addition to counting degree-three curves on a quintic three-fold, Candelas and his collaborators obtained a number of more general results for counting rational curves which went far beyond the results obtained by mathematicians. Although the methods used in this work were based on physical intuition, mathematicians have gone on to prove rigorously some of the predictions of mirror symmetry.
symmetry. In particular, the enumerative predictions of mirror symmetry have now been rigorously proven.[35]

**Theoretical physics**

In addition to its applications in enumerative geometry, mirror symmetry is a fundamental tool for doing calculations in string theory. In the A-model of topological string theory, physically interesting quantities are expressed in terms of infinitely many numbers called Gromov–Witten invariants, which are extremely difficult to compute. In the B-model, the calculations can be reduced to classical integrals and are much easier.[42] By applying mirror symmetry, theorists can translate difficult calculations in the A-model into equivalent but technically easier calculations in the B-model. These calculations are then used to determine the probabilities of various physical processes in string theory. Mirror symmetry can be combined with other dualities to translate calculations in one theory into equivalent calculations in a different theory. By outsourcing calculations to different theories in this way, theorists can calculate quantities that are impossible to calculate without the use of dualities.[43]

Outside of string theory, mirror symmetry is used to understand aspects of quantum field theory, the formalism that physicists use to describe elementary particles. For example, gauge theories are a class of highly symmetric physical theories appearing in the standard model of particle physics and other parts of theoretical physics. Some gauge theories which are not part of the standard model, but which are nevertheless important for theoretical reasons, arise from strings propagating on a nearly singular background. For such theories, mirror symmetry is a useful computational tool.[44] Indeed, mirror symmetry can be used to perform calculations in an important gauge theory in four spacetime dimensions that was studied by Nathan Seiberg and Edward Witten and is also familiar in mathematics in the context of Donaldson invariants.[45] There is also a generalization of mirror symmetry called 3D mirror symmetry which relates pairs of quantum field theories in three spacetime dimensions.[46]

**Approaches**

**Homological mirror symmetry**

In string theory and related theories in physics, a brane is a physical object that generalizes the notion of a point particle to higher dimensions. For example, a point particle can be viewed as a brane of dimension zero, while a string can be viewed as a brane of dimension one. It is also possible to consider higher-dimensional branes. The word brane comes from the word "membrane" which refers to a two-dimensional brane.[47]

In string theory, a string may be open (forming a segment with two endpoints) or closed (forming a closed loop). D-branes are an important class of branes that arise when one considers open strings. As an open string propagates through spacetime, its endpoints are required to lie on a D-brane. The letter "D" in D-brane refers to a condition that it satisfies, the Dirichlet boundary condition.[48]

Mathematically, branes can be described using the notion of a category.[49] This is a mathematical structure consisting of objects, and for any pair of objects, a set of morphisms between them. In most examples, the objects are mathematical structures (such as sets, vector spaces, or topological spaces) and the morphisms are functions between these structures.[50] One can also consider categories where the objects are D-branes and the morphisms between two branes α and β are states of open strings stretched between α and β.[51]

In the B-model of topological string theory, the D-branes are complex submanifolds of a Calabi–Yau together with additional data that arise physically from having charges at the endpoints of strings.[51] Intuitively, one can think of a submanifold as a surface embedded inside the Calabi–Yau, although submanifolds can also exist in dimensions different from two.[26] In mathematical language, the category having these branes as its objects is known as the derived category of coherent sheaves on the Calabi–Yau.[52] In the A-model, the D-branes can again be viewed as submanifolds of a Calabi–Yau manifold. Roughly speaking, they are what
mathematicians call special Lagrangian submanifolds. This means among other things that they have half the dimension of the space in which they sit, and they are length-, area-, or volume-minimizing. The category having these branes as its objects is called the Fukaya category.

The derived category of coherent sheaves is constructed using tools from complex geometry, a branch of mathematics that describes geometric curves in algebraic terms and solves geometric problems using algebraic equations. On the other hand, the Fukaya category is constructed using symplectic geometry, a branch of mathematics that arose from studies of classical physics. Symplectic geometry studies spaces equipped with a symplectic form, a mathematical tool that can be used to compute area in two-dimensional examples.

The homological mirror symmetry conjecture of Maxim Kontsevich states that the derived category of coherent sheaves on one Calabi–Yau manifold is equivalent in a certain sense to the Fukaya category of its mirror. This equivalence provides a precise mathematical formulation of mirror symmetry in topological string theory. In addition, it provides an unexpected bridge between two branches of geometry namely complex and symplectic geometry.

### Strominger–Yau–Zaslow conjecture

Another approach to understanding mirror symmetry was suggested by Andrew Strominger, Shing-Tung Yau, and Eric Zaslow in 1996. According to their conjecture, now known as the SYZ conjecture, mirror symmetry can be understood by dividing a Calabi–Yau manifold into simpler pieces and then transforming them to get the mirror Calabi–Yau.

The simplest example of a Calabi–Yau manifold is a two-dimensional torus or donut shape. Consider a circle on this surface that goes once through the hole of the donut. An example is the red circle in the figure. There are infinitely many circles like it on a torus; in fact, the entire surface is a union of such circles.

One can choose an auxiliary circle (the pink circle in the figure) such that each of the infinitely many circles decomposing the torus passes through a point of . This auxiliary circle is said to parametrize the circles of the decomposition, meaning there is a correspondence between them and points of . The circle is more than just a list, however, because it also determines how these circles are arranged on the torus. This auxiliary space plays an important role in the SYZ conjecture.

The idea of dividing a torus into pieces parametrized by an auxiliary space can be generalized. Increasing the dimension from two to four real dimensions, the Calabi–Yau becomes a K3 surface. Just as the torus was decomposed into circles, a four-dimensional K3 surface can be decomposed into two-dimensional tori. In this case the space is an ordinary sphere. Each point on the sphere corresponds to one of the two-dimensional tori, except for twenty-four "bad" points corresponding to "pinched" singular tori.

The Calabi–Yau manifolds of primary interest in string theory have six dimensions. One can divide such a manifold into 3-tori (three-dimensional objects that generalize the notion of a torus) parametrized by a 3-sphere (a three-dimensional generalization of a sphere). Each point of corresponds to a 3-torus, except for infinitely many "bad" points which form a grid-like pattern of segments on the Calabi–Yau and correspond to singular tori.

Once the Calabi–Yau manifold has been decomposed into simpler parts, mirror symmetry can be understood in an intuitive geometric way. As an example, consider the torus described above. Imagine that this torus represents the "spacetime" for a physical theory. The fundamental objects of this theory will be strings propagating through the spacetime according to the rules of quantum mechanics. One of the basic dualities of string theory is T-duality, which states that a string propagating around a circle of radius is equivalent to a string propagating around a circle of radius . In the sense that all observable quantities in one description are identified with quantities in the dual description. For example, a string has momentum as it propagates around a circle, and it can also wind
around the circle one or more times. The number of times the string winds around a circle is called the winding number. If a string has momentum \( p \) and winding number \( n \) in one description, it will have momentum \( n \) and winding number \( p \) in the dual description.[61] By applying T-duality simultaneously to all of the circles that decompose the torus, the radii of these circles become inverted, and one is left with a new torus which is "fatter" or "skinnier" than the original. This torus is the mirror of the original Calabi–Yau.[62]

T-duality can be extended from circles to the two-dimensional tori appearing in the decomposition of a K3 surface or to the three-dimensional tori appearing in the decomposition of a six-dimensional Calabi–Yau manifold. In general, the SYZ conjecture states that mirror symmetry is equivalent to the simultaneous application of T-duality to these tori. In each case, the space \( \mathcal{B} \) provides a kind of blueprint that describes how these tori are assembled into a Calabi–Yau manifold.[63]

**See also**
- Donaldson–Thomas theory
- Wall-crossing

**Notes**

1. For an accessible introduction to string theory see Greene 2000.
2. Wald 1984, p. 4
3. Zwiebach 2009, p. 8
4. Yau and Nadis 2010, Ch. 6
5. This analogy is used for example in Greene 2000, p. 186
6. Yau and Nadis 2010, p. ix
8. The shape of a Calabi–Yau manifold is described mathematically using an array of numbers called Hodge numbers. The arrays corresponding to mirror Calabi–Yau manifolds are different in general, reflecting the different shapes of the manifolds, but they are related by a certain symmetry. For more information, see Yau and Nadis 2010, p. 160–3.
10. Hori et al. 2003, p. xvi
11. Other dualities that arise in string theory are S-duality, T-duality, and the AdS/CFT correspondence
15. Witten 1990
17. Zaslow 2008, p. 531
18. Hori et al. 2003, p. xix
19. This was first observed in Kikkawa and Yamasaki 1984 and Sakai and Senda 1986.
20. Strominger, Yau, and Zaslow 1996
21. Candelas et al. 1985
22. This was observed in Dixon 1988 and Lerche, Vafa, and Warner 1989.
25. Candelas et al. 1991
26. Yau and Nadis 2010, p. 165
27. Yau and Nadis 2010, pp. 169–170
29. Vafa 1992; Witten 1992
30. Hori et al. 2003, p. xviii
31. Kontsevich 1995a
32. Kontsevich 1995b
34. Lian, Liu, Yau 1997, 1999a, 1999b, 2000
35. Yau and Nadis 2010, p. 172
37. Zaslow 2008, p. 537
38. Yau and Nadis 2010, p. 166
40. Yau and Nadis 2010, p. 169
41. Yau and Nadis 2010, p. 171
42. Zaslow 2008, pp. 533–4
43. Zaslow 2008, sec. 10
44. Hori et al. 2003, p. 677
45. Hori et al. 2003, p. 679
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47. Moore 2005, p. 214
49. Aspinwall et al. 2009
50. A basic reference on category theory is Mac Lane 1998.
51. Zaslow 2008, p. 536
52. Aspinwal et al. 2009, p. 575
53. Yau and Nadis 2010, p. 175
54. Yau and Nadis 2010, pp. 180–1
55. Aspinwall et al. 2009, p. 616
56. Yau and Nadis 2010, p. 181
57. Yau and Nadis 2010, p. 174
58. Zaslow 2008, p. 533
59. Yau and Nadis 2010, p. 175–6
61. Zaslow 2008, p. 532
62. Yau and Nadis 2010, p. 178

References

Further reading

Popularizations


Textbooks

- Aspinwall, Paul; Bridgeland, Tom; Craw, Alastair; Douglas, Michael; Gross, Mark; Kapusti, Anton; Moore, Gregory; Segal, Graeme; Szendrői, Balázs; Wilson, R.M.H., eds. (2009). *Dirichlet Branes and Mirror Symmetry* American Mathematical Society ISBN 978-0-8218-3848-8


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In string theory, a heterotic string is a closed string (or loop) which is a hybrid ('heterotic') of a superstring and a bosonic string. There are two kinds of heterotic string, the heterotic SO(32) and the heterotic $E_8 \times E_8$, abbreviated to HO and HE. Heterotic string theory was first developed in 1985 by David Gross, Jeffrey Harvey, Emil Martinec, and Ryan Rohm[1] (the so-called "Princeton String Quartet",[2]) in one of the key papers that fueled the first superstring revolution.

### Overview

In string theory, the left-moving and the right-moving excitations are completely decoupled,[3] and it is possible to construct a string theory whose left-moving (counter-clockwise) excitations are treated as a bosonic string propagating in $D = 26$ dimensions, while the right-moving (clockwise) excitations are treated as a superstring in $D = 10$ dimensions.

The mismatched 16 dimensions must be compactified on an even, self-dual lattice (a discrete subgroup of a linear space). There are two possible even self-dual lattices in 16 dimensions, and it leads to two types of the heterotic string. They differ by the gauge group in 10 dimensions. One gauge group is $SO(32)$ (the HO string) while the other is $E_8 \times E_8$ (the HE string).[4]

These two gauge groups also turned out to be the only two anomaly-free gauge groups that can be coupled to the $N = 1$ supergravity in 10 dimensions. (Although not realized for quite some time, $U(496)$ and $E_8 \times U(1)^{248}$ are anomalous[5]).

