Is String Theory the Answer?

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Introduction

The field of physics in the twentieth century was characterized by major shifts in the paradigm of established knowledge. Isaac Newton's theory of gravity as a force exerted between all massive bodies went unchallenged by the scientific community for nearly 300 years until 1916, when Albert Einstein published his theory of general relativity and redefined mankind's perspective of gravity, space, and time itself. As Einstein's elegant theory was seamlessly applied to the largest objects in the universe over the course of the following decades, physicists narrowed their focus. Pioneers like Werner Heisenberg and Neils Bohr chased the secrets of the fundamental particles of matter, eventually crystallizing a basic understanding of how the constituent building blocks of the universe interact on a quantum scale. Quantum mechanics was born, and physics was once more revolutionized by mind-bending ideas about the nature of light and the universe's inherent non-determinism.

As the new millennium approached, physicists believed another momentous paradigm shift was inevitable, one with the potential to subsume all previous theories and provide new avenues toward a complete understanding of how and why the universe behaves and appears the way it does. This 'theory of everything', called string theory, had been stubbornly and repeatedly pushed aside, waiting decades to finally claim its place in the scientific spotlight. But since being hailed as a theoretical savior of unparalleled mathematical beauty at the turn of the century, string theory has once more slipped into the background of physics, its importance universally accepted but hardly deciphered. An examination of string theory's history, details, and implications reveals its polarizing status as both a potential source of ultimate enlightenment and a limit on mankind's knowledge of the universe.

A Theoretical Paradox

Understanding the paramount importance to physicists of a working string theory requires recognition of the conflict between general relativity and quantum mechanics, the universe's two descriptions of reality. General relativity is a theory of gravity that employs classical physical principles in a slightly different manner than Newtonian theory. It postulates that space and time are fused into a single four-dimensional continuum called spacetime. If pictured as a fabric, undisturbed, empty spacetime is a flat sheet stretching infinitely in all directions. The presence of mass in the form of concentrated matter or energy, however, causes spacetime to warp from its flattened state into something possessing curvature, the way a bowling ball would distort a stretched bedsheet. In distorted spacetime, objects following the shortest distance from one point to another trace a curved path rather than a straight line. This effect on objects' trajectories is what we know as gravity, and it is simply the product of movement in curved—rather than flat—geometry, postulated to be perfectly smooth across the universe on any observational scale. On this level stage, general relativity predicts with great accuracy the motions of moons, planets, stars, and galaxies by incorporating definitive position and velocity values into equations which determine gravitational effects on particular objects at particular locations [1].

While general relativity elegantly provides deterministic predictions for dynamical outcomes of large, massive objects, quantum mechanics deals with the puzzling uncertainty of the universe's most elementary particles. Objects at the quantum level do not possess definite positions or velocities; instead, they follow probabilistic laws describing the likelihood that an event or outcome will occur. These *wave functions*, as the probabilities are known, are responsible for the unsettling conclusion that the same exact experiment repeatedly conducted on a quantum system will not necessarily yield the same result every time since no outcome is assured. There exists only a possible *range* of results, each with its own chance of occurring. Progressions in quantum theory include the discovery that light acts both as a wave and particle and that a system may enter a superpositional state—meaning it simultaneously occupies *all* of a multitude of potential outcomes—prior to being observed, at which time it 'decoheres' into the single outcome that the observer sees as reality. Quantum mechanics even suggests that upon close examination, empty space itself is not truly empty. Werner Heisenberg's quantum uncertainty principle maintains that the more precisely a spatial measurement of a system is made, the less precisely the momentum or energy of that system can be known. At scales many orders of magnitude smaller than a meter, these uncertainties are realized as fluctuations. And since energy and matter are equivalent, these fluctuations can manifest themselves as a sea of virtual particles constantly created and annihilated at every point in spacetime, 'borrowing' energy from the universe and vanishing before it is possible to observe that they existed at all [2]. The universe, down to its ostensibly empty regions, exists in a state of constant flux [1].

