

Physics for the 21st Century

Unit 4: String Theory and Extra Dimensions

Henry Tye and Juan Maldacena

String theory has been touted as the "Theory of Everything," uniting physics at all scales, from the cosmological to the subatomic. While it is the only theory that mathematically works at all levels, currently there is no observable evidence for it.

But string theory is still helping to shed light on some unanswered questions in physics.

Henry Tye, of Cornell University, uses string theory to explain the very beginning of our universe, the inflation that occurred in its first fraction of a second.

Tye is looking for evidence in the form of "cosmic strings," infinitely long and extremely thin objects in our universe. If found, cosmic strings could be the first evidence for string theory.

HENRY TYE: If ever somebody sees cosmic strings, that would be revolutionary.

Juan Maldacena, a string theorist at the Institute for Advanced Study, had been examining another enigma in our universe, black holes.

JUAN MALDACENA: It's one of the strangest predictions of general relativity, the theory that space-time can bend so much that it produces a hole in the middle of space.

While researching black holes, Maldacena uncovered an extremely useful relationship between string theory and the more familiar equations of particle physics. Physicists hope to use his model to answer questions in fields ranging from cosmology to condensed matter physics.

SUBIR SACHDEV: If somebody had told me that string theory had something to do with condensed matter, like superconductors, I would have said that's impossible.

Both theorists are applying the mathematics of string theory to decode some of the unanswered questions of our universe.

Part I: Branes and Cosmic Strings

Henry Tye

Henry is a theoretical physicist at Cornell University.

HENRY TYE: *It's very exciting. You know it's fun. For me a lot of time is thinking what's interesting question to ask? What interesting things I can say? Sometimes we are arguing. Sometimes, we disagree. And then, we try to resolve the disagreement. And, you're resolving disagreement, usually something new comes up.*

Tye is currently grappling with string theory, which some believe to be the answer to one of physics' biggest inconsistencies.

While the equations in Einstein's general relativity work for gravity at large scales, these equations cannot explain gravity in the quantum world, at the scale of atoms and sub-atomic particles.

HT: *We don't know how to merge general relativity or gravity together with quantum mechanics. And, that was the outstanding problem that been plaguing fundamental physics for many years.*

In the early 1980s, physicists believed an answer to this problem could emerge from the newly developing field of string theory. The equations of string theory are compatible with describing gravity in the quantum world.

HT: *Mathematically, the gravity described by string is consistent with quantum mechanics. In fact that's the only theory we know that's consistent with quantum mechanics today.*

String theory proposes that the building blocks of matter are not point-like particles, but instead are vibrating "strings."

HT: *What string theory does is that we say that no, no. All these little particles look like particles because we don't have enough resolution to look closely enough. They are so tiny that you really need an infinitely powerful microscope or fantastically power microscope in order to see that maybe it's not a point. Maybe, it's not a point particle. But, it's a little loop or a little string.*

String theory also proposes extra dimensions. While our universe consists of three spatial dimensions and one of time, string theory has as many as seven extra spatial dimensions.

HT: *So, what happen to the other dimensions? The other*

dimensions are so small that we don't see them. And, we only see the three large dimensions. And, that's why we look like we live in a three-spatial dimensional universe.

Over time, physicists realized that string theory contains more than just strings: it includes multi-dimensional objects, or "branes" for short. Our entire observable universe is made up of a three-dimensional brane, represented here as two dimensions, that moves through a higher-dimensional space.

HT: We realize that string theory contains other objects, branes. That means that things are two dimensional, three-dimensional. They come together in a very neatly arranged package, which actually open new areas in mathematics.

While mathematically, string theory appears capable of unifying Einstein's general relativity and quantum mechanics; this "theory of everything" has made few predictions that can be tested experimentally, and no evidence for string theory has ever been observed.

But Henry Tye is working to change that.

HT: The way to prove string theory actually, turn out the best way is probably cosmology.

