Our Universe Has More Dimensions Than We Can See

Most of us can only imagine life in 3 dimensions—length, width, and height. But physics suggests the universe might be much deeper than that:

- String theory predicts there could be 10 or 11 dimensions.
- Some models, like the Klein bottle, describe space as something with no edges or boundaries—a shape where inside and outside blend into one.
- But here's the catch: our human brains evolved to understand 3D space. Thinking beyond that feels impossible.

Higher dimensions exist all around us, but we just can't perceive them directly. Why does this matter? These extra dimensions could help explain:

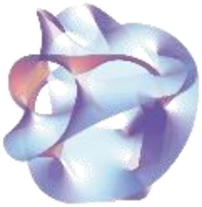
Gravity's strange weakness.
Dark matter.
The deepest laws of the universe.

The world and universe could be much stranger—than we've ever imagined. Does this blow your mind?

The universe has 11 dimensions

M-theory proposes that the universe has 11 dimensions, which includes ten spatial dimensions and one time dimension. This theory unifies the five different string theories and Supergravity, suggesting that the 11th dimension helps to explain fundamental forces and particles in the universe. The introduction of this additional dimension allows for a more comprehensive understanding of the universe, eliminating anomalies present in previous theories.

String theory



Fundamental objects

- String
- Cosmic string
- Brane
- D-brane

Perturbative theory

- Bosonic
- Superstring (Type I, Type II, Heterotic)

Non-perturbative results

- S-duality
- T-duality
- U-duality
- M-theory
- F-theory
- AdS/CFT correspondence

Phenomenology

- Phenomenology
- Cosmology
- Landscape

Mathematics

- Geometric Langlands correspondence
- Mirror symmetry
- Monstrous moonshine
- Vertex algebra
- K-theory

- **History**
- **Glossary**

In physics, **M-theory** is a theory that unifies all consistent versions of superstring theory. Edward Witten first conjectured the existence of such a theory at a string theory conference at the University of Southern California in 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 initially appeared to be very different, work by many physicists showed that the theories were related in intricate and nontrivial ways. 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.

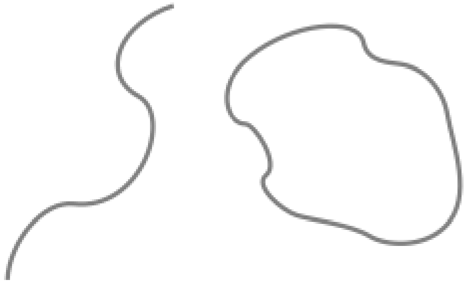
Although a complete formulation of M-theory is not known, such a formulation should describe two- and five-dimensional objects called branes and should be approximated by eleven-dimensional supergravity at low energies. Modern attempts to formulate M-theory are typically based on matrix theory or the 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 the four-dimensional world, although so far none have been verified to give rise to physics as observed in high-energy physics experiments.

Background

Quantum gravity and strings

Main articles: Quantum gravity and String theory



The fundamental objects of string theory are open and closed strings.

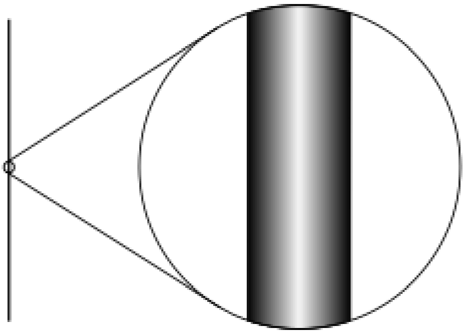
One of the deepest problems in modern physics is the problem of quantum gravity. The current understanding of gravity is based on Albert Einstein's general theory of relativity, which is formulated within the framework of classical physics. However, nongravitational forces are described within the framework 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.[3]

Number of dimensions

Main articles: Extra dimensions and Compactification (physics)



An example of compactification: At large distances, a two-dimensional surface with one circular dimension looks one-dimensional.

