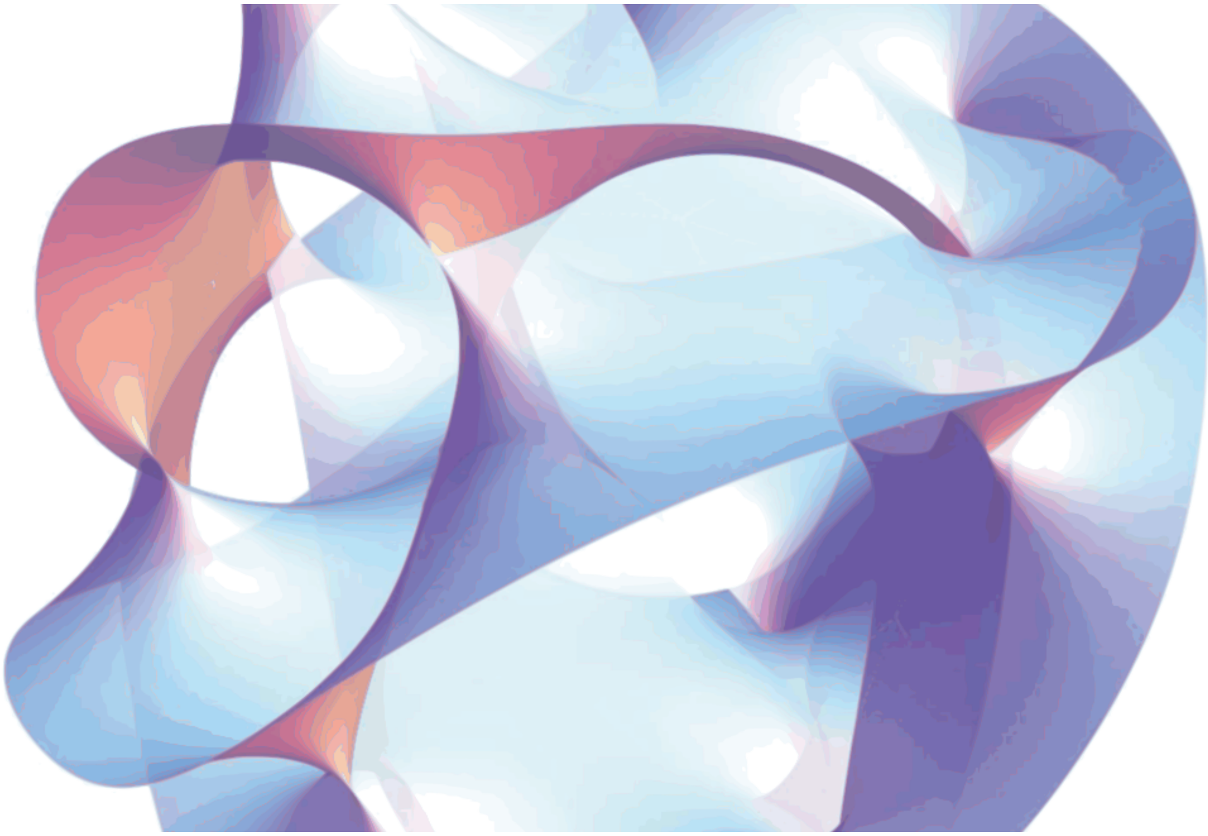

String Theory For Dummies

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Science Coffee House
IIT Kanpur

Basic Idea Of String Theory

String theory is a physics theory that the universe is composed of vibrating filaments of energy, expressed in precise mathematical language.All of the matter in our universe consists of the vibrations of these strings (and branes).
Fields: Physicists use fields to describe the things that don't just have a particular position, but exist at every point in space.
Field Theory: A field theory, then, is a set of rules that tells you how some field will behave.
Quantum Field Theory: It's a type of high-energy theoretical physics that describes the particles and forces in our universe based on compactified extra dimensions. String theory is a quantum field theory, this means that string theory would be a quantum theory of gravity, known as **Quantum Gravity.**

Purpose of String Theory

Today,the physics that we study has basically two parts. One is **Quantum Physics** that studies the very smallest objects in nature, while the other one is **relativity** that tends to study nature on the scale of planets, galaxies, and the universe as a whole.
Theories that attempt to unify these two theories are theories of quantum gravity,and the most promising of all such theories today is **string theory.**Other than this, string theory also attempts to unify the four forces in the universe — electromagnetic force, the strong nuclear force, the weak nuclear force, and gravity — together into one unified theory **"The theory of Everything".**

Let's dig a little older:History and facts

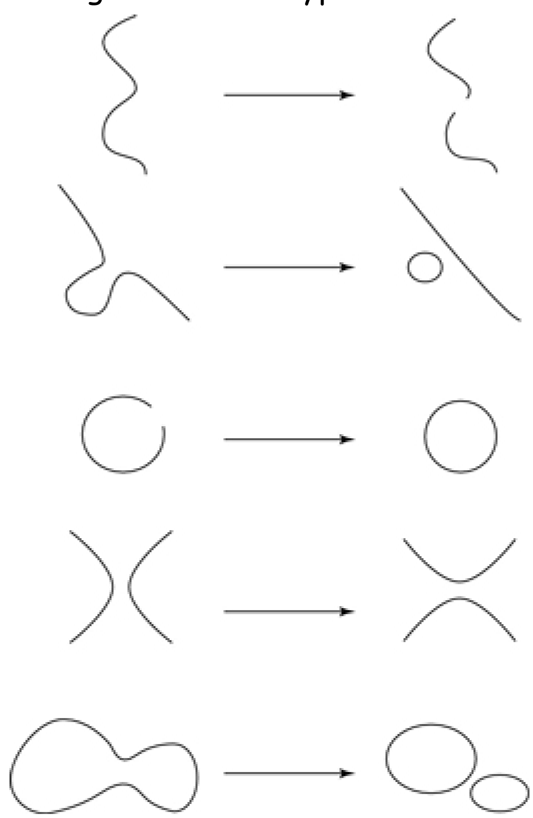
Leonard Susskind is known as the father of String theory.The theory was originally developed in 1968 as a theory that attempted to explain the behavior of **hadrons** inside particle accelerators. Physicists later realized this theory could also be used to explain some aspects of gravity.
In the mid-1990s, string theory was updated to become a more complex theory, called **M-theory**, which contains more objects than just strings. These new objects were called **branes**, and they could have anywhere from zero to nine dimensions. The earlier string theories (which now also include branes)were seen as approximations of the more complete M-theory.