Every heterotic string must be a closed string, not an open string; it is not possible to define any boundary conditions that would relate the left-moving and the right-moving excitations because they have a different character.

### String duality

String duality is a class of symmetries in physics that link different string theories. In the 1990s, it was realized that the strong coupling limit of the HO theory is type I string theory—a theory that also contains open strings; this relation is called S-duality. The HO and HE theories are also related by T-duality.

Because the various superstring theories were shown to be related by dualities, it was proposed that each type of string was a different limit of a single underlying theory called M-theory.

### References


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Bosonic string theory

Bosonic string theory is the original version of string theory, developed in the late 1960s. It is so called because it only contains bosons in the spectrum.

In the 1980s, supersymmetry was discovered in the context of string theory, and a new version of string theory called superstring theory (supersymmetric string theory) became the real focus. Nevertheless, bosonic string theory remains a very useful model to understand many general features of perturbative string theory, and many theoretical difficulties of superstrings can actually already be found in the context of bosonic strings.

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Problems

Although bosonic string theory has many attractive features, it falls short as a viable physical model in two significant areas.

First, it predicts only the existence of bosons whereas many physical particles are fermions.

Second, it predicts the existence of a mode of the string with imaginary mass, implying that the theory has an instability to a process known as "tachyon condensation".

In addition, bosonic string theory in a general spacetime dimension displays inconsistencies due to the conformal anomaly. But, as was first noticed by Claud Lovelace,[1] in a spacetime of 26 dimensions (25 dimensions of space and one of time), the critical dimension for the theory, the anomaly cancels. This high dimensionality is not necessarily a problem for string theory, because it can be formulated in such a way that along the 22 excess dimensions spacetime is folded up to form a small torus or other compact manifold. This would leave only the familiar four dimensions of spacetime visible to low energy experiments. The existence of a critical dimension where the anomaly cancels is a general feature of all string theories.

Types of bosonic strings

There are four possible bosonic string theories, depending on whether open strings are allowed and whether strings have a specified orientation. Recall that a theory of open strings also must include closed strings; open strings can be thought as having their endpoint fixed on a D25-brane that fills all of spacetime. A specific orientation of the string means that only interaction corresponding to an orientable worldsheet are allowed (e.g., two strings can only merge with equal orientation). A sketch of the spectra of the four possible theories is as follows:
Bosonic string theory

<table>
<thead>
<tr>
<th>Bosonic string theory</th>
<th>Non-positive $M^2$ states</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open and closed, oriented</td>
<td>tachyon, massless antisymmetric tensor, graviton, dilaton</td>
</tr>
<tr>
<td>Open and closed, unoriented</td>
<td>tachyon, graviton, dilaton</td>
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<tr>
<td>Closed, oriented</td>
<td>tachyon, $U(1)$ vector boson, antisymmetric tensor, graviton, dilaton</td>
</tr>
<tr>
<td>Closed, unoriented</td>
<td>tachyon, graviton, dilaton</td>
</tr>
</tbody>
</table>

Note that all four theories have a negative energy tachyon ($M^2 = -\frac{1}{\alpha'}$) and a massless graviton.

The rest of this article applies to the closed, oriented theory corresponding to borderless, orientable worldsheets.

Mathematics

Path integral perturbation theory

Bosonic string theory can be said to be defined by the path integral quantization of the Polyakov action

$$ I_0 [g, X] = \frac{T}{8\pi} \int_M d^2 \xi \sqrt{g} g^{mn} \partial_m x^\mu \partial_n x^\nu G_{\mu\nu} (x) $$

$x^\mu (\xi)$ is the field on the worldsheet describing the embedding of the string in 25+1 spacetime; in the Polyakov formulation, $g$ is not to be understood as the induced metric from the embedding, but as an independent dynamical field. $G$ is the metric on the target spacetime, which is usually taken to be the Minkowski metric in the perturbative theory. Under a Wick rotation, this is brought to a Euclidean metric $G_{\mu\nu} = \delta_{\mu\nu}$. $M$ is the worldsheet as a topological manifold parametrized by the $\xi$ coordinates. $T$ is the string tension and related to the Regge slope as $T = \frac{1}{2\pi \alpha'}$.

$I_0$ has diffeomorphism and Weyl invariance. Weyl symmetry is broken upon quantization (Conformal anomaly) and therefore this action has to be supplemented with a counterterm, along with a hypothetical purely topological term, proportional to the Euler characteristic:

$$ I = I_0 + \lambda \chi(M) + \mu_0^2 \int_M d^2 \xi \sqrt{g} $$

The explicit breaking of Weyl invariance by the counterterm can be cancelled away in the critical dimension.

Physical quantities are then constructed from the (Euclidean) partition function and $N$-point function

$$ Z = \sum_{h=0}^{\infty} \int \frac{Dg_{mn} DX^\mu}{N} \exp(-I[g, X]) $$

$$ \langle V_1 (k_1^\mu) \cdots V_p (k_p^\mu) \rangle = \sum_{h=0}^{\infty} \int \frac{Dg_{mn} DX^\mu}{N} \exp(-I[g, X]) V_1 (k_1^\mu) \cdots V_p (k_p^\mu) $$

The discrete sum is a sum over possible topologies, which for euclidean bosonic orientable closed strings are compact orientable Riemannian surfaces and are thus identified by a genus $h$. A normalization factor $N$ is introduced to compensate overcounting from symmetries. While the computation of the partition function corresponds to the cosmological constant, the $N$-point function, including $p$ vertex operators, describes the scattering amplitude of strings.

The perturbative series is expressed as a sum over topologies, indexed by the genus.
The symmetry group of the action actually reduces drastically the integration space to a finite dimensional manifold. The $g$ path-integral in the partition function is a priori a sum over possible Riemannian structures; however, quotienting with respect to Weyl transformations allows us to only consider conformal structures, that is, equivalence classes of metrics under the identifications of metrics related by

$$g'(\xi) = e^{\sigma(\xi)} g(\xi)$$

Since the world-sheet is two dimensional, there is a 1-1 correspondence between conformal structures and complex structures. One still has to quotient away diffeomorphisms. This leaves us with an integration over the space of all possible complex structures modulo diffeomorphisms, which is simply the moduli space of the given topological surface, and is in fact a finite-dimensional complex manifold. The fundamental problem of perturbative bosonic strings therefore becomes the parametrization of Moduli space, which is non-trivial for genus $h \geq 4$.

$h = 0$

At tree-level, corresponding to genus 0, the cosmological constant vanishes $\mathcal{Z}_0 = 0$.

The four-point function for the scattering of four tachyons is the Shapiro-Virasoro amplitude:

$$A_4 \propto (2\pi)^{26} \delta^{26}(k) \frac{\Gamma(-1 - s/2)\Gamma(-1 - t/2)\Gamma(-1 - u/2)}{\Gamma(2 + s/2)\Gamma(2 + t/2)\Gamma(2 + u/2)}$$

Where $k$ is the total momentum and $s, t, u$ are the Mandelstam variables.

$h = 1$

Genus 1 is the torus, and corresponds to the one-loop level. The partition function amounts to:

$$Z_1 = \int_{\mathcal{M}_1} \frac{d^2 \tau}{8\pi^2 \tau_2^2} \frac{1}{(4\pi^2 \tau_2)^12} |\eta(\tau)|^{-48}$$

$t$ is a complex number with positive imaginary part $\tau_2$; $\mathcal{M}_1$, holomorphic to the moduli space of the torus, is any fundamental domain for the modular group $PSL(2,\mathbb{Z})$ acting on the upper half-plane, for example $\left\{ \tau_2 > 0, |\tau|^2 > 1, -\frac{1}{2} < \tau_1 < {1}{2} \right\}$. $\eta(\tau)$ is the Dedekind $\eta$ function. The integrand is of course invariant under the modular group: the measure $\frac{d^2 \tau}{\tau_2}$ is simply the Poincaré metric which has $PSL(2,\mathbb{R})$ as isometry group; the rest of the integrand is also invariant by virtue of $\tau_2 \to |c\tau + d|^2 \tau_2$ and the fact that $\eta(\tau)$ is a modular form of weight 1/2.

This integral diverges. This is due to the presence of the tachyon and is related to the instability of the perturbative vacuum.

**See also**

- Nambu–Goto action
- Polyakov action

**Notes**

2. D’Hoker, Phong

### References


### External links

- How many string theories are there?
- PIRSA:C09001 - Introduction to the Bosonic String


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String field theory(SFT) is a formalism in string theory in which the dynamics of relativistic strings is reformulated in the language of quantum field theory. This is accomplished at the level of perturbation theory by finding a collection of vertices for joining and splitting strings, as well as string propagators, that give a Feynman diagram-like expansion for string scattering amplitudes. In most string field theories, this expansion is encoded by a classical action found by second-quantizing the free string and adding interaction terms. As is usually the case in second quantization, a classical field configuration of the second-quantized theory is given by a wave function in the original theory. In the case of string field theory, this implies that a classical configuration, usually called the string field, is given by an element of the free string Fock space.

The principal advantages of the formalism are that it allows the computation of off-shell amplitudes and, when a classical action is available, gives non-perturbative information that cannot be seen directly from the standard genus expansion of string scattering. In particular, following the work of Ashoke Sen:[1] it has been useful in the study of tachyon condensation on unstable D-branes. It has also had applications to topological string theory,[2] non-commutative geometry,[3] and strings in low dimensions.[4]

String field theories come in a number of varieties depending on which type of string is second quantized: Open string field theories describe the scattering of open strings, closed string field theories describe closed strings, while open-closed string field theories include both open and closed strings.

In addition, depending on the method used to fix the worldsheet diffeomorphisms and conformal transformations in the original free string theory, the resulting string field theories can be very different. Using light cone gauge, yields light-cone string field theories whereas using BRST quantization, one finds covariant string field theories. There are also hybrid string field theories, known as covariantized light-cone string field theories which use elements of both light-cone and BRST gauge-fixed string field theories.[5]

A final form of string field theory, known as background independent open string field theory, takes a very different form; instead of second quantizing the worldsheet string theory it second quantizes the space of two-dimensional quantum field theory.[6]
Light-cone string field theories were introduced by Stanley Mandelstam\textsuperscript{[7]} and developed by Mandelstam, Michael Green, John Schwarz and Lars Brink.\textsuperscript{[8]} An explicit description of the second-quantization of the light-cone string was given by Michio Kaku and Keiji Kikkawa.\textsuperscript{[9]}

Light-cone string field theories were the first string field theories to be constructed and are based on the simplicity of string scattering in light-cone gauge. For example, in the bosonic closed string case, the worldsheet scattering diagrams naturally take a Feynman diagram-like form, being built from two ingredients, propagator,

\[
p^+ \quad \Delta X^+ \\
\]

and two vertices for splitting and joining strings, which can be used to glue three propagators together.

These vertices and propagators produce a single cover of the moduli space of $n$-point closed string scattering amplitudes so no higher order vertices are required.\textsuperscript{[10]} Similar vertices exist for the open string.

When one considers light-cone quantized superstrings, the discussion is more subtle as divergences can arise when the light-cone vertices collide.\textsuperscript{[11]} To produce a consistent theory, it is necessary to introduce higher order vertices, called contact terms, to cancel the divergences.

Light-cone string field theories have the disadvantage that they break manifest Lorentz invariance. However, in backgrounds with light-like killing vectors, they can considerably simplify the quantization of the string action. Moreover, until the advent of the Berkovits string\textsuperscript{[12]} it was the only known method for quantizing strings in the presence of Ramond–Ramond fields. In recent research, light-cone string field theory played an important role in understanding strings in pp-wave backgrounds.