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.[4]

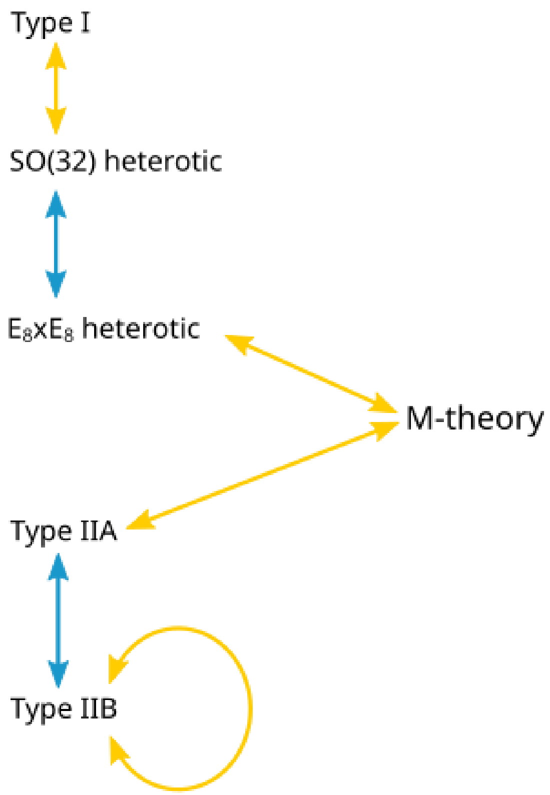
In spite of the fact that the universe is well described by four-dimensional spacetime, there are several reasons why physicists consider theories in other dimensions. In some cases, by modeling spacetime in a different number of dimensions, a theory becomes more mathematically tractable, and one can 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.[5] Finally, there exist scenarios in which there could actually be more than four dimensions of spacetime which have nonetheless managed to escape detection.[6]

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.[7]

Compactification is one way of modifying the number of dimensions in a physical theory.[f] In compactification, some of the extra dimensions are assumed to "close up" on themselves to form circles.[8] 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.[g]

Dualities

Main articles: String duality, S-duality, and T-duality



A diagram of string theory dualities. Yellow arrows indicate S-duality. Blue arrows indicate T-duality. These dualities may be combined to obtain equivalences of any of the five theories with M-theory.[9]

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.[10]

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.[10]

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.[11]

Supersymmetry

Main article: 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, superstring theories are approximated by one of the three supergravities in ten dimensions, known as type I, type IIA, and type IIB supergravity. Similarly, M-theory is approximated at low energies by supergravity in eleven dimensions.[3]

Branes

Main article: Brane

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.[13]

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.[h]

History and development

Main article: History of string theory

Kaluza–Klein theory

Main article: Kaluza–Klein theory

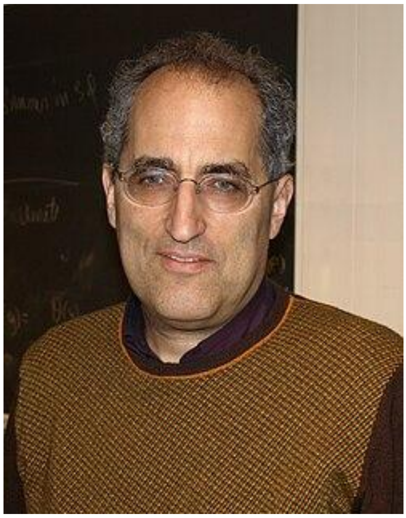
In the early 20th century, physicists and mathematicians including Albert Einstein and Hermann Minkowski pioneered the use of four-dimensional geometry for describing the physical world.[14] These efforts culminated in the formulation of Einstein's general theory of relativity, which relates gravity 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 (the radion), 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.[17]

Early work on supergravity

Main article: Supergravity



In the 1980s, Edward Witten contributed to the understanding of supergravity theories. In 1995, he introduced M-theory, sparking the second superstring revolution.