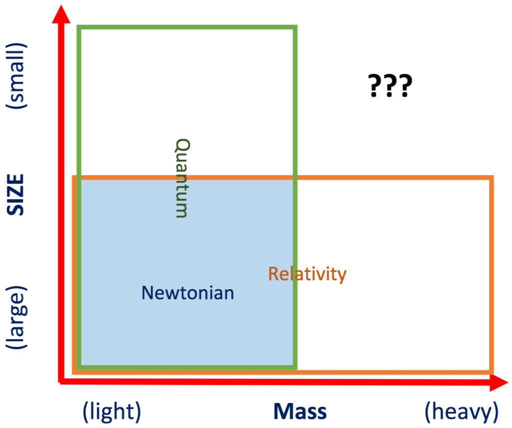


Figure 1: Quantum mechanics and general relativity are shown to describe the universe at different scales (courtesy of Charles Bailyn).

The incompatibility between general relativity and quantum mechanics is already apparent in the two theories' opposing characterizations of spacetime. While general relativity envisions a uniformly smooth expanse upon which objects gracefully interact, quantum theory maintains that spacetime on a microscopic scale is a seething sea of uncertain fluctuation. The contradiction fully manifests itself when one attempts to unify the theories by applying the principles of general relativity to quantum scales. The strength of gravitational interaction between two objects varies with the inverse square of the distance between them; this distance is measured between the centers of the objects. Mutual attraction between two planets moved to half their original distance, for example, would cause the gravitational influence between them to increase by a factor of four. But quantum mechanics regards particles as point-like objects of a single dimension, meaning they have, in essence, zero size. For two spherical objects, like planets or apples, the point at which their surfaces touch represents the minimum possible distance between them. This is permissible by general relativity since there will always remain a distance—composed of the radii of the two objects added together—over which gravitational influence can be exerted. But bringing two point-like particles of zero size sufficiently close together could theoretically unite their centers, unbounded by any surface. Dividing by a zero value for distance, the inverse square law governing gravitational force would yield the nonsensical result of infinite attraction between particles. Besides demonstrating a fundamental rift in how relativity and quantum mechanics each describes the universe at a particular scale, this dilemma provides the impetus for the unified theory of quantum gravity that string theory seeks to provide [3].

A Theory to Explain Everything?

The potential to unify two theories that have been at odds since their discoveries is not the only appealing aspect of string theory. Other problems concerning the four fundamental forces

— electro-magnetic, gravitational, strong, and weak — and the universe at large have plagued physicists and demanded solutions for decades. A problem whose solution would likely involve quantum gravity is known as the Hierarchy Problem, the vast discrepancy between the scales of the four fundamental forces. These disparate forces are thought to have been unified at some point in time less than one second after the Big Bang before they disjoined as the universe's temperature rapidly cooled below certain energy thresholds. The values of these threshold temperatures and energies have been approximated for each force and scaled relative to one another. The gravitational scale, however, is weaker than the next-closest electroweak scale by a factor of 10^{16}. We experience gravity's relative weakness every day; the simple act of raising one's arm to move food to one's mouth shows that mere muscular power can overcome the entirety of Earth's exerted gravity. An explanation for gravity's unexplained weakness and failure to unify at the same energy threshold as the other forces is another confounding puzzle for which string theory provides an answer.

Besides providing framework for quantum gravity and resolving the Hierarchy Problem, a third principal goal of string theory is to address the Fine-Tuning Problem. Around twenty numbers—representing the comparative strengths of forces and the masses of fundamental particles—serve as parameters defining the physical universe we observe. These numbers are finely tuned to their specific values; if even one or two were slightly altered, the chemical and nuclear interactions powering stars and lending the universe its properties would be sufficiently different that the universe would not exist the way we know it [4]. It is widely believed among physicists that a complete understanding of the universe and the nature of reality is only attainable with a satisfactory explanation for why the universe has the particular, finely-tuned critical values that it does.

A Tumultuous History

The roots of string theory trace back almost as far as the persistent problems it is purported to finally solve. In 1919, Polish mathematician Theodor Kaluza sent a paper to Einstein, the world's foremost authority on the structure of space and time, postulating the existence of an extra spatial dimension. Kaluza's proposal was primarily motivated by his recent breakthroughs in unifying the equations of Einstein's general relativity and James Clerk Maxwell's electromagnetic theory, and it caught the attention of other theorists. In 1926, Swedish mathematician Oskar Klein refined Kaluza's original idea with the bold claim that "the spatial fabric of our universe may have both extended and curled-up dimensions" [5]. As the now-famous Kaluza-Klein theory goes, there may be an extra, circular dimension curled up at each point in spacetime within the three large dimensions we are capable of observing, but no observational equipment is powerful enough to discern its ring-like structure. Kaluza completed calculations of general relativity while accounting for an extra dimension and was amazed to derive new equations which precisely matched those discovered by Maxwell to describe the electromagnetic force [5].