**Free covariant string field theory**

An important step in the construction of covariant string field theories (preserving manifest Lorentz invariance) was the construction of a covariant kinetic term. This kinetic term can be considered a string field theory in its own right: the string field theory of free strings. Since the work of Warren Siegel,\textsuperscript{[14]} it has been standard to first BRST-quantize the free string theory and then second quantize so that the classical fields of the string field theory include ghosts as well as matter fields. For example, in the case of the bosonic open string theory in 26-dimensional flat spacetime, a general element of the Fock-space of the BRST quantized string takes the form (in radial quantization in the upper half plane),

\[
|\Psi\rangle = \int d^{26}p \left( T(p)c_1 e^{ip\cdot X} |0\rangle + A_\mu (p)\partial X^\mu c_1 e^{ip\cdot X} |0\rangle + \chi(p)c_0 e^{ip\cdot X} |0\rangle + \ldots \right),
\]

where $|0\rangle$ is the free string vacuum and the dots represent more massive fields. In the language of worldsheet string theory, $T(p)$, $A_\mu (p)$, and $\chi(p)$ represent the amplitudes for the string to be found in the various basis states. After second quantization, they are interpreted instead as classical fields representing the tachyon $T$, gauge field $A_\mu$ and a ghost field $\chi$. 

In the worldsheet string theory, the unphysical elements of the Fock space are removed by imposing the condition $Q_B |\Psi\rangle = 0$ as well as the equivalence relation $|\Psi\rangle \sim |\Psi\rangle + Q_B |\Lambda\rangle$. After second quantization, the equivalence relation is interpreted as a gauge invariance, whereas the condition that $|\Psi\rangle$ is physical is interpreted as an equation of motion. Because the physical fields live at ghostnumber one, it is also assumed that the string field $|\Psi\rangle$ is a ghostnumber one element of the Fock space.

In the case of the open bosonic string a gauge-unfixed action with the appropriate symmetries and equations of motion was originally obtained by André Neveu, Hermann Nicolai and Peter C. West. It is given by

$$S_{\text{free open}}(\Psi) = \frac{1}{2} \langle \Psi | Q_B | \Psi \rangle,$$

where $\langle \Psi \rangle$ is the BPZ-dual of $|\Psi\rangle$.

For the bosonic closed string, construction of a BRST-invariant kinetic term requires additionally that one impose $(L_0 - \tilde{L}_0)|\Psi\rangle = 0$ and $(b_0 - \tilde{b}_0)|\Psi\rangle = 0$. The kinetic term is then

$$S_{\text{free closed}} = \frac{1}{2} \langle \Psi \mid (c_0 - \tilde{c}_0) Q_B | \Psi \rangle.$$

Additional considerations are required for the superstrings to deal with the superghost zero-modes.

**Witten's cubic open string field theory**

The best studied and simplest of covariant interacting string field theories was constructed by Edward Witten. It describes the dynamics of bosonic open strings and is given by adding to the free open string action a cubic vertex:

$$S(\Psi) = \frac{1}{2} \langle \Psi | Q_B | \Psi \rangle + \frac{1}{3} \langle \Psi, \Psi, \Psi \rangle,$$

where, as in the free case, $\Psi$ is a ghostnumber one element of the BRST-quantized free bosonic open-string Fock-space.

The cubic vertex,

$$\langle \Psi_1, \Psi_2, \Psi_3 \rangle$$

is a trilinear map which takes three string fields of total ghostnumber three and yields a number. Following Witten, who was motivated by ideas from noncommutative geometry, it is conventional to introduce the $\ast$-product defined implicitly through

$$\langle \Sigma | \Psi_1 \ast \Psi_2 \rangle = \langle \Sigma, \Psi_1, \Psi_2 \rangle.$$

The $\ast$-product and cubic vertex satisfy a number of important properties (allowing the $\Psi_i$ to be general ghost number fields):

1. **Cyclicity**:

   $$\langle \Psi_1, \Psi_2, \Psi_3 \rangle = (-1)^{g_1(\Psi_2) \cdot (g_1(\Psi_3) + g_1(\Psi_1))} \langle \Psi_3, \Psi_1, \Psi_2 \rangle$$

2. **BRST invariance**:

   $$Q_B(\Psi_1, \Psi_2, \Psi_3) = (Q_B \Psi_1, \Psi_2, \Psi_3) + (-1)^{g_1(\Psi_1) + g_1(\Psi_2)} \langle \Psi_1, Q_B \Psi_2, \Psi_3 \rangle + (-1)^{g_1(\Psi_1) + g_1(\Psi_2)} \langle \Psi_1, \Psi_2, Q_B \Psi_3 \rangle$$

   For the $\ast$-product, this implies that $Q_B$ acts as a graded derivation

   $$Q_B(\Psi_1 \ast \Psi_2) = (Q_B \Psi_1) \ast \Psi_2 + (-1)^{g_1(\Psi_1)} \Psi_1 \ast (Q_B \Psi_2)$$

3. **Associativity**

   $$(\Psi_1 \ast \Psi_2) \ast \Psi_3 = \Psi_1 \ast (\Psi_2 \ast \Psi_3)$$

   In terms of the cubic vertex,

   $$\langle \Psi_1, \Psi_2 \ast \Psi_3, \Psi_4 \rangle = \langle \Psi_1, \Psi_2, \Psi_3 \ast \Psi_4 \rangle$$
In these equations, $gn(\Psi)$ denotes the ghost number of $\Psi$.

**Gauge invariance**

These properties of the cubic vertex are sufficient to show that $S(\Psi)$ is invariant under the Yang–Mills-like gauge transformation,

$$\Psi \rightarrow \Psi + Q_B \Lambda + \Psi \ast \Lambda - \Lambda \ast \Psi,$$

where $\Lambda$ is an infinitesimal gauge parameter. Finite gauge transformations take the form

$$\Psi \rightarrow e^{-\Lambda}(\Psi + Q_B)e^{\Lambda},$$

where the exponential is defined by

$$e^{\Lambda} = 1 + \Lambda + \frac{1}{2!} \Lambda \ast \Lambda + \frac{1}{3!} \Lambda \ast \Lambda \ast \Lambda + \ldots.$$

**Equations of motion**

The equations of motion are given by the following equation:

$$Q_B \Psi + \Psi \ast \Psi = 0.$$

Because the string field $\Psi$ is an infinite collection of ordinary classical fields, these equations represent an infinite collection of non-linear coupled differential equations. There have been two approaches to finding solutions: First, numerically, one can truncate the string field to include only fields with mass less than a fixed bound, a procedure known as “level truncation”[18] This reduces the equations of motion to a finite number of coupled differential equations and has led to the discovery of many solutions[19]. Second, following the work of Martin Schnabl[20] one can seek analytic solutions by carefully picking an ansatz which has simple behavior under star multiplication and action by the BRST operator. This has led to solutions representing marginal deformations, the tachyon vacuum solution[21] and time-independent D-brane systems[22].

**Quantization**

To consistently quantize $S(\Psi)$ one has to fix a gauge. The traditional choice has been Feynman–Siegel gauge,

$$b_0 \Psi = 0.$$

Because the gauge transformations are themselves redundant (there are gauge transformations of the gauge transformations), the gauge fixing procedure requires introducing an infinite number of ghosts via the BV formalism[23]. The complete gauge fixed action is given by

$$S_{\text{gauge-fixed}} = \frac{1}{2} \langle \Psi | c_0 L_0 | \Psi \rangle + \frac{1}{3} \langle \Psi, \Psi, \Psi \rangle,$$

where the field $\Psi$ is now allowed to be of arbitrary ghostnumber. In this gauge, the Feynman diagrams are constructed from a single propagator and vertex. The propagator takes the form of a strip of worldsheet of width $\pi$ and length $T$.

![Propagator Diagram](image)

There is also an insertion of an integral of the $\gamma_5$ ghost along the red line. The modulus, $T$, is integrated from 0 to $\infty$. 
The three vertex can be described as a way of gluing three propagators together, as shown in the following picture:

In order to represent the vertex embedded in three dimensions, the propagators have been folded in half along their midpoints. The resulting geometry is completely flat except for a single curvature singularity where the midpoints of the three propagators meet.

These Feynman diagrams generate a complete cover of the moduli space of open string scattering diagrams. It follows that, for on-shell amplitudes, then-point open string amplitudes computed using Witten’s open string field theory are identical to those computed using standard worldsheet methods.

**Supersymmetric covariant open string field theories**

There are two main constructions of supersymmetric extensions of Witten’s cubic open string field theory. The first is very similar in form to its bosonic cousin and is known as *modified cubic superstring field theory*. The second, due to Nathan Berkovits is very different and is based on a WZW-type action.

**Modified cubic superstring field theory**

The first consistent extension of Witten’s bosonic open string field theory to the RNS string was constructed by Christian Preitschopf, Charles Thorn and Scott Yost and independently by Irina Aref’eva, P. B. Medvedev and A. P. Zubarev. The NS string field is taken to be a ghostnumber one picture zero string field in the small Hilbert space (i.e. \( \eta_0 | \Psi \rangle = 0 \)). The action takes a very similar form to bosonic action,

\[
S(\Psi) = \frac{1}{2} \langle \Psi | Y(i)Y(-i)Q_B | \Psi \rangle + \frac{1}{3} \langle \Psi | Y(i)Y(-i) | \Psi \ast \Psi \rangle ,
\]

where,

\[
Y(z) = -\partial \xi e^{-2\phi} c(z)
\]

is the inverse picture changing operator. The suggested \(-\frac{1}{2}\) picture number extension of this theory to the Ramond sector might be problematic.

This action has been shown to reproduce tree-level amplitudes and has a tachyon vacuum solution with the correct energy. The one subtlety in the action is the insertion of picture changing operators at the midpoint, which imply that the linearized equations of motion take the form

\[
Y(i)Y(-i)Q_B \Psi = 0 .
\]

Because \( Y(i)Y(-i) \) has a non-trivial kernel, there are potentially extra solutions that are not in the cohomology of \( Q_B \). However, such solutions would have operator insertions near the midpoint and would be potentially singular, and importance of this problem remains unclear.

**Berkovits superstring field theory**
A very different supersymmetric action for the open string was constructed by Nathan Berkovits. It takes the form

\[ S = \frac{1}{2} \langle e^{-\Phi} Q_B e^{\Phi} | e^{-\Phi} \eta_0 e^{\Phi} \rangle - \frac{1}{2} \int_0^1 dt \langle e^{-\Phi} \partial_t e^{\Phi} | \{ e^{-\Phi} Q_B e^{\Phi}, e^{-\Phi} \eta_0 e^{\Phi} \} \rangle \]

where all of the products are performed using the \(*\)-product including the anticommutator \{\}, and \(\Phi(t)\) is any string field such that \(\Phi(0) = 0\) and \(\Phi(1) = \Phi\). The string field \(\Phi\) is taken to be in the NS sector of the large Hilbert space, i.e. including the zero mode of \(\xi\). It is not known how to incorporate the R sector although some preliminary ideas exist.

The equations of motion take the form

\[ \eta_0 (e^{-\Phi} Q_B e^{\Phi}) = 0. \]

The action is invariant under the gauge transformation

\[ e^\Phi \rightarrow e^{QB^\Lambda} e^\Phi e^{\eta_0 \Lambda^\prime}. \]

The principal advantage of this action is that it free from any insertions of picture-changing operators. It has been shown to reproduce correctly tree level amplitudes and has been found, numerically, to have a tachyon vacuum with appropriate energy. The known analytic solutions to the classical equations of motion include the tachyon vacuum and marginal deformations.

Other formulations of covariant open superstring field theory

A formulation of superstring field theory using the non-minimal pure-spinor variables was introduced by Berkovits. The action is cubic and includes a midpoint insertion whose kernel is trivial. As always within the pure-spinor formulation, the Ramond sector can be easily treated. However it is not known how to incorporate the GSO- sectors into the formalism.

In an attempt to resolve the allegedly problematic midpoint insertion of the modified cubic theory, Berkovits and Siegel proposed a superstring field theory based on a non-minimal extension of the RNS string, which uses a midpoint insertion with no kernel. It is not clear if such insertions are in any way better than midpoint insertions with non-trivial kernels.