New concepts and mathematical tools provided fresh insights into general relativity, giving rise to a period in the 1960s–1970s now known as the golden age of general relativity.[18] In the mid-1970s, physicists began studying higher-dimensional theories combining general relativity with supersymmetry, the so-called supergravity theories.[19]

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.[12] In 1978, work by Werner Nahm showed that the maximum spacetime dimension in which one can formulate a consistent supersymmetric theory is eleven.[20] In the same year, Eugène Cremmer, Bernard Julia, and Joël 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.[21][22]

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.[22]

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.[22] 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.[22]

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.[22] However, as physicists began to examine string theory more closely, they realized that these theories are related in intricate and nontrivial ways.[23]

In the late 1970s, Claus Montonen and David Olive had conjectured a special property of certain physical theories.[24] 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[25] 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.[26][27] 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.[28] 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.[29]

Membranes and fivebranes

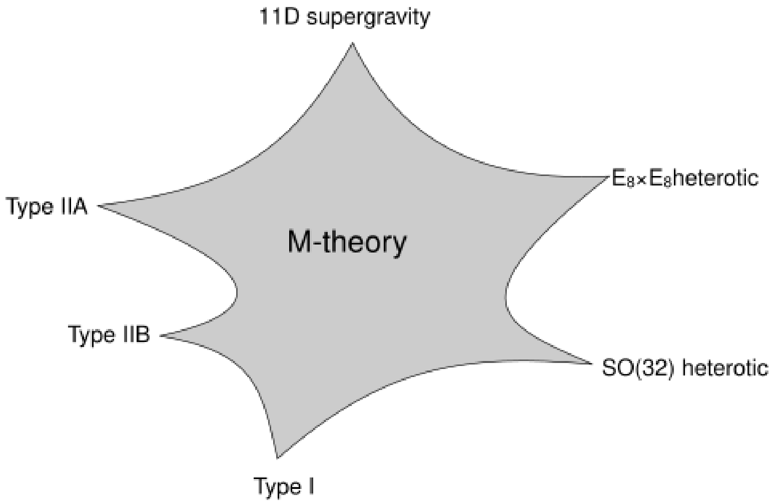
String theory extends ordinary particle physics by replacing zero-dimensional point particles by one-dimensional objects called strings. In the late 1980s, it was natural for theorists to attempt to formulate other extensions in which particles are replaced by two-dimensional supermembranes or by higher-dimensional 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



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.

Main article: Second superstring revolution

Speaking at Strings '95 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.[39][40] Witten and Hořava studied M-theory on a special spacetime geometry with two ten-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] Years later, he would state, "I thought my colleagues would understand that it really stood for membrane. Unfortunately, it got people confused."[42]

Matrix theory

BFSS matrix model

Main article: Matrix theory (physics)

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.[43][44]

One important[*why?*] 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.[43][*clarification needed*]

Noncommutative geometry

Main articles: Noncommutative geometry and Noncommutative quantum field theory

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.[45]

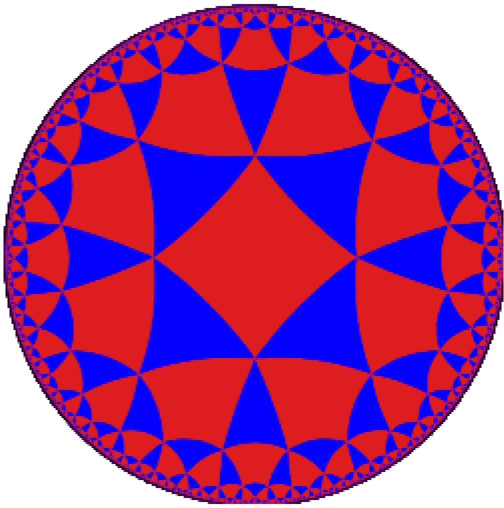
Noncommutative geometry is a branch of mathematics that attempts to generalize this situation. Rather than working with ordinary numbers, one considers some similar objects, such as matrices, whose multiplication does not satisfy the commutative law (that is, objects for which xy is not necessarily equal 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.[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.[44] 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.[47][48]