Despite seeming to unify general relativity and electromagnetism, the Kaluza-Klein model, impossible to confirm experimentally, was pushed aside by the physics community in favor of new discoveries pertaining to quantum theory until 1968, when theoretical physicist Gabriele Veneziano realized the implications of the Euler's arcane beta function while investigating properties of the strong force. In his overview of string theory, The Elegant Universe, Brian Greene of Columbia University writes,

> "Veneziano's observation provided a powerful mathematical encapsulation of many features of the strong force and it launched an intense flurry of research aimed at using Euler's beta-function… to describe the surfeit of data being collected at various atom smashers around the world.… [P]hysicists showed that if one modeled elementary particles as little, vibrating, one-dimensional strings, their nuclear interactions could be described exactly by Euler's function" [5].

When testing yielded results that contradicted known features of the Standard Model of elementary particles, physicists were quick to lose faith in this primitive version of string theory. Some, however, continued exploring its nuances, and in 1974, John Schwartz of the California Institute of Technology and Joel Scherk of the Ecole Normale Supérieure in Paris showed that certain patterns of string vibration matched the proposed properties of the theoretical graviton, the undetected transmitter of the gravitational force whose existence is implied by the parameters of the Standard Model. The results were once more received with skepticism, so the researchers embarked on another decade of analysis. In 1984, Schwarz and Michael Green of Queen Mary College London published the seminal paper which incorporated string theory to not only resolve the longstanding mathematical antagonism between quantum mechanics and general relativity, but also account for the existence and fundamental relation between each matter particle and each of the four fundamental forces [5]. The breakthrough was so comprehensive and persuasive that string theory could no longer be dismissed or ignored. Droves of physicists scrambled to uncover the underlying mysteries of the most impactful paradigm shift in modern science.

Redefining the Universe

String theory's revolutionary view of the universe is anchored upon the premise that fundamental particles are not point-like objects but vibrating, one-dimensional strands of energy 10^{20} times smaller than a proton. These strings are the basic building blocks of the universe. Each of the discrete particles of the Standard Model arises from a unique resonance pattern of the same fundamental string. As Greene summarizes, "The vibrational pattern of a string encodes the properties of the corresponding particle (its mass, its electric charge, its spin) and so may be thought of as the particle's 'fingerprint"' [4]. The truths of our universe derived even from these most basic principles of string theory are awe-inspiring. Every matter particle and every boson, or force-carrying particle, from which the universe is constructed is lent its individual properties by nothing more than a different energetic iteration of a common constituent. This means that matter and force arise from the same 'building block': pure energy, shown to be equivalent to the property of mass by Einstein and his renowned formula, $E = mc^2$. All matter with which we are familiar is simply a special arrangement of tiny, trembling strands of energy.

The theory's mathematical groundwork—characterized as something of beauty, elegance, and grand precision by mathematicians and physical theorists alike—resurrects Kaluza and Klein's rejected theory with the proposition of not one but *six* extra, unobservable spatial dimensions curled up at each point in spacetime. The three spatial dimensions and single temporal dimension with which we interact are infinite or nearly so, but the others are—exactly as Kaluza suggested of the single dimension of electromagnetic propagation—compactified into curious six-dimensional shapes called Calabi-Yau manifolds. The radius of these objects is speculated to be close to the Planck length, the mystical threshold at which known physical laws break down and surrender to the inherent quantum uncertainty of the universe.[6] Such a scale, approximately equivalent to 10^{-35} meter, explains why these hidden dimensions have never been observed.