Key Elements of String Theory

✓ String theory predicts that all objects in our universe are composed of vibrating filaments (and membranes) of energy.
✓ String theory attempts to reconcile general relativity (gravity) with quantum physics.
✓ String theory provides a way of unifying all the fundamental forces of the universe.
✓ String theory predicts a new connection (called *supersymmetry*) between two fundamentally different types of particles, *bosons* and *fermions.*
✓ String theory predicts a number of *extra* (usually unobservable) *dimensions* to the universe.

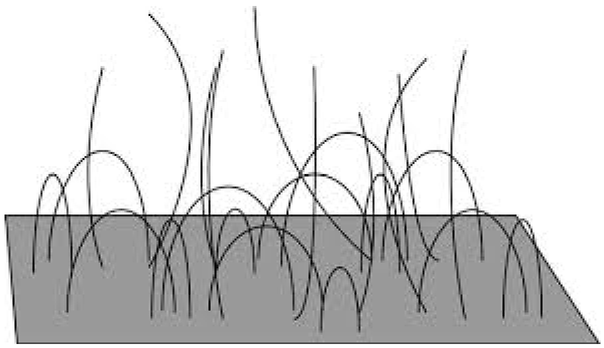
Strings and Branes

These strings came in two forms — *closed strings* and *open strings.* An open string has ends that don't touch each other, while a closed string is a loop with no open end. It was eventually found that these early strings, called Type I strings, could go through five basic types of interactions-



This is important because closed strings have properties that make physicists believe that it might explain gravity.The closed strings of string theory correspond

to the behavior expected for gravity. Specifically, they have properties that match the long sought-after ***graviton***, a particle that would carry the force of gravity between objects.
The theory requires two objects- ***strings*** and ***branes.***
Branes are sheet-like objects on which strings attach their one or both ends.



Supersymmetry

All particles in the universe can be divided into two types: ***bosons*** and ***fermions.***
Bosons: Particles with integer spin value.
Fermions: Particles with non integer spin value.

Supersymmetry: It is a type of connection which says that a fermion must exist for every boson and a boson for every fermion.
Unfortunately these extra particles have not been discovered yet. It is believed that they may have existed in the early universe, but as the universe cooled off and energy spread out after the big bang, these particles would have collapsed into the lower-energy states that we observe today.

Extra Dimensions

Another mathematical result of string theory is that the theory only makes sense in a world with more than three space dimensions!Two possible explanations currently exist for the location of the extra dimensions:
✓ The extra space dimensions are curled up (***compactified***) to incredibly small sizes, so we never perceive them.
✓ We are stuck on a 3-dimensional brane, and the extra dimensions extend off of it and are inaccessible to us.

Mass through Strings

Length of string translates to mass of the particles.As you wrap strings in compactified dimensions, you get new particles with different masses.

Explaining Space Time

To explain space time through string theory,one most common proposal is that space-time comes out of the sum total of all the string interactions in a way that hasn't yet been completely worked out within the theory.

Amazing and Controversial Facts

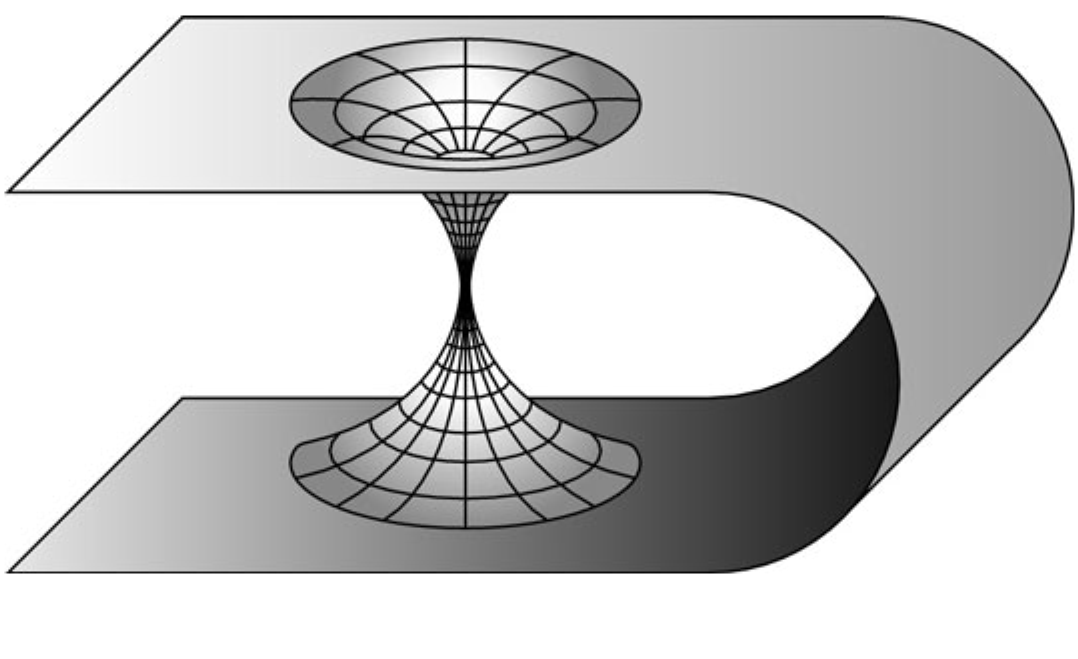
One of the most unexpected and disturbing discoveries of string theory is that instead of one single theory, it turns out there may be a huge number of possible theories.In order to avoid such number,some string theorists have turned to *anthropic principle* which tries to explain properties of our universe as a result of our presence in it.