AdS/CFT correspondence

Overview

Main article: AdS/CFT correspondence

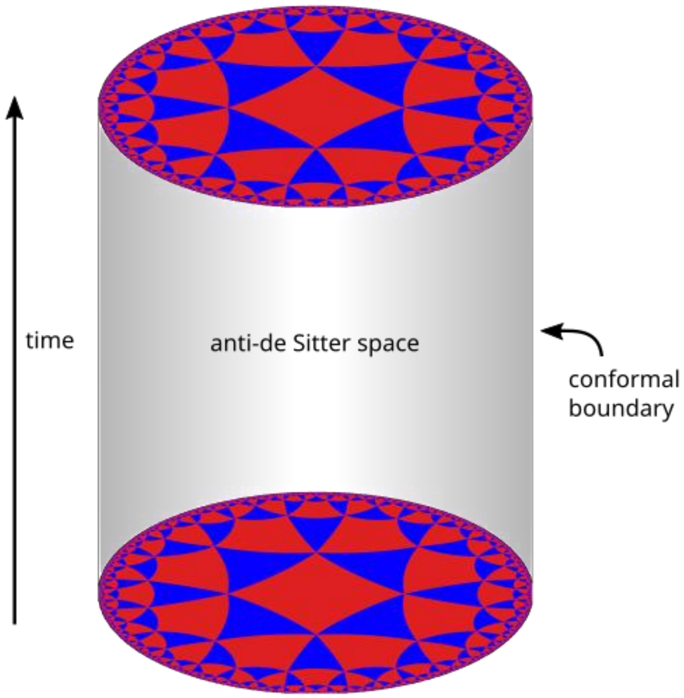


A tessellation of the hyperbolic plane by triangles and squares

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.[i] 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.[j]

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.[49] 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.[50]

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.[51] 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.[52] 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.[53]



Three-dimensional anti-de Sitter space is like a stack of hyperbolic disks, each one representing the state of the universe at a given time. One can study theories of quantum gravity such as M-theory in the resulting spacetime.

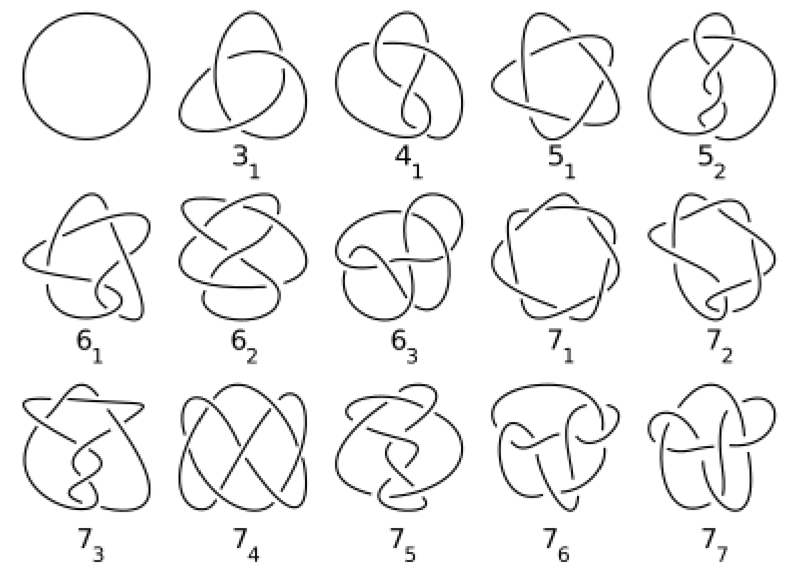
Now imagine a stack of hyperbolic disks where each disk represents the state of the universe at a given time. The resulting geometric object is three-dimensional anti-de Sitter space.[52] It looks like a solid cylinder in which any cross section is a copy of the hyperbolic disk. Time runs along the vertical 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.[53]

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.[52]

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.[54] 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.[55]

6D (2,0) superconformal field theory

Main article: 6D (2,0) superconformal field theory



The six-dimensional (2,0)-theory has been used to understand results from the mathematical theory of knots.