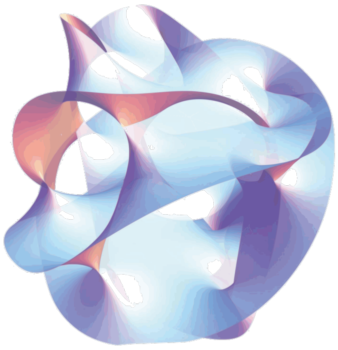
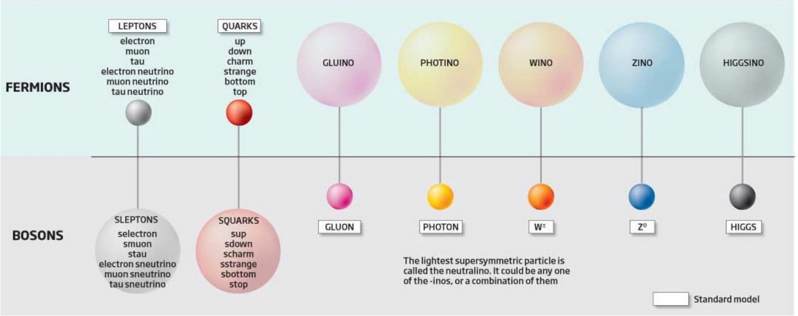


Figure 2: Conceptual model of a Calabi-Yau manifold (courtesy of Wikimedia Commons).

The properties of the Calabi-Yau manifolds are inextricably intertwined with key principles of string theory, and although these shapes cannot be directly studied, they continue to inform mankind's collective base of knowledge about the universe. Under the Standard Model, elementary particles are classified into three 'families', each more massive than the last. String theory accounts for the differentiation between these families by proposing that Calabi-Yau shapes contain multidimensional holes. Each hole within a Calabi-Yau space is associated with a family of lowest-energy string vibrations; since fundamental particles correspond to particular lowest-energy resonances, they are grouped into families according to the particular hole to which they are related. The three observed families of particles, therefore, arise not randomly but from the presence of three holes in the shape containing the extra dimensions [4]. The precise geometries of the Calabi-Yau shapes, defined at least in part by their multidimensional holes, affect the ways a string can vibrate within six-dimensional space and play a crucial role in determining the particular types of resonances—and, by extension, particles—present in the universe.

Hidden Properties Brought to Light

As string theory's basic premises were being established in the wake of its rebirth, theoretical inconsistencies pertaining to particle spin prompted physicists to devise a cleverly innovative solution known as supersymmetry. It had long been established that each known particle possesses an inherent quality known as *spin*, its ceaseless, fixed rate of rotation around an axis. Fermions, or matter particles, are quantum-mechanically characterized by a rate of spin-1/2, while bosons possess intrinsic spin-1. The hypothetical graviton is thought to have spin-2. Early iterations of string theory only described bosons with integer spin.[4] As a proposed 'theory of everything' accounting for all types of particles, string theory had to be modified to include fermions through the implementation of supersymmetry, which suggests that the fundamental particles come in pairs whose spins differ by a half-unit [4]. Under a supersymmetric model, each boson and fermion would be associated with a corresponding superpartner of the opposite classification. While no superpartners have been detected, physicists have generally accepted supersymmetry's plausibility, even if it requires the number of fundamental particles to be doubled.



The lightest supersymmetric particle is called the neutralino. It could be any one of the -inos, or a combination of them

Figure 3: The supersymmetric model (courtesy of Medium.com).

Supersymmetry represents a well-fitting piece of the theoretical puzzle that accounts for the observation of certain finely-tuned quantum processes. The worldview "transforms the coordinates of space and time such that the laws of physics are the same for all observers" [7]. Further circumstantial support arises from supersymmetry's role in force unification: incorporation of supersymmetric principles into the accepted model reveals that the three non-gravitational forces converge more precisely and at a higher energy scale than previously thought [4]. Now a central component of string theory, supersymmetry may one day be found to completely eliminate the Hierarchy Problem.

Despite its present importance to string theory, supersymmetry originally posed a major problem by permitting not just one but five theoretical permutations, each specifying boson-fermion pairing but varying in the details of string vibrational patterns. A key aspect of inconsistency among the theories was their symmetries. Symmetry is a property of a physical system that does not change when the system is transformed in some manner; for example, a sphere is rotationally symmetrical since its appearance does not change if viewed from a different angle [4]. Symmetric incompatibility threatened to douse the promise and momentum string theory had built up in the early 1990s. If this was supposed to be a theory of everything, how could there be five independent versions?