Covariant closed string field theory

Covariant closed string field theories are considerably more complicated than their open string cousins. Even if one wants to construct a string field theory which only reproduces tree-level interactions between closed strings, the classical action must contain an infinite number of vertices consisting of string polyhedra.

If one demands that on-shell scattering diagrams be reproduced to all orders in the string coupling, one must also include additional vertices arising from higher genus (and hence higher order in \(\hbar\)) as well. In general, a manifestly BV invariant, quantizable action takes the form

\[ S(\Psi) = \hbar \sum_{g \geq 0} (\hbar g_c)^{g-1} \sum_{n \geq 0} \frac{1}{n!} \{ \Psi^n \}_g \]

where \(\{ \Psi^n \}_g\) denotes an \(n\)th order vertex arising from a genus \(g\) surface and \(g_c\) is the closed string coupling. The structure of the vertices is in principle determined by a minimal area prescription although, even for the polyhedral vertices, explicit computations have only been performed to quintic order.

Covariant heterotic string field theory

A formulation of the NS sector of the heterotic string was given by Berkovits, Okawa and Zwiebach. The formulation amalgams bosonic closed string field theory with Berkovits' superstring field theory.
See also

- Conformal field theory
- F-theory
- Fuzzballs
- List of string theory topics
- Little string theory
- Loop quantum gravity
- Relationship between string theory and quantum field theory
- String cosmology
- Supergravity
- The Elegant Universe
- Zeta function regularization

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Superstring theory

Superstring theory is an attempt to explain all of the particles and fundamental forces of nature in one theory by modeling them as vibrations of tiny supersymmetric strings.

'Superstring theory' is a shorthand for supersymmetric string theory because unlike bosonic string theory, it is the version of string theory that accounts for both fermions and bosons and incorporates supersymmetry to model gravity.

Since the second superstring revolution, the five superstring theories are regarded as different limits of a single theory tentatively called M-theory.

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Background

The deepest problem in theoretical physics is harmonizing the theory of general relativity, which describes gravitation and applies to large-scale structures (stars, galaxies, super clusters), with quantum mechanics, which describes the other three fundamental forces acting on the atomic scale.

The development of a quantum field theory of a force invariably results in infinite possibilities. Physicists developed the technique of renormalization to eliminate these infinities; this technique works for three of the four fundamental forces—electromagnetic, strong nuclear and weak nuclear forces—but not for gravity. Development of quantum theory of gravity therefore requires different means than those used for the other forces.[1]

According to the theory, the fundamental constituents of reality are strings of the Planck length (about $10^{-33}$ cm) that vibrate at resonant frequencies. Every string, in theory, has a unique resonance, or harmonic. Different harmonics determine different fundamental particles. The tension in a string is on the order of the Planck force ($10^{44}$ newtons). The graviton (the proposed messenger particle of the gravitational force), for example, is predicted by the theory to be a string with wave amplitude zero.
History

Investigating how a string theory may include fermions in its spectrum led to the invention of supersymmetry (in the West)\(^2\) in 1971,\(^3\) a mathematical transformation between bosons and fermions. String theories that include fermionic vibrations are now known as "superstring theories".

Since its beginnings in the seventies and through the combined efforts of many different researchers, superstring theory has developed into a broad and varied subject with connections to quantum gravity, particle and condensed matter physics, cosmology, and pure mathematics.

Lack of experimental evidence

Superstring theory is based on supersymmetry. No supersymmetric particles have been discovered and recent research at LHC and Tevatron has excluded some of the ranges.\(^4\)\(^5\)\(^6\)\(^7\) For instance, the mass constraint of the Minimal Supersymmetric Standard Model squarks has been up to 1.1 TeV, and gluinos up to 500 GeV.\(^8\) No report on suggesting large extra dimensions has been delivered from LHC. There have been no principles so far to limit the number of vacua in the concept of a landscape of vacua.\(^9\)

Some particle physicists became disappointed by the lack of experimental verification of supersymmetry, and some have already discarded it; Jon Butterworth at University College London said that we had no sign of supersymmetry, even in higher energy region, excluding the superpartners of the top quark up to a few TeV. Ben Allanach at the University of Cambridge states that if we do not discover any new particles in the next trial at the LHC, then we can say it is unlikely to discover supersymmetry at CERN in the foreseeable future.\(^10\)

Extra dimensions

Our physical space is observed to have three large spatial dimensions and, along with time, is a boundless 4-dimensional continuum known as spacetime. However, nothing prevents a theory from including more than 4 dimensions. In the case of string theory, consistency requires spacetime to have 10 dimensions (3D regular space + 1 time + 6D hyperspace).\(^11\) The fact that we see only 3 dimensions of space can be explained by one of two mechanisms: either the extra dimensions are compactified on a very small scale, or else our world may live on a 3-dimensional submanifold corresponding to a brane, on which all known particles besides gravity would be restricted.

If the extra dimensions are compactified, then the extra 6 dimensions must be in the form of a Calabi–Yau manifold. Within the more complete framework of M-theory, they would have to take form of a G2 manifold. Calabi-Yaus are interesting mathematical spaces in their own right. A particular exact symmetry of string/M-theory called T-duality (which exchanges momentum modes for winding number and sends compact dimensions of radius R to radius 1/R),\(^12\) has led to the discovery of equivalences between different Calabi–Yau manifolds called mirror symmetry.

Superstring theory is not the first theory to propose extra spatial dimensions. It can be seen as building upon the Kaluza–Klein theory, which proposed a 4+1 dimensional (5D) theory of gravity. When compactified on a circle, the gravity in the extra dimension precisely describes electromagnetism from the perspective of the 3 remaining large space dimensions. Thus the original Kaluza–Klein theory is a prototype for the unification of gauge and gravity interactions, at least at the classical level, however it is known to be insufficient to describe nature for a variety of reasons (missing weak and strong forces, lack of parity violation, etc.) A more complex compact geometry is needed to reproduce the known gauge forces. Also, to obtain a consistent, fundamental, quantum theory requires the upgrade to string theory not just the extra dimensions.

Number of superstring theories

Theoretical physicists were troubled by the existence of five separate superstring theories. A possible solution for this dilemma was suggested at the beginning of what is called the second superstring revolution in the 1990s, which suggests that the five string theories might be different limits of a single underlying theory, called M-theory. This remains a conjecture.\(^13\)
The five consistent superstring theories are:

- The type I string has one supersymmetry in the ten-dimensional sense (16 supercharges). This theory is special in the sense that it is based on unoriented open and closed strings, while the rest are based on oriented closed strings.
- The type II string theories have two supersymmetries in the ten-dimensional sense (32 supercharges). There are actually two kinds of type II strings called type IIA and type IIB. They differ mainly in the fact that the IIA theory is non-chiral (parity conserving) while the IIB theory is chiral (parity violating).
- The heterotic string theories are based on a peculiar hybrid of a type I superstring and a bosonic string. There are two kinds of heterotic strings differing in their ten-dimensional gauge groups: the heterotic $E_8 \times E_8$ string and the heterotic SO(32) string. (The name heterotic SO(32) is slightly inaccurate since among the SO(32) Lie groups, string theory singles out a quotient Spin(32)/$\mathbb{Z}_2$ that is not equivalent to SO(32).)

Chiral gauge theories can be inconsistent due to anomalies. This happens when certain one-loop Feynman diagrams cause a quantum mechanical breakdown of the gauge symmetry. The anomalies were canceled out via the Green–Schwarz mechanism.

Even though there are only five superstring theories, making detailed predictions for real experiments requires information about exactly what physical configuration the theory is in. This considerably complicates efforts to test string theory because there is an astronomically high number—$10^{500}$ or more—of configurations that meet some of the basic requirements to be consistent with our world. Along with the extreme remoteness of the Planck scale, this is the other major reason it is hard to test superstring theory.

Another approach to the number of superstring theories refers to the mathematical structure called composition algebra. In the findings of abstract algebra there are just seven composition algebras over the field of real numbers. In 1990 physicists R. Foot and G.C. Joshi in Australia stated that "the seven classical superstring theories are in one-to-one correspondence to the seven composition algebras".[14]

**Integrating general relativity and quantum mechanics**

General relativity typically deals with situations involving large mass objects in fairly large regions of spacetime whereas quantum mechanics is generally reserved for scenarios at the atomic scale (small spacetime regions). The two are very rarely used together, and the most common case that combines them is in the study of black holes. Having peak density, or the maximum amount of matter possible in a space, and very small area, the two must be used in synchrony to predict conditions in such places. Yet, when used together, the equations fall apart, spitting out impossible answers, such as imaginary distances and less than one dimension.

The major problem with their congruence is that, at Planck scale (a fundamental small unit of length) lengths, general relativity predicts a smooth, flowing surface, while quantum mechanics predicts a random, warped surface, which are nowhere near compatible. Superstring theory resolves this issue, replacing the classical idea of point particles with strings. These strings have an average diameter of the Planck length, with extremely small variances, which completely ignores the quantum mechanical
predictions of Planck-scale length dimensional warping. Also, these surfaces can be mapped as branes. These branes can be viewed as objects with a morphism between them. In this case, the morphism will be the state of a string that stretches between brane A and brane B.

Singularities are avoided because the observed consequences of "Big Crunches" never reach zero size. In fact, should the universe begin a "big crunch" sort of process, string theory dictates that the universe could never be smaller than the size of one string, at which point it would actually begin expanding.

**Mathematics**

**D-branes**

D-branes are membrane-like objects in 10D string theory. They can be thought of as occurring as a result of a Kaluza–Klein compactification of 11D M-theory that contains membranes. Because compactification of a geometric theory produces extra vector fields the D-branes can be included in the action by adding an extra U(1) vector field to the string action.

\[ \partial_z \to \partial_z + iA_z(z, \bar{z}) \]

In type I open string theory, the ends of open strings are always attached to D-brane surfaces. A string theory with more gauge fields such as SU(2) gauge fields would then correspond to the compactification of some higher-dimensional theory above 11 dimensions, which is not thought to be possible to date. Furthermore, the tachyons attached to the D-branes show the instability of those d-branes with respect to the annihilation. The tachyon total energy is (or reflects) the total energy of the D-branes.

**Why five superstring theories?**

For a 10 dimensional supersymmetric theory we are allowed a 32-component Majorana spinor. This can be decomposed into a pair of 16-component Majorana-Weyl (chiral) spinors. There are then various ways to construct an invariant depending on whether these two spinors have the same or opposite chiralities:

<table>
<thead>
<tr>
<th>Superstring model</th>
<th>Invariant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heterotic</td>
<td>[ \partial \bar{\theta} \Gamma^\mu \partial_z \theta = 0 ]</td>
</tr>
<tr>
<td>IIA</td>
<td>[ \partial \bar{\theta} \Gamma^\mu \partial_z \theta - \partial \bar{\theta} \Gamma^\mu \partial_z \theta = 0 ]</td>
</tr>
<tr>
<td>IIB</td>
<td>[ \partial \bar{\theta} \Gamma^\mu \partial_z \theta - \partial \bar{\theta} \Gamma^\mu \partial_z \theta = 0 ]</td>
</tr>
</tbody>
</table>

The heterotic superstrings come in two types SO(32) and E8×E8 as indicated above and the type I superstrings include open strings.

**Beyond superstring theory**

It is conceivable that the five superstring theories are approximated to a theory in higher dimensions possibly involving membranes. Because the action for this involves quartic terms and higher so is non-Gaussian, the functional integrals are very difficult to solve and so this has confounded the top theoretical physicists. Edward Witten has popularised the concept of a theory in 11 dimensions, called M-theory, involving membranes interpolating from the known symmetries of superstring theory. It may turn out that there exist membrane models or other non-membrane models in higher dimensions—which may become acceptable when we find new unknown symmetries of nature, such as noncommutative geometry. It is thought, however, that 16 is probably the maximum since SO(16) is a maximal subgroup of E8, the largest exceptional Lie group, and also is more than large enough to contain the Standard Model. Quartic integrals of the non-functional kind are easier to solve so there is hope for the future. This is the series solution, which is always convergent when a is non-zero and negative:
In the case of membranes the series would correspond to sums of various membrane interactions that are not seen in string theory.