Tye is using string theory to describe and explain the beginning of our universe.

In the late 1970s, cosmologists proposed that our universe began with a period of rapid inflation. In its first fraction of a second, our universe expanded by a factor of 10^{30} - that's one with thirty zeroes after it. In this brief blip of time, our universe grew by a greater percentage than it has in the 14 billion years since. Supported by numerous lines of evidence, this period of inflation is now an accepted part of our standard model of cosmology, but how it happened is far from clear.

HT: Now, we know that inflation probably happen. But, how does it happen? What causes it? What lead to inflation? That's still open. And, that question you have to answer only when you have a more fundamental theory. And, the only more fundamental theory we have is string theory.

In 1998, while strolling through the Cornell campus, Henry Tye and fellow physicist Gia Dvali had a breakthrough idea for how they could explain inflation using the tools of string theory.

HT: *Gia Dvali and I walk around Beebe Lake talking about branes, large extra dimensions. And all of a sudden we realized that inflationary universe can be explained by having branes moving towards each other. And that was the eureka moment.*

According to their model, during the period of inflation, two branes were moving towards each other, and as they got closer and closer, the interaction between the branes drove the inflation.

The branes are attracted to each other and collide because one is a brane and one is an anti-brane. These branes would eventually collide.

HT: *And when they collide, they annihilate, ok. And when they annihilate, they release a lot of energy.*

According to Tye's theory, this collision marks the end of inflation. And the vast amount of energy released in the collision gets converted to matter. It is the moment in the Big Bang when all the matter in the universe as we know it is created. And since strings are the fundamental building blocks in string theory, this matter is in the form of strings.

These strings are created in various sizes, some large enough to stretch across our entire universe. These are called cosmic strings.

HT: *Because in string theory, the only thing you can go to at this stage is strings. Some of them are tiny little strings. Brane, anti-brane annihilation, will also produce excited strings, or very excited strings, or very big strings. So, there were a whole spectrum of them. And some of them would be so big that they are larger than horizon size, ok, or universe size. So, those are cosmic strings.*

Although, in 2010, cosmic strings have not yet been observed, they could be the key to providing the first evidence for Tye's Brane Inflation and for string theory.

HT: *If the basic idea is correct, we would expect to see some cosmic strings in our universe even today. And, question is how to detect them?*

Physicists search for cosmic strings in different ways. One way is through the lensing of far away objects.

HT: *Lensing's a way to do it. If a cosmic string tension is big enough, then you can lens a galaxy.*

Gravitational lensing occurs when a dense object, such as a massive star,

bends space-time and causes the path of a light ray from a more distant cosmic object to be deflected around it, producing a distorted image. Therefore, a massive cosmic string would also cause the light of a galaxy to bend around it, resulting in a double image.

In 2004, physicists thought they might have found evidence of a cosmic string through gravitational lensing.

HT: They find something, which is like two galaxies are very close to each other, same color, which mean the same spectroscopy, same luminosity and same distance from us. So, this is very much what you expect if you have a cosmic string between one galaxy and us. And, the light will bend around the cosmic string. And, you can bend left side and right side. And so, one galaxy will look like two galaxies. But, those two galaxies would be identical. So, people think that maybe this is a signature of cosmic string.

To look at these galaxies in finer detail, they turned to the Hubble telescope.

HT: In January 2006, Hubble space telescope look at it very carefully and find that it so happen that there will be two very similar looking galaxies next to each other. Ok, but, they are not a single galaxy due to cosmic strings providing double image. If it's a cosmic string, then what happen these two images would have clearly a line between them, that one is shift a little bit from the other one. And, that line would be a very, very distinctive line. And, that would be a signature of cosmic strings. So, this is example which turned out not to be the case, but it's this kind of detection and continued searching for these kind of events that hopefully one day will show that cosmic strings exist.

Tye is hopeful that he will find cosmic strings, which would provide the first hint of evidence for string theory.