M-Theory

At a 1995 string theory conference attended by the world's foremost theoretical experts, Edward Witten of the Institute for Advanced Study at Princeton ignited the 'Second Superstring Revolution' with the astounding assertion that string theory could be unified through a new formulation

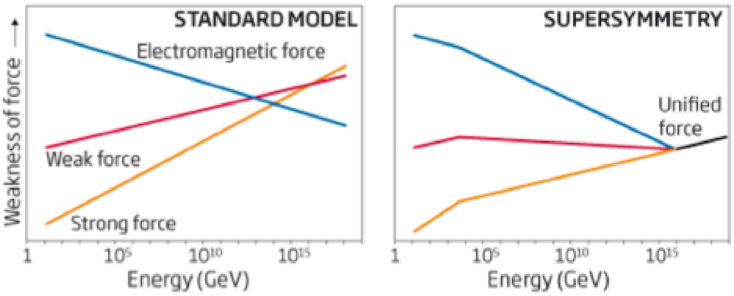


Figure 4: Supersymmetry provides an alternate unification energy for the non-gravitational forces, and physicists hope its precision will be found to include gravity as well (courtesy of Dulwich Science).

of a concept called duality. Duality is a characteristic of theoretical models that appear different but can be shown to describe the exact same physics, yielding new physical and mathematical insights in the process [4]. Prior to 1995, one type of duality had been accepted. T-duality suggests that the universe looks identical near the Planck scale and on large scales.5 Specifically, T-duality analogizes spacetime as curled into a cylinder with a string looped around it. The string has two energy states, one—the vibration mode—arising from the number of times the string fits around the cylinder and the other—the winding mode—from the amount of stretching required for the string to loop at all. A fatter cylinder will allow for a smaller number of loops but necessitate that the string stretch with greater energy to complete those loops. A skinnier cylinder enables the string to loop around it many more times, but the energy required to do so will be far less. The energy states of the vibration and winding modes have been established as inverse to each other, meaning that while the quantities of the two modes are not equal, they yield the same total energy for both the fat and thin tubes when added together. Extrapolated to our universe, the two modes represent particle energies, and T-duality implies that the universe may have the exact same properties on Planck and astronomical scales [7].

A new form of duality called S-duality suggests that certain types of charges are dually related to one another. Various symmetries within physical laws have been proven to conserve particle properties such as mass and charge, but some of these conservations arise from so-called ‘topological’ deformations in fields. S-duality maintains that charges conserved by symmetry, such as electric charge, and those conserved by topological distortions, like magnetic charge, could have reversed roles, eliminating problematic obstacles for mathematical calculation [7]. The long-speculative S-duality was lent the same credibility as T-duality when the two were shown to be dual *themselves* by the Duality of Dualities, proposed in 1994 by Christopher M. Hull of Queen Mary and Westfield College at the University of London along with Paul K. Townsend of the University of Cambridge. The Duality of Dualities can be extrapolated to show that previously disparate versions of string theory are actually dually related.

Witten’s landmark achievement was the unification of T-duality, S-duality, and string-string duality to define parameters for M-theory, a single overarching string theory encompassing all five preexisting versions. M-theory reveals that the five separate models were nothing more than different ways of looking at the same broader theory. Since its introduction to the world in 1995, the vaguely-named M-theory has become mankind’s most well-formulated and plausible model of the universe’s behavior at the smallest scales. It does not stray from the previous conceptions established by string theory, but it makes some notable additions, the most crucial of which is the postulation of an extra *eleventh* dimension. Supersymmetry permits the existence of eleven dimensions, and string theorists had long been unsettled by its inclusion of only ten. Under M-theory, the knowledge gap is filled and the structure of the universe is predicated upon the existence of a new class of objects referred to as *p-branes*, objects of p dimensions that exist within the eleven-dimensional world. Witten’s insights showed that the eleventh dimension is inherently ‘locked’ into the structure of the strings themselves and directly related to the value of the coupling constant, a number governing how likely it is for a given string to split apart or for two strings to