One particular realization of the AdS/CFT correspondence states that M-theory on the product space $AdS_7 \times S^4$ is equivalent to the so-called (2,0)-theory on the six-dimensional boundary.[49] 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 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.[k]

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.[56] More recently, theorists have extended these ideas to study the theories obtained by compactifying down to three dimensions.[57]

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.[58] In subsequent work, Witten showed that the (2,0)-theory could be used to understand a concept in mathematics called Khovanov homology.[59] 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.[60] 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.[61]

ABJM superconformal field theory

Main article: ABJM superconformal field theory

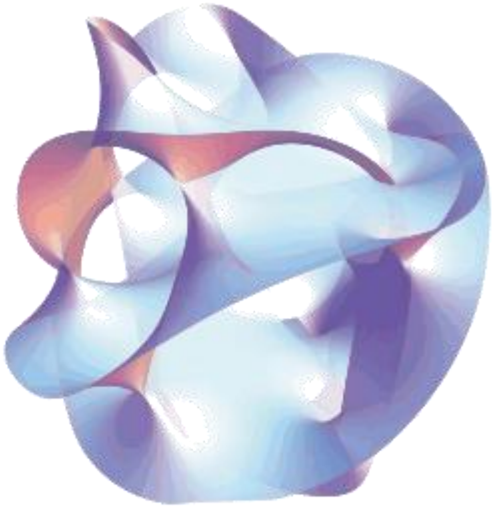
Another realization of the AdS/CFT correspondence states that M-theory on $AdS_4 \times S^7$ is equivalent to a quantum field theory called the ABJM theory in three dimensions. In this version of the correspondence, seven of the dimensions of M-theory are curled up, leaving four non-compact dimensions. Since the spacetime of our universe is four-dimensional, this version of the correspondence provides a somewhat more realistic description of gravity.[62]

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.[63] In addition, the ABJM theory serves as a semi-realistic simplified model for solving problems that arise in condensed matter physics.[62]

Phenomenology

Overview

Main article: String phenomenology



A cross section of a Calabi–Yau manifold

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.[64]

Typically, such models are based on the idea of compactification.[l] 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,[65] 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.[66] 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.[67]

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.[68]

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.[69] 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.[70]

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.[70]

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.[70]

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.[70]

See also

- F-theory
- Multiverse

External links

- Superstringtheory.com – The "Official String Theory Web Site", created by Patricia Schwarz. References on string theory and M-theory for the layperson and expert.
- Not Even Wrong – Peter Woit's blog on physics in general, and string theory in particular.
- M-Theory – Edward Witten (1995) – Witten's 1995 lecture introducing M-Theory.

What is M-Theory?

M-Theory

It is the name of the unknown theory of everything which would combine all five Superstring theories and the Supergravity at 11 dimensions together.

The theory requires mathematical tools which have yet to be invented in order to be fully understood. The theory was proposed by Edward Witten.

The following article is somewhat technical in nature, see M-theory simplified for a less technical article.
M-theory's relation to superstrings and supergravity. In various geometric backgrounds, It is associating with the different superstring theories (in different geometric backgrounds), and the principle of duality are relating these limits to each other. Two physical theories are dual to each other if they have identical physics after a certain mathematical transformation.

Types

- Type IIA and IIB are related by T-duality, as are the two Heterotic theories.
- While Type I and Heterotic SO(32) are related by the S-duality. Type IIB is also S-dual with itself.
- The type II theories have two supersymmetries in the ten-dimensional sense, the rest just one.
- The type I theory is special in that it is based on unoriented open and closed strings.
- The other four are based on oriented closed strings.
- The IIA theory is special because it is non-chiral (parity conserving).
- The other four are chiral (parity violating).