HT: And by measuring these distinctive signatures and showing that their existence and showing that they are really part of a super string theory will be a fantastic triumph of theoretical physics or fundamental physics or physics in general.

While Tye uses string theory to understand the beginning of our universe, Juan Maldacena has uncovered an extremely useful relationship between string theory and the more familiar equations of particle physics. Physicists hope to use his model to answer questions in fields ranging from cosmology to condensed matter physics.

Part II: Maldacena's Duality

Juan Maldacena

Juan Maldacena is a theoretical physicist at the Institute for Advanced Study in Princeton, New Jersey. Growing up, Maldacena was always interested in how things work.

JUAN MALDACENA: I was interested in how the TV works, how the radio works, how technological things work. And then I was interested in reading about the basic laws of physics in the sense of what are the smallest things that govern the behavior of bigger things.

In the 1990s, Maldacena began studying the dynamics of one of the most surprising predictions of general relativity: black holes.

JM: A black hole is an object that forms when you put too much matter in a small region of space so that the gravitational forces become so big that essentially nothing can escape. Not even light can escape, and that's why it's called black. It's one of the strangest predictions of general relativity: space-time can bend so much that it produces a hole in the middle of space.

According to general relativity, once something crosses the surface or horizon of a black hole, it is lost forever. But in the 1970s, physicist Stephen Hawking proposed a radical new idea. He realized that according to quantum mechanics, black holes are actually continuously emitting tiny amounts of matter. This is known as Hawking radiation.

IGOR KLEBANOV: In a classical black hole nothing escapes from it. What Hawking realized, which was an amazing discovery, was that if you actually consider quantum mechanics in the vicinity of the horizon, actually things do get out.

Because a black hole is constantly emitting Hawking radiation, it slowly evaporates over time and will eventually disappear, like water in a teakettle. This has led to another scientific quandary called the black hole information paradox.

JUAN MALDACENA: Since a black hole would form and then emit this radiation and completely disappear because it's losing mass to this radiation and, in the end, you would be left with nothing, you would have a situation where you would form the black hole in many different ways. They always evaporate in the same way and, therefore, you would have different initial states that would lead to

the same final state. And this is not allowed in quantum mechanics.

In quantum mechanics, if you have different initial states, you should get different final states.

But with black holes, although they are formed from different objects, they all end up in the same final state, so there is no information left about how they were created.

This became an important paradox for string theorists to solve. If black holes violate the laws of quantum mechanics, this would be devastating for string theory.

JM: Due to results of Hawking, people had the suspicion that perhaps black holes violate the laws of quantum mechanics and if that were the case that would be dramatic for string theory and so on. That would be a way to disprove string theory.

Many physicists were struggling to solve the black hole information paradox.

And in 1997, Maldacena had a breakthrough when he uncovered a mathematical relationship between two seemingly unrelated theories, one with gravity and one without- that could provide insight into different problems in physics including this paradox.

It is commonly known as the AdS/CFT Correspondence.

SUBIR SACHDEV: Maldacena's remarkable contribution has developed into what is called the AdS/CFT correspondence. That's quite a mouthful but what it ends up doing is relating two theories, which are seemingly unrelated.

This relationship is an example of a duality.

IGOR KLEBANOV: His paper got people tremendously excited. Duality, it's a very familiar notion in theoretical physics. It's basically that the same physical system may have two different descriptions, and usually they're complementary.

AdS/CFT equates a string theory with gravity to a particle theory without gravity. Within a given space-time, represented here as a sphere, the string theory lives on the interior and the particle theory lives on the boundary.

Additionally, the string theory has one dimension more than the particle theory.