**Compactification**

Investigating theories of higher dimensions often involves looking at the 10 dimensional superstring theory and interpreting some of the more obscure results in terms of compactified dimensions. For example, D-branes are seen as compactified membranes from 11D M-theory. Theories of higher dimensions such as 12D F-theory and beyond produce other effects, such as gauge terms higher than U(1). The components of the extra vector fields (A) in the D-brane actions can be thought of as extra coordinates (X) in disguise. However, the known symmetries including supersymmetry currently restrict the spinors to 32-components—which limits the number of dimensions to 11 (or 12 if you include two time dimensions.) Some commentators (e.g., John Baez et al.) have speculated that the exceptional Lie groups E_6, E_7 and E_8 having maximum orthogonal subgroups SO(10), SO(12) and SO(16) may be related to theories in 10, 12 and 16 dimensions; 10 dimensions corresponding to string theory and the 12 and 16 dimensional theories being yet undiscovered but would be theories based on 3-branes and 7-branes respectively. However, this is a minority view within the string community. Since E_7 is in some sense F_4 quaternified and E_8 is F_4 octonified, the 12 and 16 dimensional theories, if they did exist, may involve the noncommutative geometry based on the quaternions and octonions respectively. From the above discussion, it can be seen that physicists have many ideas for extending superstring theory beyond the current 10 dimensional theory, but so far all have been unsuccessful.

**Kac–Moody algebras**

Since strings can have an infinite number of modes, the symmetry used to describe string theory is based on infinite dimensional Lie algebras. Some Kac–Moody algebras that have been considered as symmetries for M-theory have been E_{10} and E_{11} and their supersymmetric extensions.

**See also**

- AdS/CFT correspondence
- dS/CFT correspondence
- Grand unification theory
- Large Hadron Collider
- List of string theory topics
- Quantum gravity
- String field theory

**Notes**

Type II string theory

In theoretical physics, type II string theory is a unified term that includes both type IIA strings and type IIB strings theories. Type II string theory accounts for two of the five consistent superstring theories in ten dimensions. Both theories have the maximal amount of supersymmetry — namely 32 supercharges — in ten dimensions. Both theories are based on oriented closed strings. On the worldsheet, they differ only in the choice of GSO projection.

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Type IIA string theory

At low energies, type IIA string theory is described by type IIA supergravity in ten dimensions which is a non-chiral theory (i.e. left–right symmetric) with (1,1)d=10 supersymmetry; the fact that the anomalies in this theory cancel is therefore trivial.

In the 1990s it was realized by Edward Witten (building on previous insights by Michael Duff, Paul Townsend, and others) that the limit of type IIA string theory in which the string coupling goes to infinity becomes a new 11-dimensional theory called M-theory.[1]

The mathematical treatment of type IIA string theory belongs to symplectic topology and algebraic geometry, particularly Gromov–Witten invariants.

Type IIB string theory

At low energies, type IIB string theory is described by type IIB supergravity in ten dimensions which is a chiral theory (left–right asymmetric) with (2,0)d=10 supersymmetry; the fact that the anomalies in this theory cancel is therefore nontrivial.

In the 1990s it was realized that type II string theory with the string coupling constant g is equivalent to the same theory with the coupling 1/g. This equivalence is known as S-duality.

Orientifold of type IIB string theory leads to type I string theory

The mathematical treatment of type IIB string theory belongs to algebraic geometry, specifically the deformation theory of complex structures originally studied by Kunihiko Kodaira and Donald C. Spencer.

In 1997 Juan Maldacena gave some arguments indicating that type IIB string theory is equivalent to N = 4 supersymmetric Yang–Mills theory in the 't Hooft limit; it was the first suggestion concerning the AdS/CFT correspondence[2]

Relationship between the type II theories

In the late 1980s, it was realized that type IIA string theory is related to type IIB string theory by T-duality.

See also
Superstring theory
- Type I string
- Heterotic string

References


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M-theory is a theory in physics that unifies all consistent versions of superstring theory. The existence of such a theory was first conjectured by Edward Witten at a string theory conference at the University of Southern California in the Spring of 1995. Witten's announcement initiated a flurry of research activity known as the second superstring revolution.

Prior to Witten's announcement, string theorists had identified five versions of superstring theory. Although these theories appeared, at first, to be very different, work by several physicists showed that the theories were related in intricate and nontrivial ways. In particular, physicists found that apparently distinct theories could be unified by mathematical transformations called S-duality and T-duality. Witten's conjecture was based in part on the existence of these dualities and in part on the relationship of the string theories to a field theory called eleven-dimensional supergravity.

Although a complete formulation of M-theory is not known, the theory should describe two- and five-dimensional objects called branes and should be approximated by eleven-dimensional supergravity at low energies. Modern attempts to formulate M-theory are typically based on matrix theory or the AdS/CFT correspondence.

According to Witten, M should stand for “magic”, “mystery”, or “membrane” according to taste, and the true meaning of the title should be decided when a more fundamental formulation of the theory is known.¹

Investigations of the mathematical structure of M-theory have spawned important theoretical results in physics and mathematics. More speculatively, M-theory may provide a framework for developing a unified theory of all of the fundamental forces of nature. Attempts to connect M-theory to experiment typically focus on compactifying its extra dimensions to construct candidate models of our four-dimensional world, although so far none has been verified to give rise to physics as observed in high energy physics experiments.

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Background

Quantum gravity and strings
One of the deepest problems in modern physics is the problem of quantum gravity. The current understanding of gravity is based on Albert Einstein's general theory of relativity, which is formulated within the framework of classical physics. However, nongravitational forces are described within the framework of quantum mechanics, a radically different formalism for describing physical phenomena based on probability.[a] A quantum theory of gravity is needed in order to reconcile general relativity with the principles of quantum mechanics,[b] but difficulties arise when one attempts to apply the usual prescriptions of quantum theory to the force of gravity.[c]

String theory is a theoretical framework that attempts to reconcile gravity and quantum mechanics. In string theory, the point-like particles of particle physics are replaced by one-dimensional objects called strings. String theory describes how strings propagate through space and interact with each other. In a given version of string theory, there is only one kind of string, which may look like a small loop or segment of ordinary string, and it can vibrate in different ways. On distance scales larger than the string scale, a string will look just like an ordinary particle, with its mass, charge, and other properties determined by the vibrational state of the string. In this way, all of the different elementary particles may be viewed as vibrating strings. One of the vibrational states of a string gives rise to the graviton, a quantum mechanical particle that carries gravitational force.[d]

There are several versions of string theory: type I, type IIA, type IIB, and two flavors of heterotic string theory (SO(32) and $E_8 \times E_8$). The different theories allow different types of strings, and the particles that arise at low energies exhibit different symmetries. For example, the type I theory includes both open strings (which are segments with endpoints) and closed strings (which form closed loops), while types IIA and IIB include only closed strings.[2] Each of these five string theories arises as a special limiting case of M-theory. This theory, like its string theory predecessors, is an example of a quantum theory of gravity. It describes a force just like the familiar gravitational force subject to the rules of quantum mechanics.[e]

Number of dimensions
In everyday life, there are three familiar dimensions of space: height, width and depth. Einstein's general theory of relativity treats time as a dimension on par with the three spatial dimensions; in general relativity, space and time are not modeled as separate entities but are instead unified to a four-dimensional spacetime, three spatial dimensions and one time dimension. In this framework, the phenomenon of gravity is viewed as a consequence of the geometry of spacetime.[d]

In spite of the fact that the universe is well described by four-dimensional spacetime, there are several reasons why physicists consider theories in other dimensions. In some cases, by modeling spacetime in a different number of dimensions, a theory becomes more mathematically tractable, and one can perform calculations and gain general insights more easily.[e] There are also situations
where theories in two or three spacetime dimensions are useful for describing phenomena in condensed matter physics. Finally, there exist scenarios in which there could actually be more than four dimensions of spacetime which have nonetheless managed to escape detection.

One notable feature of string theory and M-theory is that these theories require extra dimensions of spacetime for their mathematical consistency. In string theory, spacetime is ten-dimensional (nine spatial dimensions, and one time dimension), while in M-theory it is eleven-dimensional (ten spatial dimensions, and one time dimension). In order to describe real physical phenomena using these theories, one must therefore imagine scenarios in which these extra dimensions would not be observed in experiments.

Compactification is one way of modifying the number of dimensions in a physical theory. In compactification, some of the extra dimensions are assumed to "close up" on themselves to form circles. In the limit where these curled up dimensions become very small, one obtains a theory in which spacetime has effectively a lower number of dimensions. A standard analogy for this is to consider a multidimensional object such as a garden hose. If the hose is viewed from a sufficient distance, it appears to have only one dimension, its length. However, as one approaches the hose, one discovers that it contains a second dimension, its circumference. Thus, an ant crawling on the surface of the hose would move in two dimensions.

### Dualities

Theories that arise as different limits of M-theory turn out to be related in highly nontrivial ways. One of the relationships that can exist between these different physical theories is called S-duality. This is a relationship which says that a collection of strongly interacting particles in one theory can, in some cases, be viewed as a collection of weakly interacting particles in a completely different theory. Roughly speaking, a collection of particles is said to be strongly interacting if they combine and decay often and weakly interacting if they do so infrequently. Type I string theory turns out to be equivalent by S-duality to the SO(32) heterotic string theory. Similarly, type IIB string theory is related to itself in a nontrivial way by S-duality.

Another relationship between different string theories is T-duality. Here one considers strings propagating around a circular extra dimension. T-duality states that a string propagating around a circle of radius $R$ is equivalent to a string propagating around a circle of radius $1/R$ in the sense that all observable quantities in one description are identified with quantities in the dual description. For example, a string has momentum $p$ and winding number $n$ in one description, it will have momentum $n$ and winding number $p$ in the dual description. For example, type IIA string theory is equivalent to type IIB string theory via T-duality, and the two versions of heterotic string theory are also related by T-duality.