Parallel Universe

Some interpretations of string theory and quantum physics as well predict that our universe is not the only one. In fact, in the most extreme versions of the theory, an infinite number of other universes exist, some of which contain exact duplicates of our own universe.

Wormholes

Einstein's theory of relativity predicts warped space called a wormhole (also called an Einstein-Rosen bridge). In this case, two distant regions of space are connected by a shorter wormhole, which gives a shortcut between those two distant regions.



String theory allows for the possibility that wormholes extend not only between distant regions of our own universe, but also between distant regions of parallel universes. Perhaps universes that have different physical laws could even be connected by wormholes

Universe as a Hologram

Holographic Principle: In this theory, if you have a volume of space, you can take all the information contained in that space and show that it corresponds to information “written” on the surface of the space.

Time Travel

Some physicists believe that string theory may allow for multiple dimensions of time

The Big Bang

Inflation theory predicts that, very shortly after the original big bang, the universe began to undergo a period of rapid, exponential inflation.

Ekpyrotic Universe : In string theory, there also exists a possible alternate model to our current big bang model in which two branes collided together and our universe is the result. In this model, called the ***ekpyrotic universe***, the universe goes through cycles of creation and destruction, over and over.

Einstein and the Quanta Don't Get Along

Einstein's theory of general relativity, which explains gravity, does an excellent job at explaining the universe on the scale of the cosmos. Quantum physics does an excellent job of explaining the universe on the scale of an atom or smaller. In between those scales, good old-fashioned classical physics usually rules.
Each of the theories works fine on its own, but when you get into areas where both have something specific to say about the same thing — such as what's going on at the border of a black hole — things get very complicated.
Quantum electrodynamics successfully created a quantum theory of electro magnetism.Later, the *electroweak theory* unified this theory together with the weak nuclear force. The strong nuclear force is explained by *quantum chromodynamics*. The current model of physics that explains all three of these forces is called the *Standard Model of particle physics*

Viewing matter at a quantum scale: Chunks of energy

With the rise of modern physics in the 20th century, two key facts about matter became clear:
✓ As Einstein had proposed with his famous E = mc2 equation, matter and energy are, in a sense, interchangeable.
✓ Matter was incredibly complex, made up of an array of bizarre and unexpected types of particles that joined together to form other types of particles.

The atom, it turned out, was composed of a nucleus surrounded by electrons. The nucleus was made up of protons and neutrons, which were, in turn, made up of strange new particles called *quarks.*
Today, the Standard Model of particle physics contains 18 distinct fundamental particles, 17 of which have been observed experimentally. (Physicists are still waiting on the *Higgs boson*.)

Electromagnetism: Super-speedy energy waves

Discovered in the 19th century, the electromagnetic force (or electromagnetism) is a unification of the electrostatic force and the magnetic force. In the mid-20th century, this force was explained in a framework of quantum mechanics called *quantum electrodynamics*, or *QED*. In this framework, the electromagnetic force is transferred by particles of light, called *photons.*

Strong and Weak Nuclear Force

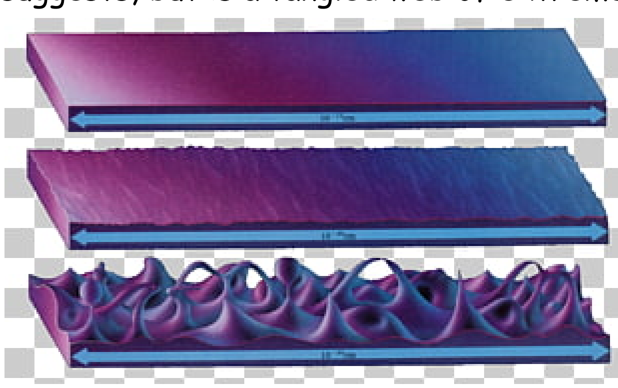
The strong force is mediated by a type of particle called a ***gluon.*** The weak force is mediated by three particles: ***Z, W+, and W- bosons.***
The ***strong nuclear force*** holds quarks together to form protons and neutrons, but it also holds the protons and neutrons together inside the atom's nucleus.
The ***weak nuclear force***, on the other hand, is responsible for radioactive decay, such as when the neutron decays into a proton. The processes governed by the weak nuclear force are responsible for the burning of stars and the formation of heavy elements inside of stars

Singularities

Because matter causes a bending of space-time, cramming a lot of matter into a very small space causes a lot of bending of space-time. In fact, some solutions to Einstein's general relativity equations show situations where space time bends an infinite amount — called a ***singularity.***Specifically, a space-time singularity shows up in the mathematical equations of general relativity in two situations:
1.During the early big bang period of the universe's history
2.Inside black holes.

Quantum jitters: Space-time under a quantum microscope

A second type of infinity, proposed by John Wheeler in 1955, is the quantum foam or, as it's called by string theorist and best-selling author Brian Greene, the ***quantum jitters***.Quantum effects mean that space-time at very tiny distance scales (called the ***Planck length***) is a chaotic sea of virtual particles being created and destroyed. At these levels, space-time is certainly not smooth as relativity suggests, but is a tangled web of extreme and random energy fluctuations,



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A particle of gravity: The graviton

The Standard Model of particle physics explains electromagnetism, the strong nuclear force, and the weak nuclear force as fields that follow the rules of gauge theory. **Gauge theory** is based heavily on mathematical symmetries.Because these forces are quantum theories, the gauge fields come in discrete units (that's where the word quantum comes from) — and these units actually turn out to be particles in their own right, called **gauge bosons.**The forces described by a gauge theory are carried, or **mediated**, by these gauge bosons. For example, the electromagnetic force is mediated by the proton. When gravity is written in the form of a gauge theory, the gauge boson for gravity is called the **graviton.**

Spin: Spin is a quantum number indicating an inherent property of a particle that acts kind of like angular momentum. Fundamental particles have an inherent spin, meaning that they interact with other particles like they're spinning even when they aren't.

Physicists have identified some features of the theoretical graviton so that, if it exists, it can be recognized.