In each of these cases there is an 11th dimension that becomes large at strong coupling. While the IIA case the 11th dimension is a circle. In the HE case it is a line interval , which makes eleven-dimensional space-time display two ten-dimensional boundaries. The strong coupling limit of either theory produces an 11-dimensional spacetime. This eleven-dimensional description of the underlying theory is called “M- theory”. A string’s space-time history can be viewed mathematically by functions like XÃŽÂ¼(Ã□Æ’,Ã□â€ž) that describe how the string’s two-dimensional sheet coordinates (Ã□Æ’,Ã□â€ž) map into space-time XÃŽÂ¼.

One interpretation of this result is that the 11th dimension was always present but invisible because the radius of the 11th dimension is proportional to the string coupling contant and the traditional perturbative string theory presumes it to be infinitesimal. Another interpretation is that dimension is not a fundamental concept of M-theory at all.

Characteristics of M-theory

M-theory contains much more than just strings. It contains both higher and lower dimensional objects. These objects term is p-branes where p denotes their dimensionality (thus, 1-brane for a string and 2-brane for a membrane). Higher dimensional objects were always present in superstring theory but could never be studied before the Second Superstring Revolution because of their non-perturbative nature.
Insights into non-perturbative properties of p-branes stem from a special class of p-branes called Dirichlet p-branes (Dp-branes). This name results from the boundary conditions assigned to the ends of open strings in type I superstrings.

Open strings of the type I theory can have endpoints which satisfy the Neumann boundary condition. Under this condition, the endpoints of strings are free to move about but no momentum can flow into or out of the end of a string. The T duality infers the existence of open strings with positions fixed in the dimensions that are T-transformed.

Generally, in type II theories, we can imagine open strings with specific positions for the end-points in some of the dimensions. This lends an inference that they must end on a preferred surface. Superficially, this notion seems to break the relativistic invariance of the theory, possibly paradoxical. The resolution of this paradox is that strings end on a p-dimensional dynamic object, the Dp-brane.

The importance of D-branes stems from the fact that they make it possible to study the excitations of the brane using the renormalizable 2D quantum field theory of the open string instead of the non-renormalizable world-volume theory of the D-brane itself. In this way it becomes possible to compute non-perturbative phenomena using perturbative methods.

-

Many of the previously identified p-branes are D-branes ! Others are related to D-branes by duality symmetries, so that they can also be brought under mathematical control. D-branes have found many useful applications, the most remarkable being the study of black holes. Scientists can use Strominger and Vafa have shown that D-brane techniques count the quantum microstates associated to classical black hole configurations.

The simplest case first explored was static extremal charged black holes in five dimensions. Strominger and Vafa proved for large values of the charges the entropy S = log N, where N is equal to the number of quantum states that system can be in, agrees with the Bekenstein-Hawking prediction (1/4 the area of the event horizon). This result has been generalized to black holes in 4D as well as to ones that are near extremal (and radiate correctly) or rotating, a remarkable advance. It has not yet been proven that there is any problematic breakdown of quantum mechanics due to black holes.

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DEFINITION

What is the 11th dimension in M-theory?

Published: Dec 13, 2024

The 11th dimension is a characteristic of spacetime that has been proposed as a possible answer to questions that arise in superstring theory. It unifies these theories into a potential single theory of everything.

The theory of superstrings involves the existence of nine dimensions of space and one dimension of time for a total of 10 dimensions. Over the years, multiple variants of string theory have emerged, all attempting to provide a theory of everything that explains how the universe works, with the goal of uniting general relativity and quantum mechanics. Of these variants, five theories are considered the most viable.

All five variants demonstrate mathematical consistency. However, they look different from each other and exhibit different characteristics, to the point of seeming contradictory in places. More importantly, each one offers only a partial glimpse into how everything works. To address these limitations, M-theory emerged, tying together the five string variants and introducing the concept of an 11th dimension to unify these five potential solutions.