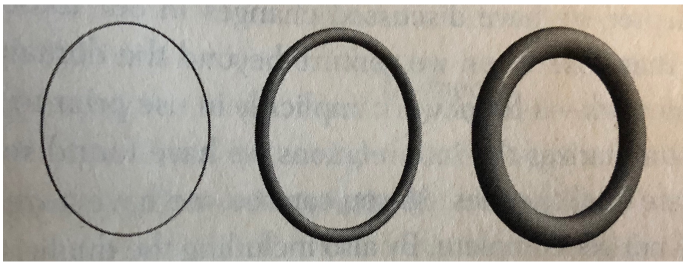


Figure 5: When the value of the coupling constant grows, the eleventh dimension becomes more apparent and one-dimensional strings become two-dimensional branes (Greene, The Elegant Universe 311).

join together into one [4]. When the value of this coupling constant is low—as it was assumed to be throughout all of string theory's early history—the eleventh dimension is so small that it cannot even be accounted for in theoretical equations. When this value is enlarged, however, the dimension and the strings grow with it, and the result of this manipulation is that the universe—previously thought to be a ten-dimensional space containing one-dimensional strings—is revealed to be an eleven-dimensional space full of two-dimensional *branes*.

Strings are branes, but branes can be characterized by up to nine dimensions. Under M-theory, our own universe is one of many contained on three-dimensional branes—accounting for the number of spatial dimensions we observe—within an eleven-dimensional space called the bulk. Six extra spatial dimensions are still compactified within Calabi-Yau shapes at each point in our brane's spacetime, time remains a distinct temporal dimension, and the bulk itself is the hidden eleventh dimension revealed by Witten's revolutionary theory. Particles, as two-dimensional entities, are open strings anchored to our universal brane and unable to interact with parallel branes. The hypothetical graviton, however, is a closed string that is detached from our brane and free to communicate with other branes. This ability to transmit across higher dimensions could account for gravity's relative weakness in our universe, as well as the observed gravitational effects of dark matter, an undetectable substance which exerts influence on our universal structure.

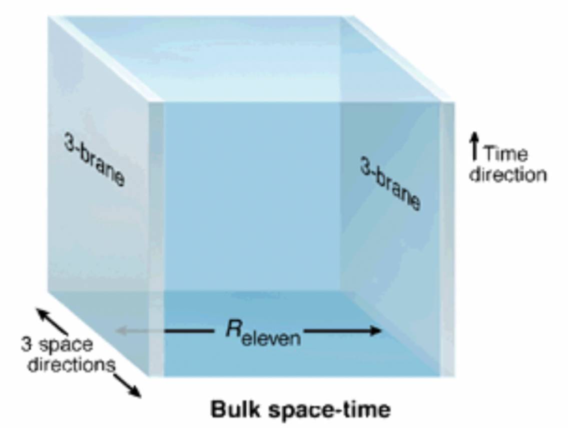


Figure 6: The structure of our universe within a higher-dimensional bulk as envisioned under M-theory (Gibbons 49).

Our three-brane universe, besides being one of many floating within the bulk, may not even be special in any way. Each possible universal configuration of strings, branes, and forces is associated with a potential energy known as its vacuum energy, which represents the energy of spacetime when the four large dimensions are devoid of matter or fields [8]. A theory of string 'landscape' envisions a topology of possible potential energies represented by troughs, or minima, of stable vacua—stable configurations of spacetime. The theory proposes that as forces within a particular stable configuration decay, stability can be upset and the configuration can quantumly tunnel to a new stable configuration of lower vacuum energy. Like a ball rolling through a topology of ridges and valleys, a given universe will settle within valleys of stable vacuum energy indefinitely until it reaches a negative vacuum energy, at which point stability is so disrupted that the configuration collapses upon itself.