1.The particle is **massless**, which means it has no rest mass — the particle is always in motion, and that probably means it travels at the speed of light.
2.It has a **spin of 2**.
3.**No electrical charge**.
4.It's a **stable** particle, which means it would **not decay.**

The possible existence of the graviton in string theory is one of the major motivations for looking toward the theory as a likely solution to the problem of quantum gravity.

Part II

To understand the theory and its implications, you have to first understand certain fundamental concepts, such as how scientific theories develop.
In this part, you see how science progresses, which will be helpful as you encounter the various scientific revolutions that have led to string theory.

Chapter 4

String theory is mathematical theory of nature that,at present,makes few predictions that are testable.This begs the question of what it takes for a theory to be scientific.
This chapter looks a bit closely at the methods scientists use to investigate nature's structure,explore how scientists perform science and some of the ways their work is viewed.The goal of the chapter is to make it clear that scientists have differing views about how the nature of science is supposed to work.

Exploring the Practice of Science

What is Science?

Science is the methodical practice of trying to understand and predict the consequences of natural phenomena. This is done through two distinct but closely related means: theory and experiment.Not all science is created equal.
String theory has spent more than 30 years focusing on the theory side of the scientific equation and, sadly, is lacking on the experimental side, as critics never hesitate to point out. Ideally, the theories developed would eventually be validated by experimental evidence.

The myth of the scientific method

The *scientific method*- take observations, break them down (the reductionism part), and use them to create generalized laws (the inductive logic part). String theory's history certainly doesn't follow this nice classical model.
Frequently the scientific method has been seen as Observing a phenomenon,formulating a hypothesis,testing the hypothesis(performing an experiment),analyzing data(confirm or reject the hypothesis).

In a way, this scientific method is a myth.Turns out there's no single scientific method that all scientists follow,they don't look for such a list of tasks,instead science is a dynamic activity involving continuous and active analysis of the world.

Science is a translation between observations, experimental evidence, and the hypotheses and theoretical frameworks that are built to explain and expand on those observations.
Still, the basic ideas of the scientific method do tend to hold. They aren't so hard and fast rules, but they're guiding principles that can be combined in different ways depending on what's being studied.

The need for experimental falsifiability

Traditionally, the idea has been that an experiment can either confirm or refute a theory. An experimental result yields positive evidence if it supports the theory, while a result that contradicts the hypothesis is negative evidence.

The focus on this falsifiability is traced back to philosopher Karl Popper's 1934 book The Logic of Scientific Discovery. He was opposed to the reductionist and inductive methods that Francis Bacon had popularized three centuries earlier.

Popper reasoned that the principles of physics arose not merely by viewing little chunks of information, but by creating theories that were tested and repeatedly failed to be proved false. Observation alone could not have led to these insights, he claimed, if they'd never been put in positions to be proven false. In the most extreme form, this emphasis on falsifiability states that scientific theories don't tell you anything definite about the world, but are only the best guesses about the future based on past experience.

For example, if I predict that the sun will rise every morning, I can test this by looking out my window every morning for 50 days. If the sun is there every day, I have not proved that the sun will be there on the 51st day. After I actually observe it on the 51st day, I'll know that my prediction worked out again, but I haven't proved anything about the 52nd day, the 53rd, and so on.

"the slaying of a beautiful hypothesis by an ugly fact." --No matter how good a scientific prediction is, if you can run a test that shows that it's false, you have to throw out the idea (or, at least, modify your theory to explain the new data).

Popper's claim--The defining component of a scientific theory, the thing that separates it from mere speculation, is that it makes a falsifiable claim.
Popper's claim is sometimes controversial

String theory founder Leonard Susskind's argument--He believes not in falsification, but rather in confirmation — you can have direct positive evidence for a theory, rather than just a lack of negative evidence against it.(this viewpoint came out of an online debate between Susskind and physicist Lee Smolin.In the debate, Susskind lists several examples of theories that have been denounced as unfalsifiable)

> It may seem as if this debate over confirmation and falsifiability is academic. That's probably true, but some physicists see string theory as a battle over the very meaning of physics. Many string theory critics believe that it's inherently unfalsifiable, while string theorists believe a mechanism to test (and falsify) the prediction of string theory will be found.

The foundation of theory is mathematics

Science requires both experiment and theory to build explanations of what happens in the world. To paraphrase Einstein, science without theory is lame, while science without experiment is blind.

If physics is built on a foundation of experimental observation, then theoretical physics is the blueprint that explains how those observations fit together. The insights of theory have to move beyond the details of specific observations and connect them in new ways. Ideally, these connections lead to other predictions that are testable by experiment. String theory has not yet made this significant leap from theory to experiment.

A large part of the work in theoretical physics is developing mathematical models — frequently including simplifications that aren't necessarily realistic — that can be used to predict the results of future experiments. When physicists "observe" a particle, they're really looking at data that contains a set of numbers that they have interpreted as having certain characteristics. When they look into the heavens, they receive energy readings that fit certain parameters and explanations. To a physicist, these aren't "just" numbers; they're clues to understanding the universe.

Though scientific research can be conducted with these different methods, there is certainly overlap but what all of these approaches have in common is that the scientific results are expressed in the language of science: mathematics.

The rule of simplicity

Take Occam's razor, which is a principle developed in the 14th century by Franciscan friar and logician William of Occam. His "law of parsimony" is basically translated (from Latin) as "entities must not be multiplied beyond necessity." (In other words, keep it simple.) Albert Einstein famously stated a similar rule as "Make everything as simple as possible, but not simpler." Though not a scientific law itself, Occam's razor tends to guide how scientists formulate their theories.

In some ways, string theory seems to violate Occam's razor. For example, in order for string theory to work, it requires the addition of a lot of odd components (extra dimensions, new particles, and other features mentioned in Chapters 10 and 11) that scientists haven't actually observed yet. However, if these components are indeed necessary, then string theory is in accord with Occam's razor.

The role of objectivity in science

Some people believe that science is purely objective. And, of course, science is objective in the sense that the principles of science can be applied in the same way by anyone and get the same results. But the idea that scientists are themselves inherently objective is a nice thought, but it's about as true as the notion of pure objectivity in journalism. The debate over string theory demonstrates that the discussion isn't always purely objective. At its core, the debate is over different opinions about how to view science.

