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String Theory

Vibrating Strings and Hidden Dimensions

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Chapter 1: The Discovery of String Theory

Five consistent superstring formulations took shape before the mid-1990s conjecture that they were all different limits of one eleven-dimensional parent theory, M-theory. In late 1997 came a second landmark: a dictionary, now called the AdS/CFT correspondence, relating a gravitational string world to an ordinary quantum field theory living on its boundary. A recognized shortcoming persists alongside these successes, namely that the complete non-perturbative definition of the theory is still missing.

Another issue is that the theory is thought to describe an enormous landscape of possible universes, which has complicated efforts to derive realistic particle-physics models from the framework. Detractors inside the community have taken both facts as grounds for skepticism about the whole unification program. In the 20th 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 spacetime at the macro-level. The other is quantum mechanics, a completely different formulation, which uses known probability principles to describe physical phenomena at the micro-level. 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.

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. 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. String theory is a theoretical framework that attempts to address these questions. 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 consistent with non-string models of elementary particles, with its mass, charge, and other properties determined by the vibrational state of the string.

String theory's application as a form of quantum gravity proposes a vibrational state responsible for the graviton, a yet unproven quantum particle that is theorized to

carry gravitational force. 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. 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 (AdS/CFT for short). This is a theoretical result that 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 and condensed matter physics. Since string theory incorporates all of the fundamental interactions, including gravity, many physicists hope that it will eventually be developed to the point where it fully describes 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.

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. 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.

Chapter 2: Understanding String Theory

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. 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.

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 by the mid-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.

The subject's founding observation is that the point-like particles of quantum field theory can likewise be treated as tiny one-dimensional filaments. 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 with a two-dimensional (2D) surface representing the motion of a string.

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. 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.

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. The original version of string theory was bosonic string theory, but this version described only bosons, a class of particles that 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. In theories with supersymmetry, each boson has a counterpart which is a fermion, and vice versa. The superstring comes in several flavors — type I, the two type II variants, and two heterotic branches (SO(32) and $E8\times E8$). 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. In everyday life, there are three familiar dimensions (3D) 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 (4D) spacetime.

In this framework, the phenomenon of gravity is viewed as a consequence of the geometry of spacetime. In spite of the fact that the Universe is well described by 4D 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.

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 4D of spacetime which have nonetheless managed to escape detection. String 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. 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. 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. 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. Another approach to reducing the number of dimensions is the so-called brane-world scenario.

Chapter 3: Key Characteristics of String Theory

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. A 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 that 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 says the descriptions on a circle of radius R and on its reciprocal 1/R are physically identical, every observable in one description matching a counterpart in the other.

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. 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 an example of an S-duality relationship between quantum field theories.

The AdS/CFT correspondence is an example of a duality that 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.

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 is a zero-brane and a string a one-brane. 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.

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. 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.

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. 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.

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. 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. In 1978, work by Werner Nahm showed that the maximum spacetime dimension in which one can formulate a consistent supersymmetric theory is eleven.

Chapter 4: The Science Behind String Theory

In the same year, Eugene 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. 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. 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. They found that a tangle of strongly interacting strings sometimes admits an equivalent description as weakly coupled strings of a different theory. This phenomenon is known as S-duality. It was studied by Ashoke Sen in the context of heterotic strings in four dimensions and by Chris Hull and Paul Townsend in the context of the type IIB theory.

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. At around the same time, as many physicists were studying the properties of strings, a small group of physicists were 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. 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. 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. Duff and his collaborators showed that this construction reproduces exactly the strings appearing in type IIA superstring theory.

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. In the months following Witten's announcement, hundreds of new papers appeared on the Internet confirming different parts of his proposal.

Today this flurry of work is known as the second superstring revolution. 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." 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.

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. 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.

Chapter 5: Observation and Measurement of String Theory

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. 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. 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.

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. 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. In the twentieth century, physicists began to apply the same concepts to black holes.

In most systems such as gases, the entropy scales 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 may escape its gravitational attraction. When combined with ideas of the physicist Stephen Hawking, Bekenstein's work yielded a precise formula for the entropy of a black hole.

The Bekenstein–Hawking formula expresses the entropy S as $S = c\ k\ A\ G$ where c is the speed of light, k is the Boltzmann constant, ħ is the reduced Planck constant, G is Newton's constant, and A is the surface area of the event horizon. 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. In a paper from 1996, Andrew Strominger and Cumrun Vafa showed how to derive the Bekenstein–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. Subsequent work by Strominger, Vafa, and others refined the original calculations and gave the precise values of the "quantum corrections" needed to describe very small black holes.

The black holes that Strominger and Vafa considered in their original work were quite different from real astrophysical black holes. One difference was that Strominger and Vafa considered only extremal black holes in order to make the calculation tractable.

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. 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 that implies that string theory is in some cases equivalent to a quantum field theory.

Chapter 6: Important Features of String 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. 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, or above. 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

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Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

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