The 11th dimension is a mathematical concept. In this context, dimension is best understood as an additional variable added to a math equation to make it solvable. It is not equivalent to the dimensions of space as we understand them in daily usage.

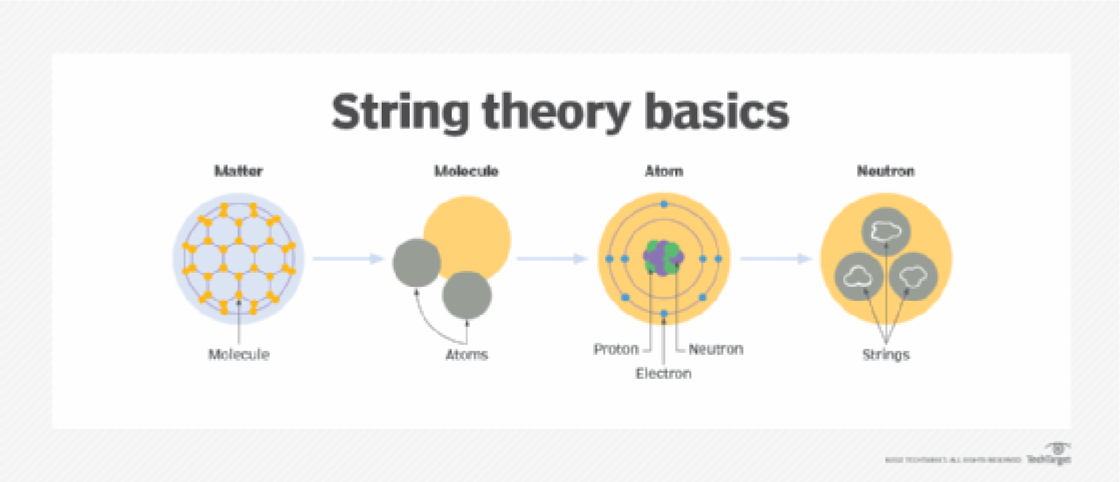
What is superstring theory?

According to string theory, all the elementary particles in the universe are vibrating, one-dimensional filaments of energy known as strings. Strings have no width or height, but they do have length, which is estimated to be 10^{-35} meters -- many times smaller than the diameter of an atom's nucleus.

Every subatomic particle is a vibrating string, according to string theory. The string's movement determines the type of particle and its characteristics, whether a photon, electron, graviton or other type of particle. In this respect, a string acts much like a violin string whose vibrations determine the note and tone.

The concept of supersymmetry postulates that for each particle there is an associated anti-particle. Supersymmetric string theory is shortened to superstring theory.

String theory is only a mathematical model and still lacks concrete experimental evidence to prove its accuracy. Even so, the model provides an elegant description of the fundamental components that make up the universe. It also predicts the existence of 10 dimensions that the strings can vibrate in, rather than four.



According to string theory, the most basic components of all matter are tiny vibrating strands or 'strings' of energy.

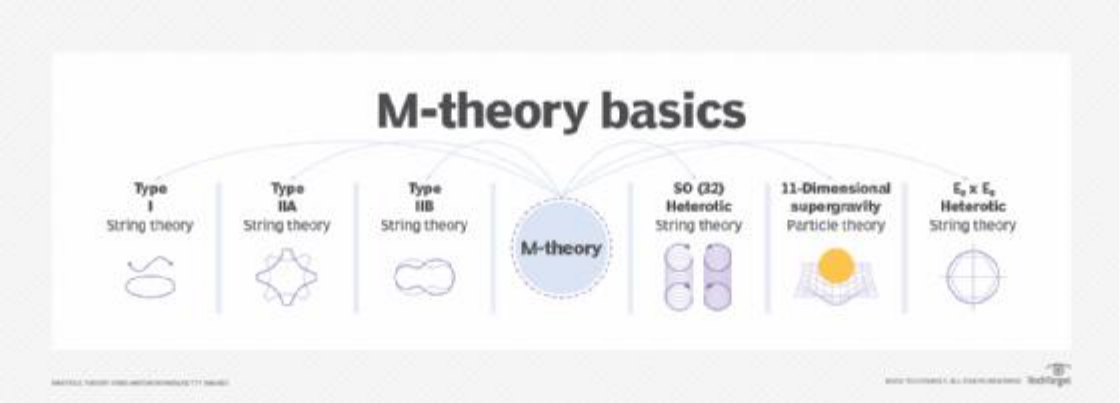
Prior to the introduction of string theory, it was generally believed that we lived in a universe with four dimensions -- three spatial and one temporal.