In general, the term *duality* refers to a situation where two seemingly different physical systems turn out to be equivalent in a nontrivial way. If two theories are related by a duality, it means that one theory can be transformed in some way so that it ends up looking just like the other theory. The two theories are then said to be dual to one another under the transformation. Put differently, the two theories are mathematically different descriptions of the same phenomena.
**Supersymmetry**

Another important theoretical idea that plays a role in M-theory is supersymmetry. This is a mathematical relation that exists in certain physical theories between a class of particles called bosons and a class of particles called fermions. Roughly speaking, fermions are the constituents of matter, while bosons mediate interactions between particles. In theories with supersymmetry, each boson has a counterpart which is a fermion, and vice versa. When supersymmetry is imposed as a local symmetry, one automatically obtains a quantum mechanical theory that includes gravity. Such a theory is called a supergravity theory.\[12\]

A theory of strings that incorporates the idea of supersymmetry is called a superstring theory. There are several different versions of superstring theory which are all subsumed within the M-theory framework. At low energies, the superstring theories are approximated by supergravity ten spacetime dimensions. Similarly, M-theory is approximated at low energies by supergravity in eleven dimensions.\[3\]

**Branes**

In string theory and related theories such as supergravity theories, a brane is a physical object that generalizes the notion of a point particle to higher dimensions. For example, a point particle can be viewed as a brane of dimension zero, while a string can be viewed as a brane of dimension one. It is also possible to consider higher-dimensional branes. In dimension \( p \), these are called \( p \)-branes. Branes are dynamical objects which can propagate through spacetime according to the rules of quantum mechanics. They can have mass and other attributes such as charge. A \( p \)-brane sweeps out a \((p+1)\)-dimensional volume in spacetime called its worldvolume. Physicists often study fields analogous to the electromagnetic field which live on the worldvolume of a brane. The word brane comes from the word "membrane" which refers to a two-dimensional brane.\[3\]

In string theory, the fundamental objects that give rise to elementary particles are the one-dimensional strings. Although the physical phenomena described by M-theory are still poorly understood, physicists know that the theory describes two- and five-dimensional branes. Much of the current research in M-theory attempts to better understand the properties of these branes.\[8\]

**History and development**

**Kaluza–Klein theory**

In the early 20th century, physicists and mathematicians including Albert Einstein and Hermann Minkowski pioneered the use of four-dimensional geometry for describing the physical world.\[14\] These efforts culminated in the formulation of Einstein's general theory of relativity which relates gravity to the geometry of four-dimensional spacetime.\[15\]

The success of general relativity led to efforts to apply higher dimensional geometry to explain other forces. In 1919, work by Theodor Kaluza showed that by passing to five-dimensional spacetime, one can unify gravity and electromagnetism into a single force.\[15\] This idea was improved by physicist Oskar Klein, who suggested that the additional dimension proposed by Kaluza could take the form of a circle with radius around \( 10^{-30} \) cm.\[16\]

The Kaluza–Klein theory and subsequent attempts by Einstein to develop unified field theory were never completely successful. In part this was because Kaluza–Klein theory predicted a particle that has never been shown to exist, and in part because it was unable to correctly predict the ratio of an electron's mass to its charge. In addition, these theories were being developed just as other physicists were beginning to discover quantum mechanics, which would ultimately prove successful in describing known forces such as electromagnetism, as well as new nuclear forces that were being discovered throughout the middle part of the century. Thus it would take almost fifty years for the idea of new dimensions to be taken seriously again.\[7\]

**Early work on supergravity**
New concepts and mathematical tools provided fresh insights into general relativity, giving rise to a period in the 1960s–70s now known as the golden age of general relativity. In the mid-1970s, physicists began studying higher-dimensional theories combining general relativity with supersymmetry, the so-called supergravity theories.

General relativity does not place any limits on the possible dimensions of spacetime. Although the theory is typically formulated in four dimensions, one can write down the same equations for the gravitational field in any number of dimensions. Supergravity is more restrictive because it places an upper limit on the number of dimensions. In 1978, work by Werner Nahm showed that the maximum spacetime dimension in which one can formulate a consistent supersymmetric theory is eleven. In the same year, Eugene Cremmer, Bernard Julia, and Joel Scherk of the École Normale Supérieure showed that supergravity not only permits up to eleven dimensions but is in fact most elegant in this maximal number of dimensions.

Initially, many physicists hoped that by compactifying eleven-dimensional supergravity, it might be possible to construct realistic models of our four-dimensional world. The hope was that such models would provide a unified description of the four fundamental forces of nature: electromagnetism, the strong and weak nuclear forces, and gravity. Interest in eleven-dimensional supergravity soon waned as various flaws in this scheme were discovered. One of the problems was that the laws of physics appear to distinguish between clockwise and counterclockwise, a phenomenon known as chirality. Edward Witten and others observed this chirality property cannot be readily derived by compactifying from eleven dimensions.

In the first superstring revolution in 1984, many physicists turned to string theory as a unified theory of particle physics and quantum gravity. Unlike supergravity theory, string theory was able to accommodate the chirality of the standard model, and it provided a theory of gravity consistent with quantum effects. Another feature of string theory that many physicists were drawn to in the 1980s and 1990s was its high degree of uniqueness. In ordinary particle theories, one can consider any collection of elementary particles whose classical behavior is described by an arbitrary Lagrangian. In string theory, the possibilities are much more constrained: by the 1990s, physicists had argued that there were only five consistent supersymmetric versions of the theory.

Relationships between string theories

Although there were only a handful of consistent superstring theories, it remained a mystery why there was not just one consistent formulation. However, as physicists began to examine string theory more closely, they realized that these theories are related in intricate and nontrivial ways.

In the late 1970s, Claus Montonen and David Olive had conjectured a special property of certain physical theories. A sharpened version of their conjecture concerns a theory called $N = 4$ supersymmetric Yang–Mills theory, which describes theoretical particles formally similar to the quarks and gluons that make up atomic nuclei. The strength with which the particles of this theory interact is measured by a number called the coupling constant. The result of Montonen and Olive, now known as Montonen–Olive duality, states that $N = 4$ supersymmetric Yang–Mills theory with coupling constant $g$ is equivalent to the same theory with coupling constant $1/g$. In other words, a system of strongly interacting particles (large coupling constant) has an equivalent description as a system of weakly interacting particles (small coupling constant) and vice versa by spin-moment.

In the 1990s, several theorists generalized Montonen–Olive duality to the S-duality relationship, which connects different string theories. Ashoke Sen studied S-duality in the context of heterotic strings in four dimensions. Chris Hull and Paul Townsend showed that type IIB string theory with a large coupling constant is equivalent via S-duality to the same theory with small coupling constant. Theorists also found that different string theories may be related by T-duality. This duality implies that strings propagating on completely different spacetime geometries may be physically equivalent.
Membranes and fivebranes

String theory extends ordinary particle physics by replacing zero-dimensional point particles by one-dimensional objects called strings. In the late 1980s, it was natural for theorists to attempt to formulate other extensions in which particles are replaced by two-dimensional supermembranes or by higher-dimensional objects called branes. Such objects had been considered as early as 1962 by Paul Dirac[30] and they were reconsidered by a small but enthusiastic group of physicists in the 1980s[22].

Supersymmetry severely restricts the possible number of dimensions of a brane. In 1987, Eric Bergshoeff, Ergin Sezgin, and Paul Townsend showed that eleven-dimensional supergravity includes two-dimensional branes.[31] Intuitively, these objects look like sheets or membranes propagating through the eleven-dimensional spacetime. Shortly after this discovery, Michael Duff, Paul Howe, Takeo Inami, and Kellogg Stelle considered a particular compactification of eleven-dimensional supergravity with one of the dimensions curled up into a circle.[32] In this setting, one can imagine the membrane wrapping around the circular dimension. If the radius of the circle is sufficiently small, then this membrane looks just like a string in ten-dimensional spacetime. In fact, Duff and his collaborators showed that this construction reproduces exactly the strings appearing in type IIA superstring theory.[25]

In 1990, Andrew Strominger published a similar result which suggested that strongly interacting strings in ten dimensions might have an equivalent description in terms of weakly interacting five-dimensional branes.[33] Initially, physicists were unable to prove this relationship for two important reasons. On the one hand, the Montonen–Olive duality was still unproven, and so Strominger’s conjecture was even more tenuous. On the other hand, there were many technical issues related to the quantum properties of five-dimensional branes.[34] The first of these problems was solved in 1993 when Ashoke Sen established that certain physical theories require the existence of objects with both electric and magnetic charge which were predicted by the work of Montonen and Olive.[35]

In spite of this progress, the relationship between strings and five-dimensional branes remained conjectural because theorists were unable to quantize the branes. Starting in 1991, a team of researchers including Michael Duff, Ramzi Khuri, Jianxin Lu, and Ruben Minasian considered a special compactification of string theory in which four of the ten dimensions curl up. If one considers a five-dimensional brane wrapped around these extra dimensions, then the brane looks just like a one-dimensional string. In this way, the conjectured relationship between strings and branes was reduced to a relationship between strings and strings, and the latter could be tested using already established theoretical techniques.[29]

Second superstring revolution

Speaking at the string theory conference at the University of Southern California in 1995, Edward Witten of the Institute for Advanced Study made the surprising suggestion that all five superstring theories were in fact just different limiting cases of a single theory in eleven spacetime dimensions. Witten’s announcement drew together all of the previous results on S- and T-duality and the appearance of two- and five-dimensional branes in string theory.[36] In the months following Witten’s announcement, hundreds of new papers appeared on the Internet confirming that the new theory involved membranes in an important way.[37] Today this flurry of work is known as the second superstring revolution[38].

One of the important developments following Witten’s announcement was Witten’s work in 1996 with string theorist Petr Hořava.[30][40] Witten and Hořava studied M-theory on a special spacetime geometry with two ten-dimensional supergravity. The shaded region represents a family of different physical scenarios that are possible in M-theory. In certain limiting cases corresponding to the cusps, it is natural to describe the physics using one of the six theories labeled there.

A schematic illustration of the relationship between M-theory, the five superstring theories and eleven-dimensional supergravity. The shaded region represents a family of different physical scenarios that are possible in M-theory. In certain limiting cases corresponding to the cusps, it is natural to describe the physics using one of the six theories labeled there.
dimensional boundary components. Their work shed light on the mathematical structure of M-theory and suggested possible ways of connecting M-theory to real world physics.\[41\]

**Origin of the term**

Initially, some physicists suggested that the new theory was a fundamental theory of membranes, but Witten was skeptical of the role of membranes in the theory. In a paper from 1996, Hořava and Witten wrote:

> As it has been proposed that the eleven-dimensional theory is a supermembrane theory, but there are some reasons to doubt that interpretation, we will non-committally call it the M-theory, leaving to the future the relation of M to membranes.\[39\]

In the absence of an understanding of the true meaning and structure of M-theory, Witten has suggested that the M should stand for "magic", "mystery", or "membrane" according to taste, and the true meaning of the title should be decided when a more fundamental formulation of the theory is known.\[1\]

**Matrix theory**

**BFSS matrix model**

In mathematics, a matrix is a rectangular array of numbers or other data. In physics, a matrix model is a particular kind of physical theory whose mathematical formulation involves the notion of a matrix in an important way. A matrix model describes the behavior of a set of matrices within the framework of quantum mechanics.\[42\][43]

One important example of a matrix model is the BFSS matrix model proposed by Tom Banks, Willy Fischler, Stephen Shenker, and Leonard Susskind in 1997. This theory describes the behavior of a set of nine large matrices. In their original paper, these authors showed, among other things, that the low energy limit of this matrix model is described by eleven-dimensional supergravity. These calculations led them to propose that the BFSS matrix model is exactly equivalent to M-theory. The BFSS matrix model can therefore be used as a prototype for a correct formulation of M-theory and a tool for investigating the properties of M-theory in a relatively simple setting.\[42\]

**Noncommutative geometry**

In geometry, it is often useful to introduce coordinates. For example, in order to study the geometry of the Euclidean plane, one defines the coordinates \(x\) and \(y\) as the distances between any point in the plane and a pair of axes. In ordinary geometry, the coordinates of a point are numbers, so they can be multiplied, and the product of two coordinates does not depend on the order of multiplication. That is, \(xy = yx\). This property of multiplication is known as the commutative law, and this relationship between geometry and the commutative algebra of coordinates is the starting point for much of modern geometry.\[44\]

Noncommutative geometry is a branch of mathematics that attempts to generalize this situation. Rather than working with ordinary numbers, one considers some similar objects, such as matrices, whose multiplication does not satisfy the commutative law (that is, objects for which \(xy\) is not necessarily equal to \(yx\)). One imagines that these noncommuting objects are coordinates on some more general notion of "space" and proves theorems about these generalized spaces by exploiting the analogy with ordinary geometry.\[45\][46]

In a paper from 1998, Alain Connes, Michael R. Douglas, and Albert Schwarz showed that some aspects of matrix models and M-theory are described by a noncommutative quantum field theory, a special kind of physical theory in which the coordinates on spacetime do not satisfy the commutativity property.\[43\] This established a link between matrix models and M-theory on the one hand, and noncommutative geometry on the other hand. It quickly led to the discovery of other important links between noncommutative geometry and various physical theories.\[46\][47]
The application of quantum mechanics to physical objects such as the electromagnetic field, which are extended in space and time, is known as quantum field theory. In particle physics, quantum field theories form the basis for our understanding of elementary particles, which are modeled as excitations in the fundamental fields. Quantum field theories are also used throughout condensed matter physics to model particle-like objects called quasiparticles.