The degree to which a scientist relies on theory versus experiment in guiding his activities is another subjective choice.

Understanding How Scientific Change Is Viewed

Old becomes new again:Science as revolution

The interplay between experiment and theory is never so obvious as in those realms where they fail to match up. At that point, unless the experiment contained a flaw, scientists have no choice but to adapt the existing theory to fit the new evidence. The old theory must transform into a new theory. The philosopher of science Thomas Kuhn spoke of such transformations as scientific revolutions.

Scientists are forced not only to amend their theory, but to construct an entirely new paradigm. It isn't just that some factual details were wrong, but their most basic assumptions were wrong. In a period of scientific revolution, scientists begin to question everything they thought they knew about nature.

Combining forces : Science as unification

Science can be seen as a progressive series of unifications between ideas that were, at one point, seen as separate and distinct.

This process of unification has been astoundingly successful, because nearly everything in nature can be traced back to the Standard Model — except for gravity. String theory, if successful, will be the ultimate unification theory, finally bringing gravity into harmony with the other forces.

What happens when you break it ? Science as symmetry

Symmetry exists when you can take something, transform it in some way, and nothing seems to change about the situation. The principle of symmetry is crucial to the study of physics and has special implications for string theory in particular. When a transformation to the system causes a change in the situation, scientists say that it represents a broken symmetry.

Without broken symmetry, everything would be absolutely uniform everywhere. The very fact that we have a chemistry that allows us to exist is proof that some aspects of symmetry don't hold up in the universe.

Many theoretical physicists believe that a symmetry exists between the four fundamental forces (gravity, electromagnetism, weak nuclear force, strong nuclear force), a symmetry that broke early in the universe's formation and causes the differences we see today. String theory is the primary (if not the only) means of understanding that broken symmetry, if it does (or did) indeed exist.

This broken symmetry may be closely linked to supersymmetry, which is necessary for string theory to become viable. Supersymmetry has been investigated in many areas of theoretical physics, even though there's no direct experimental evidence for it, because it ensures that the theory includes many desirable properties.

Supersymmetry and the unification of forces are at the heart of the string theory story. As you read more about string theory, it's up to you to determine whether the lack of experimental evidence condemns it from the start.

Chapter 6

Do you ever wonder what allows light waves to travel? Though we all know that, waves have to pass through a medium, a substance that actually did the waving. But what about light travelling through the empty space , like a vacuum? Let's find out!

So in the later part of the 19th century, physicists had predicted the 'luminous ether' that must exist everywhere and was a reason for travelling of light in empty space. In other words the empty space was not really empty because it contains ether. The prediction was speed of light depends on whether the ether was along the path or perpendicular to it, just like a speed of the swimmer depends on river flow. That doesn't mean the ether itself was moving ,even if it was completely still ,earth was moving within the ether ,which is effectively the same thing .So based on this ,physicists wanted to conduct an experiment that would test light traveled different speeds in different directions .In 1881,Albert Michelson created a device called an 'interferometer' to do that. It contained partially reflective mirrors at an angle, splitting a single beam of light so it ended up travelling two different paths. No matter how many times he conducted experiment ,he never found difference in speeds. In 1905, Albert Einstein published a paper about special relativity which stated about how to interpret motion between different inertial frames of reference, instead of appealing to the ether as an absolute frame of reference that defines what was going on. So he removed ether completely!

Let's find out, what he did in his special relativity theory. It was based on the two key principles, First one was 'The principle of relativity' and second one was 'The principle of speed of light'. Einstein assumed that the speed of light equals to c no matter how it travels. First thing he does was he unified the space and time. He stated that two observers travelling through the 'space time continuum' (3 space dimensions +1 time dimension) with different speeds will record different observations, but their calculated speed of light would remain same because where time taken were different, distance travelled too. And also gave formulas about these changes. this phenomenon is called time dilation, which can be used to allow time travel .second thing he does was he unified mass and energy .The equation E=mc^2 .We all know that .Later it was related to conservation of mass and energy concept.

The another work of Einstein was general relativity, which is nothing but theory of gravity and just a extension of special relativity to take into account non inertial frames of reference. The effect of matter and space time on each other are what we perceive as gravity. The first principle about gravity was principle of equivalence ,and it stated that an accelerated system is completely equivalent to a system inside a gravitational field. By which we can understand gravity as acceleration,by which he concluded gravity can bend light wave. The other way to describe a gravity was bending of space -time geometry. For that he defined a set of field equations .According to principle of covariance, space time coordinates in gravitational field had to work exactly same way as space time coordinates in accelerating spaceship. Meaning if you are accelerating through empty space, the geometry of space time would appear to curve. So now ,What do you think about the curved motion of planets around sun? Yes! It’s because the sun bends space time around it.

Some of stunning modern examples of applying relativity are GPS, electromagnets etc. But there are some cases where relativity predicts some strange behavior, such as singularities(centre of black holes) where the curvature of space time become infinite. String theory today continues this work by extending concept of relativity to cosmos. But despite the strange implications ,Einstein’s theory of relativity has been around for nearly a century and has met every challenge.

Chapter 7

The first step into the quantum world: Planck, Einstein

So, the beginning of quantum theory is a problem with the prediction of thermodynamics. So, classical theories gave rise to infinite energies while explaining Black body radiation. This steeply varied with the experimental observation, so much that it came to be called the Ultraviolet catastrophe. Planck brilliantly resolved this problem with infinite energy of radiation at ultraviolet frequency by assuming that energy is found in discrete bundles. This was thought to be a clever mathematical construct until Einstein used it for another theory and the same Planck's constant came out under very different circumstances. Another phenomenon which is impossible to explain by classical theories is Photoelectric Effect. The reason is that classical theories believe that energy is proportional to the intensity of the light and independent of the colour. However, in experiments the results told otherwise. High intensity radiation of a certain wavelength couldn't cause the release of electrons whereas low intensity radiation of a lower wavelength could produce the effect. The theory Einstein gave to explain this is that light is made up of tiny bundles of fixed energy called quanta that is proportional to the frequency. And when the kinetic energy of electrons released were plotted against frequency of radiation, the Planck's constant popped up. So, that meant that quantisation wasn't just a clever mathematical construct but a physical reality.