- **First dimension.** Linear dimension that has length, but no width or height. This dimension is typically represented as a line that connects two points.
- **Second dimension.** Flat dimension that has length and width to create a defined area, but no height, much like a sheet of paper or computer display.
- **Third dimension.** Dimension in which we experience the world around us, with length, width and height. Three-dimensional objects -- such as cubes or spheres -- contain volume.
- **Fourth dimension.** Time dimension that extends the three-dimensional world by incorporating events that enable three-dimensional objects to move forward and change. The concept of a fourth dimension plays a key role in the general theory of relativity.

String theory introduces six more dimensions that are "curled up" or "compactified" into very small spaces. The six dimensions can be perceived only by the strings and are otherwise undetectable, but their configurations play a pivotal role in determining the properties of subatomic particles. They also provide the conceptual underpinnings needed by the five primary variants of string theory to make the mathematics work. Yet even with 10 dimensions, the variants still fall short in the quest for a theory of everything.

What is M-theory?

M-theory attempts to address these limitations by adding an 11th dimension, along with the concept of membrane, or brane. Like the string, a brane is theorized to be a universal building block that provides the foundation of all matter. However, unlike the original strings, branes add dimensionality, making them more flexible than strings alone. For example, a universe with 11 dimensions can support one-dimensional strings (1-brane), two-dimensional planes (2-branes) and perhaps other dimensional branes.



M-theory ties together the five most viable variants of string theory and introduces the concept of an 11th dimension.

This added dimensionality requires an 11th dimension to make it mathematically feasible. The new dimension and its accompanying branes also resolve the limitations of the five string theory variants. Rather than treating them as conflicting theories, the 11th dimension makes it possible to see them as different aspects of a much larger whole, each viewing the universe from its own perspective. Furthermore, M-theory, with its 11 dimensions and collection of branes, offers a viable mathematical theory of everything, unlike its string predecessors. Nevertheless, as with string theory, M-theory still lacks concrete experimental evidence to move it beyond equations.

What are the 11 dimensions?

In M-theory, the various dimensions are best understood as the number of variables in an equation, and not the same as the dimensions of spacetime we are familiar with -- namely height, width, length and time.

To help understand this, imagine trying to fully describe an airplane moving through a three-dimensional space. You would need four variables to fully describe it: the yaw, pitch, roll and magnitude. These four numbers are known as quaternions. Quaternions are common in computing, where they are used to compute things like 3D graphics or the motions of spacecraft. Now add in time, and you are using five variables to fully describe a point in four-dimensional spacetime.

In string theory, eight variables known as octonions are used to describe the one-dimensional strings. Octonions can be operated on using algebra the same way as quaternions and imaginary numbers can. With it, all interactions of the strings, understood as forces and particles, can be calculated using octonion multiplication in the same numerical space.

Imagine a piece of string being moved; the path it takes describes a two-dimensional plane. This is what happens when time is added to the one-dimensional strings operating in eight-dimensional space. The two-dimensional path is what is called a brane. This adds two additional dimensions to our equation -- one of time and one to describe the brane. This brings the total number of variables, or dimensions, to 10.

As discussed earlier, using 10-dimensional string theory resulted in five separate systems that are all mathematically consistent within themselves, but contradict each other. By adding in an additional variable, or dimension for the brane to move through, these five systems can be made consistent with each other.

This gives us the total number of 11 dimensions.