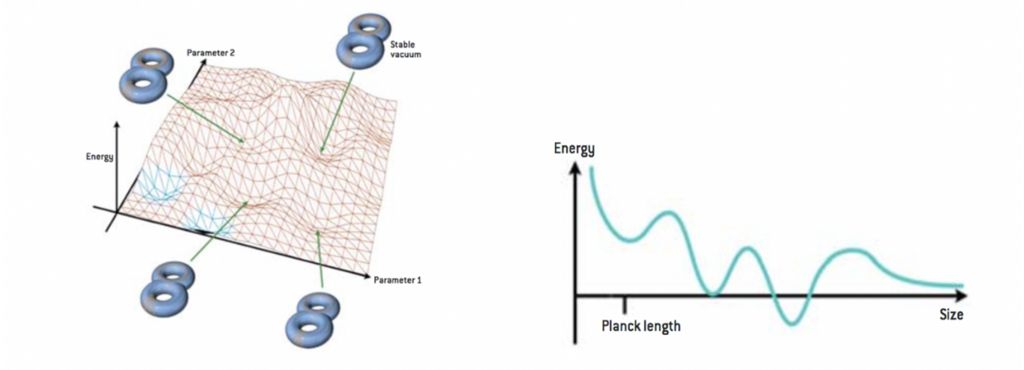


Figure 7: Models of the topological string landscape and minima of stable vacua (Bousso 85).

An observer accompanying the ball rolling gradually through every possible configuration would find that each stable vacuum is governed by its own specific physical laws. Under this theory, our own universe on its three-brane with its specific physical laws is an unremarkable one of nearly 10^{500} possible stable vacua, and the Big Bang was a rather common event—the most recent transition of our universe from one valley to another [8]. The landscape theory, as an offshoot of string theory and M-theory, provides a possible explanation for the Fine-Tuning Problem by postulating that our universe is one of nearly infinitely many that just so happens to possess well-adjusted critical values conducive to life and the formation of the complex celestial structures with which we are familiar.

An Incomplete Vision

Though string theory, revitalized by the new insights of M-theory, remains the most promising explanation of the structure of the universe and our place within it, a slew of problems prevents it from being fully and unquestioningly accepted. Limited by the vanishingly small size of strings and the absence of technology powerful enough to discern objects at quantum scales, string theory is, for now, not directly testable. The question hangs overhead at every conference of string theorists: it works in principle, but how can string theory ever be definitively proven correct? Some skeptics have gone so far as to label the theory philosophy rather than science since, at this point in time, it remains nothing more than a system of beliefs regarding the natural order and structure of the universe. Scientists often require the existence of an experiment that could potentially falsify a theory in order for that theory to be considered scientifically valid [9]. Both string theory and the idea that our universe is but one of infinite possibilities fail to meet this standard, and although many theorists are reluctant to abandon plausible, theoretically-sound ideas simply because of technological barriers, there is growing concern over the present ideological stalemate. Peter Woit of Columbia University believes high-energy particle physics is "in danger of ending" due not only to a lack of technology able to probe Planck-scale depths but also to "the absence of experimental results that point to a better theory, as well as a refusal to abandon failed theoretical ideas" [10]. Potential experiments seek to search for superpartners and collide particles at near-light speed to observe whether any mass is lost in the process, potentially due to the release of gravitons into higher dimensions. Dark matter and dark energy, the mysterious force driving accelerating universal expansion, have been suggested as components of a parallel universe communicating with our own through the exertion of gravity. But these other universes can never be studied from ours, and the properties and nature of dark matter and energy remain as unknown as ever. Even if these experiments make some headway, they still would not constitute direct confirmation of string theory as the true theory of everything.

The lack of progress made in advancing string theory itself since the 1990s has allowed its influence to spread into a diverse array of other fields. From mathematics to black hole dynamics, the principles of string theory continue to play a crucial role in providing new insights related to extra-dimensional geometry, particle behavior, and properties of spacetime. Fields Medal-winning contributions to mathematics have been made with the investigation of amplituhedrons, multi-dimensional objects used to calculate particle interactions, through the lens of string theory [11]. A Japanese research group has provided evidence that neutrinos, long assumed to be massless, can acquire mass through interaction with a field diffused across extra dimensions [12]. In cosmology, inflationary models of the early universe have been enhanced by the integration of ideas related to string theory's association with the multiverse [11]. Some physicists incorporate string theory methodologies into their studies of extreme matter states—plasmas produced by particle colliders and lab-created materials close to absolute zero [13].