And quantum theory offers a solution to the centuries-old problem: nature of light

The nature of light is a phenomenon which has baffled scientists over centuries. Newton believed it was corpuscular and then it was waves for the next two centuries. Maxwell's equations provide the theoretical background and Young's double slit experiment gave it the experimental validation. However, the photon theory made it particulate in nature again. So, what was light?

Louis de Broglie came up with a bold hypothesis that light could be both particles and waves. This showed that all that we believed to be particles previously have wave nature by symmetry. The solution to this problem came in the form of a quantum wavefunction developed by Schroedinger. The wavefunction, which describes the probability of the particle arriving at a point, can be thought of as passing through both slits and creating the interference pattern which was observed in electrons.

Uncertainty principle and probability in this theory.

Heisenberg's Uncertainty principle is one of the most perplexing ideas. It states that the more certainty you have with respect to measuring a quantity, greater is the uncertainty in measuring an associated quantity. The most common example is position- momentum pair. This is surprising because it is hard to grapple with the concept that some things are inherently unknown; not because of human error or error in technique, they just cannot be known accurately.

Coming back to the matter of probability, the wave function is seen as a representation of the probability of finding a particle in a given region of space. So when a measurement is made, the wavefunction collapses and the particle gets a definite value for the measured quantity. This is the Born Interpretation.

The Copenhagen interpretation.

The core of the Copenhagen Interpretation is that when an observation is made the wave function completely collapses, that it comes from a general state of probabilities to a specific state. Today, most scientists view the particles in the wave function as continuously interacting with the surroundings. These interactions are enough to cause the wavefunctions to undergo a process called decoherence and result in its collapsing to a specific value.

Many worlds interpretation? Maybe.

In this theory, the wavefunction doesn't collapse. Instead all alternatives become realities too, just in an alternate universe. This is something that kept me thinking for a while. That each molecule in the universe could have behaved a different way and this would be happening in an alternate universe. The vast number of combinations of events baffled me and was an unimaginably large number. However, the nature of the universe is unimaginable. So, can't guess either way(*shrugs*).

Hidden variable interpretation: An interesting theory.

This is a theory which believes that the quantum equation hides another level of physical reality and understanding this makes it completely deterministic. The most popular version was given by Bohm in 1952. The core of his argument was that the quantum theory is consistent with particles which have definite position and momentum. He assumed that these particles reproduced the results of the Schroedinger wavefunctions on an average. He was then able to produce a quantum potential wave that could guide the particles this way.

What are the Planck units and why are they what they are?

Physicists occasionally use a system of natural units, called Planck units, which are calculated based on fundamental constants of nature like Planck's constant, the gravitational constant, and the speed of light. These are sometimes considered to be the quantum quantities of space and time. There is a huge difference in order in these quantities and we are yet to discover the reason why, even if we ever can.

Chapter 8

Are there atoms? What lurks within?

It has been accepted since the ancient Greeks (who were wise beyond their times) that matter isn't infinitely divisible and the smallest indivisible part was considered to be atoms. The existence of atoms was repeatedly proved by scientists around the world across centuries. However, this notion of indivisibility had to be abandoned because electrons and nucleus were discovered by the early 20th century. Many theories were proposed by many people and many were disproved. This finally led to a quantum Bohr-Rutherfordian model. This was fine for the simple Hydrogen but didn't work for other complex molecules.

Photon as seen in a quantum theory textbook

Quantum electrodynamics is about redefining electromagnetism with quantum mechanics principles. The result of it was the beginning of quantum field theory. According to this theory two particles communicate electromagnetic information by exchanging virtual photons.

Yin and Yang: Matter and antimatter

Along with the understanding of quantum electrodynamics, there came a growing understanding that there existed antimatter, a different form of matter that was identical to known matter, but with opposite charge. The mathematics of the theory implied a symmetry between the known particles and identical particles with opposite charge, a prediction that eventually proved to be correct. When antimatter comes in contact with ordinary matter, the two types of matter annihilate each other in a burst of energy in the form of a photon.

Virtual Particles: I am there and yet I am not

In quantum electrodynamics, virtual particles can exist briefly, arising from the energy fluctuations of the quantum fields that exist at every point in space. Virtual particles can exist because the uncertainty principle, in essence, allows them to carry a large fluctuation of energy, so long as they exist for only a brief period of time.

Quarks with quirks

Within the nucleus you can find the protons and neutrons. These are not elementary particles. They are further made of different kinds of quarks. This theory is called quantum chromodynamics.

The quarks are held together by other particles called gluons (super-glue yeah!). There are six flavours of quarks- up, down, top, bottom, charm and strange. The quarks have another property called colour. This is similar to an electromagnetic charge but unique. That's what is probably the origin of the chromo is quantum chromodynamics *shrug*. They come in 3 varieties- red, blue and green. However, in reality they can't be coloured. This is just a name to label the charges.

Particles of force and matter

According to quantum mechanics most particles have an innate spin. This isn't the rotating spin; instead it is just a property of the particle. There are particles without any spin also like Higgs Boson (spin is 0). So, this can be used as a criterion to distinguish particles into fermions and bosons. Fermions have non-integer spin number. Examples would be electrons, neutrinos and quarks. They follow Pauli's Exclusion Principle. On the other hand, bosons have integer values for spin and don't follow the Pauli's Exclusion Principle. Examples would be all the force-carrying bosons like the

photons, gluons and the Higgs Boson. There are 5 fundamental kinds of bosons and 12 kinds of fermions.

The Higgs mechanism: pulling its weight to explain the ways of the world

In the Standard Model of particle physics, particles get their mass through something called the Higgs mechanism. The Higgs mechanism is based on the existence of a Higgs field, which permeates all of space. The Higgs field creates a type of particle called a Higgs boson.

Hierarchy Problem: Why are the scales what they are?