One approach to formulating M-theory and studying its properties is provided by the anti-de Sitter/conformal field theory (AdS/CFT) correspondence. Proposed by Juan Maldacena in late 1997, the AdS/CFT correspondence is a theoretical result which implies that M-theory is in some cases equivalent to a quantum field theory. In addition to providing insights into the mathematical structure of string and M-theory, the AdS/CFT correspondence has shed light on many aspects of quantum field theory in regimes where traditional calculational techniques are ineffective.

In the AdS/CFT correspondence, the geometry of spacetime is described in terms of a certain vacuum solution of Einstein's equation called anti-de Sitter space. In very elementary terms, anti-de Sitter space is a mathematical model of spacetime in which the notion of distance between points (the metric) is different from the notion of distance in ordinary Euclidean geometry. It is closely related to hyperbolic space, which can be viewed as a disk as illustrated on the left. This image shows a tessellation of a disk by triangles and squares. One can define the distance between points of this disk in such a way that all the triangles and squares are the same size and the circular outer boundary is infinitely far from any point in the interior.

Now imagine a stack of hyperbolic disks where each disk represents the state of the universe at a given time. The resulting geometric object is three-dimensional anti-de Sitter space. It looks like a solid cylinder in which any cross section is a copy of the hyperbolic disk. Time runs along the vertical direction in this picture. The surface of this cylinder plays an important role in the AdS/CFT correspondence. As with the hyperbolic plane, anti-de Sitter space is curved in such a way that any point in the interior is actually infinitely far from this boundary surface.

This construction describes a hypothetical universe with only two space dimensions and one time dimension, but it can be generalized to any number of dimensions. Indeed, hyperbolic space can have more than two dimensions and one can "stack up" copies of hyperbolic space to get higher-dimensional models of anti-de Sitter space.

An important feature of anti-de Sitter space is its boundary (which looks like a cylinder in the case of three-dimensional anti-de Sitter space). One property of this boundary is that, within a small region on the surface around any given point, it looks just like Minkowski space, the model of spacetime used in nongravitational physics. One can therefore consider an auxiliary theory.
in which "spacetime" is given by the boundary of anti-de Sitter space. This observation is the starting point for AdS/CFT correspondence, which states that the boundary of anti-de Sitter space can be regarded as the "spacetime" for a quantum field theory. The claim is that this quantum field theory is equivalent to the gravitational theory on the bulk anti-de Sitter space in the sense that there is a "dictionary" for translating entities and calculations in one theory into their counterparts in the other theory. For example, a single particle in the gravitational theory might correspond to some collection of particles in the boundary theory. In addition, the predictions in the two theories are quantitatively identical so that if two particles have a 40 percent chance of colliding in the gravitational theory then the corresponding collections in the boundary theory would also have a 40 percent chance of colliding.

6D (2,0) superconformal field theory

One particular realization of the AdS/CFT correspondence states that M-theory on the product space $\text{AdS}_7 \times S^4$ is equivalent to the so-called (2,0)-theory on the six-dimensional boundary. Here "(2,0)" refers to the particular type of supersymmetry that appears in the theory. In this example, the spacetime of the gravitational theory is effectively seven-dimensional (hence the notation $\text{AdS}_7$), and there are four additional "compact" dimensions (encoded by the $S^4$ factor). In the real world, spacetime is four-dimensional, at least macroscopically, so this version of the correspondence does not provide a realistic model of gravity. Likewise, the dual theory is not a viable model of any real-world system since it describes a world with six spacetime dimensions.

Nevertheless, the (2,0)-theory has proven to be important for studying the general properties of quantum field theories. Indeed, this theory subsumes many mathematically interesting effective quantum field theories and points to new dualities relating these theories. For example, Luis Alday, Davide Gaiotto, and Yuji Tachikawa showed that by compactifying this theory on a surface, one obtains a four-dimensional quantum field theory, and there is a duality known as the AGT correspondence which relates the physics of this theory to certain physical concepts associated with the surface itself. More recently, theorists have extended these ideas to study the theories obtained by compactifying down to three dimensions.

In addition to its applications in quantum field theory, the (2,0)-theory has spawned important results in pure mathematics. For example, the existence of the (2,0)-theory was used by Witten to give a "physical" explanation for a conjectural relationship in mathematics called the geometric Langlands correspondence. In subsequent work, Witten showed that the (2,0)-theory could be used to understand a concept in mathematics called Khovanov homology. Developed by Mikhail Khovanov around 2000, Khovanov homology provides a tool in knot theory, the branch of mathematics that studies and classifies the different shapes of knots. Another application of the (2,0)-theory in mathematics is the work of Davide Gaiotto, Greg Moore, and Andrew Neitzke, which used physical ideas to derive new results in hyperkähler geometry.

ABJM superconformal field theory

Another realization of the AdS/CFT correspondence states that M-theory on $\text{AdS}_4 \times S^7$ is equivalent to a quantum field theory called the ABJM theory in three dimensions. In this version of the correspondence, seven of the dimensions of M-theory are curled up, leaving four non-compact dimensions. Since the spacetime of our universe is four-dimensional, this version of the correspondence provides a somewhat more realistic description of gravity.
The ABJM theory appearing in this version of the correspondence is also interesting for a variety of reasons. Introduced by Aharony, Bergman, Jafferis, and Maldacena, it is closely related to another quantum field theory called Chern–Simons theory. The latter theory was popularized by Witten in the late 1980s because of its applications to knot theory. In addition, the ABJM theory serves as a semi-realistic simplified model for solving problems that arise in condensed matter physics.

### Phenomenology

#### Overview

In addition to being an idea of considerable theoretical interest, M-theory provides a framework for constructing models of real world physics that combine general relativity with the standard model of particle physics. Phenomenology is the branch of theoretical physics in which physicists construct realistic models of nature from more abstract theoretical ideas. String phenomenology is the part of string theory that attempts to construct realistic models of particle physics based on string and M-theory.

Typically, such models are based on the idea of compactification. Starting with the ten- or eleven-dimensional spacetime of string or M-theory, physicists postulate a shape for the extra dimensions. By choosing this shape appropriately, they can construct models roughly similar to the standard model of particle physics, together with additional undiscovered particles usually supersymmetric partners to analogues of known particles. One popular way of deriving realistic physics from string theory is to start with the heterotic theory in ten dimensions and assume that the six extra dimensions of spacetime are shaped like a six-dimensional Calabi–Yau manifold. This is a special kind of geometric object named after mathematicians Eugenio Calabi and Shing-Tung Yau. Calabi–Yau manifolds offer many ways of extracting realistic physics from string theory. Other similar methods can be used to construct models with physics resembling to some extent that of our four-dimensional world based on M-theory.

Partly because of theoretical and mathematical difficulties and partly because of the extremely high energies (beyond what is technologically possible for the foreseeable future) needed to test these theories experimentally, there is so far no experimental evidence that would unambiguously point to any of these models being a correct fundamental description of nature. This has led some in the community to criticize these approaches to unification and question the value of continued research on these problems.

#### Compactification on $G_2$ manifolds

In one approach to M-theory phenomenology, theorists assume that the seven extra dimensions of M-theory are shaped like a $G_2$ manifold. This is a special kind of seven-dimensional shape constructed by mathematician Dominic Joyce of the University of Oxford. These $G_2$ manifolds are still poorly understood mathematically, and this fact has made it difficult for physicists to fully develop this approach to phenomenology.

For example, physicists and mathematicians often assume that space has a mathematical property called smoothness, but this property cannot be assumed in the case of a $G_2$ manifold if one wishes to recover the physics of our four-dimensional world. Another problem is that $G_2$ manifolds are not complex manifolds, so theorists are unable to use tools from the branch of mathematics known as complex analysis. Finally, there are many open questions about the existence, uniqueness, and other mathematical properties of $G_2$ manifolds, and mathematicians lack a systematic way of searching for these manifolds.

#### Heterotic M-theory
Because of the difficulties with $G_2$ manifolds, most attempts to construct realistic theories of physics based on M-theory have taken a more indirect approach to compactifying eleven-dimensional spacetime. One approach, pioneered by Witten, Hořava, Burt Ovrut, and others, is known as heterotic M-theory. In this approach, one imagines that one of the eleven dimensions of M-theory is shaped like a circle. If this circle is very small, then the spacetime becomes effectively ten-dimensional. One then assumes that six of the ten dimensions form a Calabi–Yau manifold. If this Calabi–Yau manifold is also taken to be small, one is left with a theory in four-dimensions.\[69\]

Heterotic M-theory has been used to construct models of brane cosmology in which the observable universe is thought to exist on a brane in a higher dimensional ambient space. It has also spawned alternative theories of the early universe that do not rely on the theory of cosmic inflation.\[69\]

References

Notes

a. For a standard introduction to quantum mechanics, see Griffiths 2004.
b. The necessity of a quantum mechanical description of gravity follows from the fact that one cannot consistently couple a classical system to a quantum one. See Wild 1984, p. 382.
c. From a technical point of view the problem is that the theory one gets in this way is notrenormalizable and therefore cannot be used to make meaningful physical predictions. See Zee 2010, p. 72 for a discussion of this issue.
d. For an accessible introduction to string theory see Greene 2000.
e. For example, in the context of the AdS/CFT correspondence theorists often formulate and study theories of gravity in unphysical numbers of spacetime dimensions.
f. Dimensional reduction is another way of modifying the number of dimensions.
g. This analogy is used for example in Greene 2000, p. 186.
h. For example, see the subsections on the 6D (2,0) superconformal field theory and ABJM superconformal field theory.
i. A standard text is Peskin and Schroeder 1995.
j. For an introduction to the applications of quantum field theory to condensed matter physics, see Zee 2010.
k. For a review of the (2,0)-theory see Moore 2012.
l. Brane worlds provide an alternative way of recovering real world physics from string theory see Randall and Sundrum 1999.

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History of string theory

The history of string theory spans several decades of intense research including two superstring revolutions. Through the combined efforts of many researchers, string theory has developed into a broad and varied subject with connections to quantum gravity, particle and condensed matter physics, cosmology, and pure mathematics.

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### 1943–1959: S-matrix theory

String theory represents an outgrowth of S-matrix theory,[1] a research program begun by Werner Heisenberg in 1943[2] following John Archibald Wheeler’s 1937 introduction of the S-matrix).[3] Many prominent theorists picked up and advocated S-matrix theory, starting in the late 1950s and throughout the 1960s. The field became marginalized and discarded in the mid 1970s[4] and disappeared by the 1980s. Physicists neglected it because some of its mathematical methods were alien, and because quantum chromodynamics supplanted it as an experimentally better-qualified approach to the strong interactions.[5]

The theory presented a radical rethinking of the foundations of physical laws. By the 1940s it had become clear that the proton and the neutron were not pointlike particles like the electron. Their magnetic moment differed greatly from that of a pointlike spin-½ charged particle, too much to attribute the difference to a small perturbation. Their interactions were so strong that they scattered like a small sphere, not like a point. Heisenberg proposed that the strongly interacting particles were in fact extended objects, and because there are difficulties of principle with extended relativistic particles, he proposed that the notion of a space-time point broke down at nuclear scales.

Without space and time, it becomes difficult to formulate a physical theory. Heisenberg proposed a solution to this problem: focusing on the observable quantities—those things measurable by experiments. An experiment only sees a microscopic quantity if it can be transferred by a series of events to the classical devices that surround the experimental chamber. The objects that fly to infinity are stable particles, in quantum superpositions of different momentum states.

Heisenberg proposed that even when space and time are unreliable, the notion of momentum state, which is defined far away from the experimental chamber, still works. The physical quantity he proposed as fundamental is the quantum mechanical amplitude for a group of incoming particles to turn into a group of outgoing particles, and he did not admit that there were any steps in between.
The S-matrix is the quantity that describes how a collection of incoming particles turn into outgoing ones. Heisenberg proposed to study the S-matrix directly, without any assumptions about space-time structure. But when transitions from the far-past to the far-future occur in one step with no intermediate steps, it becomes difficult to calculate anything. In quantum field theory, the intermediate steps are the fluctuations of fields or equivalently the fluctuations of virtual particles. In this proposed S-matrix theory, there are no local quantities at all.