The area perhaps benefitting the most from concepts originally arising from string theory is the study of black holes. Using principles derived from the unique properties of Calabi-Yau spaces, a team in 1996 provided new insights into a black hole's inner makeup that agreed with previous landmark studies conducted by Jacob Bekenstein and Stephen Hawking on black hole entropy [13]. Juan Maldacena of the Institute for Advanced Study has pioneered investigation of anti-de Sitter spacetime: hyperbolic spacetime with curious properties. From his work, Maldacena has established the holographic theory, which describes how clouds of particles on the boundary of anti-de Sitter spacetime can equivalently describe complex objects located in the interior within a higher dimension. One type of gluon, the mediator of the strong force, behaves in four-dimensional spacetime as a graviton, establishing a further cohesion between string theory and particle physics [1]. When applied to black holes, the holographic theory predicts that quark-gluon plasma behavior at high temperatures in four dimensions has an extremely low shear viscosity, or resistance to flow. Maldacena has suggested a correlation between four-dimensional quark-gluon plasma on the boundary of anti-de Sitter spacetime and five-dimensional black holes on the interior. New data support this potential correlation, finding that black holes have shear viscosities lower than any known fluid [1]. Progress developing string theory may have slowed in recent decades, but the theory continues to manifest itself in other fields and contribute to cutting-edge research and major advancements in knowledge.

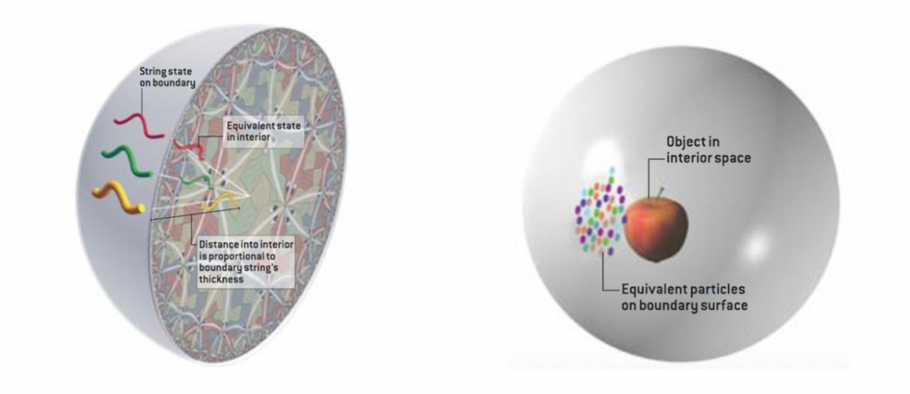


Figure 8: Juan Maldacena's holographic theory finds that particles on the boundary of anti-de Sitter spacetime correspond to complex structures within the interior (Maldacena 61).

Next Steps

Looking back on its complicated history, string theory seems to have failed to live up to the lofty expectations with which it was saddled upon discovery as the long-awaited theory of everything, the 'Holy Grail' of physics. But closer examination reveals that while string theory is not yet directly testable and has progressively faded further and further from the public spotlight, its formulation remains a prodigious achievement of the human intellect and continues to inform groundbreaking discoveries in a variety of related physical and mathematical fields. String theory has accounted for many of the unknowns its architects hoped to resolve: it unites quantum mechanics and general relativity, supports force unification to eliminate the Hierarchy Problem, provides a potential explanation for the Fine-Tuning Problem, and describes our universe's place within the cosmos with grace and solid mathematical underpinnings. Concepts that sounded like science fiction half a century ago have been introduced to the scientific community and the world as plausible phenomena that can contribute to other areas of study.

Physicists were wrong to believe that, like the advent of the Standard Model, understanding of string theory would come in one fell swoop and encapsulate the secrets of the universe within a neat group of equations. The hammering out of string theory's details has been an arduous, discouraging process, the next step of which—direct confirmation—seems hopelessly out of reach at the present time. But just as the first string theorists and all physicists of the past century have revised, learned, and eventually presented paradigm-shifting results, the men and women of the field will persist in their quest for enlightenment, and they, too, will eventually prevail. Problems abound, specifically obstacles preventing experimentation. String theory is incomplete. But as Brian Greene so eloquently declares, this generation of pioneers within the field ought not to feel anything but pride in its achievements at the forefront of human understanding. "If experimental confirmation of string theory is in the offing," Greene writes, "future generations will look back on our era as transformative, a time when science had the fortitude to nurture a remarkable and challenging theory, resulting in one of the most profound steps toward understanding reality" [14]. Whether or not string theory is 'the answer', its continued development is undoubtedly a noble and worthy pursuit.

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