One of the major questions that remains is the hierarchy problem, which seeks an explanation for the diverse values that the Standard Model lets physicists work with. The masses of these 18 fundamental particles aren't predicted by the Standard Model. Physicists had to find these by experiment and plug them into the equations to get everything to work out right. So this is something we need to understand from the underlying theories. Just like the theory of atoms and electrons helped us understand the properties of elements in the periodic table, we need a theory to explain the properties of the 18 fundamental particles.

THE HISTORY OF OUR EXPANDING UNIVERSE

BY: -ARYA BHATTA
B.Tech.(EE)

Our universe began around 13-14 billion years ago. Our understanding of the universe has undergone tremendous changes and progressed in the past few centuries due to work of Ptolemy, Copernicus, Kepler and finally with Newton with his Theory of Gravitation. For all these years the concept of an unchanging universe was generally accepted and believed. Even when Einstein's General Theory of Relativity predicted a dynamic universe in 1917, he introduced the cosmological constant into his field equations to make our universe static and eternal. To fully understand the expansion of our universe, we have to go back to the starting of our universe.

The big bang theory proposed in 1927 by Lemaitre is the idea of how our universe expanded from a single point of high energy and pressure is the generally accepted cosmological model (even though it faced some competition from steady-state model). According to Alan Guth, the bang in the big bang refers to inflation. Inflation is a theory that explains the exponential expansion in the early universe using gravitational repulsion. Even after inflation, our universe kept on expanding due to the inertia. Gravitational repulsion was first seen in the general theory of relativity but was ignored by Einstein (he considers this his biggest blunder!), but subsequent work done by de Sitter, Friedmann, Lemaitre showed that an isotropic and homogeneous universe should expand. Finally, in 1927 when Hubble discovered that the light from distant galaxies gets red-shifted, it proved that our universe is expanding. Thus, it was assumed that the cosmological constant is zero as there was no need for antigravity (because they thought that the universe is expanding with a uniform rate). For the next few years work done by physicists like George Gamow and Fred Hoyle led to the development of stellar nucleosynthesis. Gamow proposed that hydrogen and helium were created due to the heat of the big bang, and Hoyle showed that other heavier elements may have been made in stars and supernovas, which subsequently drifted and formed planets. Gamow and his students also predicted that the dense ball of matter and energy during the big bang should emit some sort of black body radiation in the microwave region. In 1965, this cosmic microwave background radiation (CMBR) was accidentally discovered. This CMBR obtained by the WMAP satellite obtains the radiation when the universe was only 380,000 years old(before it there was no radiation).The CMBR data shows that the temperature(and thus wavelength) of different parts of the universe, millions of light years away(and thus not communicable) to be same. This is called the horizon problem and the inflation theory provides a solution for this. It proposes that the visible universe would have been very close to each other before the inflation and could account for the same temperature.

In any uniform universe, three types of space-time geometry are possible i.e. flat, open, closed. Different models and inflation theory predict that our universe is flat. Even though previously the observed data didn't match with this prediction, since the discovery of dark energy we are observing the desired critical mass density. It was discovered in 1998 that the expansion rate of our universe is accelerating. To account this, we use dark energy. One form of dark energy is in the form of positive cosmological constant or negative pressure. In Einstein's gravitation, due to relativistic invariance, pressure and energy density are interchangeable. This negative pressure is like a property of empty space (like vacuum energy) which acts like a repulsive gravity and is constant throughout the universe. For more on this topic, click here. Even though around 73 percent of the present universe is made of dark energy, it was in vanishingly small amounts some few billion years ago and it is one of the mysteries that modern cosmology tries to solve. One of the other mysteries is dark matter. It was discovered to account for the extra mass needed by the spiral galaxies to not fly apart. This dark matter has to be many times more than the baryonic matter to keep the galaxies together. Scientists are still not sure what this dark matter consists of.

THE BLACKHOLE INFORMATION PARADOX

Einstein's General Theory of Relativity allows solutions in which spacetime curves so much that even a beam of light gets trapped. These are black holes. A point of infinite curvature and gravity is called a space-time singularity. Anything going near it gets ripped apart. But near the edge of the blackhole is the event horizon, a barrier after which even light can't come out of it. Even though it is generally believed that everything gets sucked into the blackhole, Hawking showed that they emit energy in the form of Hawking radiation. Due to this it loses mass and heats up. Hawking proposed that eventually the black hole evaporates giving bursts of energy. This leads to the blackhole information paradox as information about the matter that went into the blackhole is seems lost, but quantum mechanics is all against it.

Even though a range of solutions to this paradox are suggested such as the holographic principle, the idea that information may seep out of the blackhole due to field fluctuations or may pass into a parallel universe, no one knows for sure. This still remains one of the most intriguing fields of modern cosmology which most of the quantum gravity theories today hope to unravel.

Making Space for Extra Dimensions

A compilation of some important points

by Asish Kumar Mandoi

In this chapter, we get to explore and understand the meaning of these extra dimensions. The concept of dimensions is introduced in a very general way, we see different approaches mathematicians have used to study 2- and 3-dimensional space. Then the idea of time as the fourth dimension is tackled. We analyse the ways in which the extra dimensions may manifest in string theory and whether the extra dimensions are really necessary.

For consistency bosonic string theory required 25 space dimensions, superstring theory required 9, M-theory seems to require 10, and the later F-theory includes 12 total dimensions. (More in chapter 11 and 12) Under some theories, some of these extra dimensions may actually be long enough to interact with our own universe in a way that could be observed.

What are Dimensions?

Each dimension represents a degree of freedom within the space. When scientists talk about the number of dimensions in string theory, they mean the degrees of freedom required for these theories to work without going haywire.

Books (on Fiction) of many dimensions

Flatland: A Romance of Many Dimensions (1884) by Edwin A. Abbott, *Alice's Adventures in Wonderland* (1865) and *Through the Looking Glass* (1872) by Lewis Carroll, *The Time Machine* (1895) by H. G. Wells, and more...

Geometry to describe dimensions

Cartesian geometry = Algebra + Euclidean geometry.