Heisenberg proposed to use unitarity to determine the S-matrix. In all conceivable situations, the sum of the squares of the amplitudes must equal 1. This property can determine the amplitude in a quantum field theory order by order in a perturbation series once the basic interactions are given, and in many quantum field theories the amplitudes grow too fast at high energies to make a unitary S-matrix. But without extra assumptions on the high-energy behavior, unitarity is not enough to determine the scattering, and the proposal was ignored for many years.

Heisenberg's proposal was revived in 1956 when Murray Gell-Mann recognized that dispersion relations—like those discovered by Hendrik Kramers and Ralph Kronig in the 1920s (see Kramers–Kronig relations)—allow the formulation of a notion of causality, a notion that events in the future would not influence events in the past, even when the microscopic notion of past and future are not clearly defined. He also recognized that these relations might be useful in computing observables for the case of strong interaction physics.[6] The dispersion relations were analytic properties of the S-matrix[7] and they imposed more stringent conditions than those that follow from unitarity alone. This development in S-matrix theory stemmed from Murray Gell-Mann and Marvin Leonard Goldberger’s (1954) discovery of crossing symmetry, another condition that the S-matrix had to fulfill.[8][7]

Prominent advocates of the new "dispersion relations" approach included Stanley Mandelstam[9] and Geoffrey Chew,[10] both at UC Berkeley at the time. Mandelstam discovered the double dispersion relations, a new and powerful analytic form, in 1958,[9] and believed that it would provide the key to progress in the intractable strong interactions.

1959–1968: Regge theory and bootstrap models

By the late 1950s, many strongly interacting particles of ever higher spins had been discovered, and it became clear that they were not all fundamental. While Japanese physicist Shoichi Sakata proposed that the particles could be understood as bound states of just three of them (the proton, the neutron and the Lambda; see Sakata model),[11] Geoffrey Chew believed that none of these particles are fundamental[12][13] (for details, see Bootstrap model). Sakata’s approach was reworked in the 1960s into the quark model by Murray Gell-Mann and George Zweig by making the charges of the hypothetical constituents fractional and rejecting the idea that they were observed particles. At the time, Chew’s approach was considered more mainstream because it did not introduce fractional charge values and because it focused on experimentally measurable S-matrix elements, not on hypothetical pointlike constituents.

In 1959, Tullio Regge, a young theorist in Italy, discovered that bound states in quantum mechanics can be organized into families known as Regge trajectories, each family having distinctive angular momenta.[14] This idea was generalized to relativistic quantum mechanics by Stanley Mandelstam, Vladimir Gribov and Marcel Froissart, using a mathematical method (the Sommerfeld–Watson representation) discovered decades earlier by Arnold Sommerfeld and Kenneth Marshall Watson: the result was dubbed the Froissart–Gribov formula[15]

In 1961, Geoffrey Chew and Steven Frautschi recognized that mesons had straight line Regge trajectories[16] (in their scheme, spin is plotted against mass squared on a so-called Chew–Frautschi plot), which implied that the scattering of these particles would have very strange behavior—it should fall off exponentially quickly at large angles. With this realization, theorists hoped to construct a theory of composite particles Regge trajectories, whose scattering amplitudes had the asymptotic form demanded by Regge theory.

In 1967, a notable step forward in the bootstrap approach was the principle of DHS duality introduced by Richard Dolen, David Horn, and Christoph Schmid in 1967,[17] at Caltech (the original term for it was “average duality” or “finite energy sum rule (FESR) duality”). The three researchers noticed that Regge pole exchange (at high energy) and resonance (at low energy) descriptions offer multiple representations/approximations of one and the same physically observable process.[18]

1968–1974: dual resonance model
The first model in which hadronic particles essentially follow the Regge trajectories was the dual resonance model that was constructed by Gabriele Veneziano in 1968,[19] who noted that the Euler beta function could be used to describe 4-particle scattering amplitude data for such particles. The Veneziano scattering amplitude (or Veneziano model) was quickly generalized to an N-particle amplitude by Ziro Koba and Holger Bech Nielsen,[20] their approach was dubbed the Koba–Nielsen formalism, and to what are now recognized as closed strings by Miguel Virasoro[21] and Joel A. Shapiro[22] (their approach was dubbed the Shapiro–Virasoro model).

In 1969, the Chan–Paton rules (proposed by Jack E. Paton and Hong-Mo Chan)[23] enabled isospin factors to be added to the Veneziano model.[24]

In 1969–70, Yoichiro Nambu,[25] Holger Bech Nielsen,[26] and Leonard Susskind[27][28] presented a physical interpretation of the Veneziano amplitude by representing nuclear forces as vibrating, one-dimensional strings. However, this string-based description of the strong force made many predictions that directly contradicted experimental findings.

In 1971, Pierre Ramond[29] and, independently, John H. Schwarz and André Neveu[30] attempted to implement fermions into the dual model. This led to the concept of "spinning strings", and pointed the way to a method for removing the problematic tachyon (see RNS formalism).[31]

Dual resonance models for strong interactions were a relatively popular subject of study between 1968 and 1973.[32] The scientific community lost interest in string theory as a theory of strong interactions in 1973 when quantum chromodynamics became the main focus of theoretical research (mainly due to the theoretical appeal of asymptotic freedom).[34]

1974–1984: bosonic string theory and superstring theory

In 1974, John H. Schwarz and Joel Scherk,[35] and independently Tamiaki Yoneya,[36] studied the boson-like patterns of string vibration and found that their properties exactly matched those of the graviton, the gravitational force's hypothetical messenger particle. Schwarz and Scherk argued that string theory had failed to catch on because physicists had underestimated its scope. This led to the development of bosonic string theory.

String theory is formulated in terms of the Polyakov action [37] which describes how strings move through space and time. Like springs, the strings tend to contract to minimize their potential energy, but conservation of energy prevents them from disappearing, and instead they oscillate. By applying the ideas of quantum mechanics to strings it is possible to deduce the different vibrational modes of strings, and that each vibrational state appears to be a different particle. The mass of each particle, and the fashion with which it can interact, are determined by the way the string vibrates—in essence, by the “note” the string “sounds.” The scale of notes, each corresponding to a different kind of particle, is termed the “spectrum” of the theory.

Early models included both open strings, which have two distinct endpoints, and closed strings, where the endpoints are joined to make a complete loop. The two types of string behave in slightly different ways, yielding two spectra. Not all modern string theories use both types; some incorporate only the closed variety.

The earliest string model has several problems: it has a critical dimension \( D = 26 \), a feature that was originally discovered by Claud Lovelace in 1971.[38] The theory has a fundamental instability, the presence of tachyons (see tachyon condensation); additionally, the spectrum of particles contains only bosons, particles like the photon that obey particular rules of behavior. While bosons are a critical ingredient of the Universe, they are not its only constituents. Investigating how a string theory may include fermions in its spectrum led to the invention of supersymmetry (in the West) in 1971.[40] A mathematical transformation between bosons and fermions. String theories that include fermionic vibrations are now known as superstring theories.

In 1977, the GSO projection (named after Ferdinando Gliozzi, Joel Scherk, and David I. Olive) led to a family of tachyon-free unitary free string theories,[42] the first consistent superstring theories (see below).

The first superstring revolution is a period of important discoveries that began in 1984. It was realized that string theory was capable of describing all elementary particles as well as the interactions between them. Hundreds of physicists started to work on string theory as the most promising idea to unify physical theories. The revolution was started by a discovery of anomaly cancellation in type I string theory via the Green–Schwarz mechanism (named after Michael Green and John H. Schwarz) in 1984. The ground-breaking discovery of the heterotic string was made by David Gross, Jeffrey Harvey, Emil Martinec, and Ryan Rohm in 1985. It was also realized by Philip Candelas, Gary Horowitz, Andrew Strominger, and Edward Witten in 1985 that to obtain $N = 1$ supersymmetry, the six small extra dimensions (the $D = 10$ critical dimension of superstring theory had been originally discovered by John H. Schwarz in 1972) need to be compactified on a Calabi–Yau manifold. (In string theory, compactification is a generalization of Kaluza–Klein theory, which was first proposed in the 1920s.)

By 1985, five separate superstring theories had been described: type I, type II (IIA and IIB), and heterotic (SO(32) and $E_8 \times E_8$).

Discover magazine in the November 1986 issue (vol. 7, #11) featured a cover story written by Gary Taubes, "Everything's Now Tied to Strings", which explained string theory for a popular audience.

In 1987, Eric Bergshoeff, Ergin Sezgin and Paul Townsend showed that there are no superstrings in eleven dimensions (the largest number of dimensions consistent with a single graviton in supergravity theories), but supermembranes.

1994–2003: second superstring revolution

In the early 1990s, Edward Witten and others found strong evidence that the different superstring theories were different limits of an 11-dimensional theory that became known as M-theory (for details, see Introduction to M-theory). These discoveries sparked the second superstring revolution that took place approximately between 1994 and 1995.

The different versions of superstring theory were unified, as long hoped, by new equivalences. These are known as S-duality, T-duality, U-duality, mirror symmetry, and conifold transitions. The different theories of strings were also related to M-theory.

In 1995, Joseph Polchinski discovered that the theory requires the inclusion of higher-dimensional objects, called D-branes; these are the sources of electric and magnetic Ramond–Ramond fields that are required by string duality. D-branes added additional rich mathematical structure to the theory, and opened possibilities for constructing realistic cosmological models in the theory (for details, see Brane cosmology).

In 1997–98, Juan Maldacena conjectured a relationship between string theory and $N = 4$ supersymmetric Yang–Mills theory, a gauge theory. This conjecture, called the AdS/CFT correspondence has generated a great deal of interest in high energy physics. It is a realization of the holographic principle which has far-reaching implications: the AdS/CFT correspondence has helped elucidate the mysteries of black holes suggested by Stephen Hawking’s work and is believed to provide a resolution of the black hole information paradox.

2003–present

In 2003, Michael R. Douglas's discovery of the string theory landscape, which suggests that string theory has a large number of inequivalent false vacua, led to much discussion of what string theory might eventually be expected to predict, and how cosmology can be incorporated into the theory.

See also

- History of quantum field theory
- History of loop quantum gravity
- Pomerons in string theory
1. Rickles 2014, p. 28 n. 17: "S-matrix theory had enough time to spawn string theory".


4. Rickles 2014, p. 113: "An unfortunate (for string theory) series of events terminated the growing popularity that string theory was enjoying in the early 1970s."


32. Rickles 2014, pp. 5–6, 44.


34. Rickles 2014, p. 11 n. 22.


43. Rickles 2014, p. 147: "Green and Schwarz’s anomaly cancellation paper triggered a very large increase in the production of papers on the subject, including a related pair of papers that between them had the potential to provide the foundation for a realistic unified theory of both particle physics and gravity".

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This was demonstrated in Nahm, Werner. "Supersymmetries and their representations"Nuclear Physics B 135 no 1 (1978) pp 149-166, doi:10.1016/0550-3213(78)90218-3


When Witten named it M-theory he did not specify what the "M" stood for presumably because he did not feel he had the right to name a theory he had not been able to fully describe. The "M" sometimes is said to stand for Mystery, or Magic, or Mother More serious suggestions include Matrix or MembraneSheldon Glashow has noted that the "M" might be an upside down "W", standing for Witten. Others have suggested that the "M" in M-theory should stand for Missing, Monstrous or even MurkyAccording to Witten himself, as quoted in the PBS documentary (https://www.pbs.org/wgbh/nova/elegant/) based on Brian Greene's The Elegant Universe the "M" in M-theory stands for "magic, mystery or matrix according to taste."


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### Further reading


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