Around the same time that Galileo was revolutionizing the heavens, Descartes was revolutionizing mathematics. In algebra, the degrees of freedom are represented by variables, meaning that an equation that can be shown on a 2-dimensional surface has two variable quantities similarly in 3-dimensional space, every vector is defined by three quantities. Vectors can, of course, exist in one, two, or more than three dimensions, and even zero dimensions. One early field of mathematics that focuses on the study of vectors is called linear algebra, which allows you to analyze vectors and things called vector spaces of any dimensionality.

One of the major steps of working with vector spaces is to find the basis for the vector space, a way of defining how many vectors you need to define any point in the entire vector space. For example, a 5-dimensional space has a basis of five vectors. One way to look at superstring theory is to realize that the directions a string can move can only be described with a basis of ten distinct vectors, so the theory describes a 10-dimensional vector space.

Mobius strip, Klien bottle (No beginning or end, no up or down, no inside or outside) are some obtained by “twisting their dimensions into higher dimensions”.

One version of non-Euclidean geometry is Riemannian geometry, but there are others, such as projective geometry.

One of the greatest mathematicians of the 1800s was Carl Friedrich Gauss, who turned his attention to ideas about non-Euclidean geometry. Gauss passed the majority of the work off to his former student, Bernhard Riemann. Riemann worked out how to perform geometry on a curved surface — a field of mathematics called Riemannian geometry. One consequence — that the angles of a triangle do not add up to 180 degrees.

Parallel railroad tracks appear to meet at the horizon, though they never meet in reality. On a 2-dimensional surface (a photograph or a drawing), the basis for the railroad tracks is a triangle that does, in fact, have a corner at the horizon line. This is precisely the basis of the mathematical field of non-Euclidean geometry called projective geometry, where you take one 2-dimensional space and project it in a precise mathematical way onto a second surface. There is an exact 1-to-1 correspondence between the two spaces, even though they look completely different. The two images represent different mathematical ways of looking at the same physical space — one of them an infinite space and one a finite space.

When Albert Einstein developed general relativity as a theory about the geometry of space-time, it turned out that Riemannian geometry was exactly what he needed. Hermann Minkowski, not Albert Einstein, realized that relativity could be expressed in a 4-dimensional space-time framework.

The 4D space-time

Even though time is a dimension, it’s fundamentally different from the space dimensions. Mathematically, you can generally exchange “left” for “up” and end up with results that are fairly consistent. If you, however, exchange “left one meter” for “one hour from now,” it doesn’t work out so well. Minkowski divided the dimensions into spacelike dimensions and timelike dimensions. One spacelike dimension can be exchanged for another, but can’t be exchanged with a timelike dimension. (More about Minkowski space in Chapter 16.) The reason for this distinction is that Einstein’s equations are written in such a way that they result in a term defined by the space dimensions squared minus a term defined by the time dimension squared. The space dimensional values can be exchanged without any mathematical problem, but the minus sign means that the time dimension can’t be exchanged with the space dimensions.

The wraparound universe: Some cosmologists propose the idea that our universe wraps around so it has no particular boundary, sort of like the Klein bottle. Distant stars may actually be closer than expected, but the light travels a larger path along the wraparound universe to reach us.

Adding More Dimensions to Make a Theory Work

The reason string theory requires extra dimensions is that trying to eliminate them results in much more complicated mathematical equations. *It's not impossible.*

As mentioned earlier, from the time of Descartes, mathematicians have been able to translate between geometric and physical representations. Mathematicians can tackle their equations in virtually any number of dimensions that they choose, even if they can't visually picture what they're talking about. One of the tools mathematicians use in exploring higher dimensions is analogy.

Whole fields of mathematics — linear algebra, abstract algebra, topology, knot theory, complex analysis, and others — exist with the sole purpose of trying to take abstract concepts, frequently with large numbers of possible variables, degrees of freedom, or dimensions, and make sense of them. These sorts of mathematical tools are at the heart of string theory. *Regardless of the ultimate success or failure of string theory as a physical model of reality, it has motivated mathematics to grow and explore new questions in new ways, and for that alone, it has proved useful.*

The typical approach to string theory's extra dimensions has been to wind them up in a tiny, Planck length–sized shape. This process is called compactification.

Are Extra Dimensions Really Necessary?

Some work has been done to formulate a 4-dimensional string theory where the extra degrees of freedom aren't physical space dimensions; but the results are incredibly complex, and it doesn't seem to have caught on. One early, technically complex (and largely ignored) approach to 4-dimensional string theory is work performed by S. James Gates Jr.

Offering an alternative to multiple dimensions

Nicolas Kemmer proposed that the quantum mechanical properties of charge and spin were different manifestations of the same thing. The resulting mathematics, which analyses the physical properties of these particles, is called an isotopic charge space (originally developed by Werner Heisenberg and Wolfgang Pauli, then used by Kemmer). Gates's approach was to take Kemmer's idea in the opposite direction: If you wanted to get rid of extra dimensions, perhaps you could view them as imaginary and get charges. When Gates applied this concept to the heterotic string, the trading didn't come out even — to give up six space dimensions, he ended up gaining more than 496 right charges! In fact, together with Siegel, Gates was able to find a version of heterotic string theory that matched these 496 right charges. Furthermore, their solution showed that the left charges would correspond to the family number. (*The family number indicates which generation the particle belongs to.*)

This may explain why there are multiple families of particles in the Standard Model of particle physics. Based on these results, a string theory in four dimensions could require extra particle families! In fact, it would require many more particle families than the three that physicists have seen. These extra families (if they exist) could include particles that could make up the unseen dark matter in our universe.

Weighing fewer dimensions against simpler equations

This goes back to the idea that the principle of Occam's razor, which says that a scientist shouldn't make a theory unnecessarily complex. The simplest explanation that fits the facts is the one that physicists tend to gravitate toward. *In this case, Occam's razor cuts both ways!*

In the end, the 4-dimensional interpretations of string theory are a powerful way of understanding how complex string theory can be. One of the most basic aspects of string theory has been the idea that it requires extra space dimensions, but this work shows that string theory doesn't necessarily require even that. If these approaches are right, and the degrees of freedom inherent in the theory don't require extra space dimensions, then the physical principles at the heart of string theory may be completely unexpected.

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