EDWARD WITTEN: *Juan Maldacena explains that, what I'll call a conventional theory, a theory of ordinary elementary particles but without gravity, can actually be equivalent to a theory that does include gravity. But there's a trick, which is that one theory is in one dimension and the three with gravity is in one dimension more.*

JUAN MALDACENA: *The duality's a relationship between a particle theory that lives on the boundary and a gravity theory that lives in the interior. So you could have a space-time, which is, let's say, the surface of a sphere or let's say an apple or an orange. Then the surface or the skin of the apple would be the boundary and the rest is the interior. Then, you can either have a theory that lives only on the boundary. That's the particle theory. And an equivalent description would be the gravitational theory living in the interior. There is a lot of mathematical evidence that the duality is true since it relates two theories, you can calculate in two theories, and you find that the results are the same.*

This duality is the first concrete example for a realization of what physicists call the holographic principle, which relates one set of physical laws on the boundary of a region with a set of laws for the interior.

JM: *It's called holographic because the idea is that all the physics that occurs in the interior is encoded on the boundary of some region. In a hologram, an optical hologram you have a three-dimensional image is stored on a two-dimensional photographic plate. So you have the information encoded in these two dimensions but when you look at it you see a three-dimensional image.*

Along with contributions from other physicists, AdS/CFT also led to a resolution for the black hole information paradox.

According to Maldacena's model, a black hole within a certain space-time is mathematically equivalent to a gas of particles on the boundary of that space-time. And while it is very difficult to solve the black hole equations, understanding how the gas of particles behaves is relatively straightforward. Studying these particles on the boundary reveals a clearer description of the black hole and its Hawking radiation. In this description, information about how the black hole was created is not lost.

JM: *The duality helps us understand the fact that black holes respect the laws of quantum mechanics, which was something that was called into question. It says that Hawking radiation is an approximation to the exact answer. So, the exact answer is given*

by this gas of particles on the boundary and it allows you to compute things precisely in a way that information is not lost.

IGOR KLEBANOV: *So I think this convinced a lot of people, including Hawking himself apparently, but it's still a little bit abstract. I think we still have a lot of work to do.*

While the duality has been successful in helping to resolve the black hole information paradox, the duality is based in a hypothetical universe, one not found in nature.

IK: *So, the models we can solve I'm afraid that literally they are not realized in nature but they can be used as kind of schematic models for things that are realized in nature.*

As a model, AdS/CFT has been a useful approach to understanding theories in the real world.

JUAN MALDACENA: *It has been used to analyze or to get some intuition about theories in nature.*

One area where it has been applied is in condensed matter physics. Subir Sachdev is a condensed matter theorist at Harvard University.

SUBIR SACHDEV: *My field of physics is called condensed matter physics and we study the motion of electrons and crystals. So, the challenge in the field is knowing what we know about quantum mechanics, can we predict the quantum state of trillions and trillions of electrons. Given the structure of a crystal and say something about the density of electrons in it, can you tell me is it going to be a metal or an insulator or a superconductor?*

Currently, Sachdev is investigating superconductors. While standard conductors conduct electricity with resistance, superconductors do so with zero resistance at extremely low temperatures.

For Sachdev and his colleagues, the goal is to find materials that superconduct at relatively higher temperatures, allowing for practical applications such as ultra-efficient power grids that could transmit electricity over great distances without energy loss.

SS: *What we'd really like to do is once we have a complete theory is predict, "Ah ha, if you went to the laboratory and you put together this element and that element and this element from the periodic table, you'll get this beautiful superconductor." We are very far from that goal, but that's the ultimate aim.*

Sachdev realized that the complicated mathematics he was using to understand superconductors is closely related to the particle physics without gravity in AdS/CFT. So in order to gain insight into his own work, he began exploring the other side of the duality: string theory that includes gravity.

SS: If someone had told me that string theory has something to do with condensed matter, like superconductors, I would have said that's impossible. In some sense, these fields are about as far as any two fields of physics could be. And then, I learned of Maldacena's correspondence where he and others realized that there was a connection between the type of theories we've been looking at without gravity to theories with gravity and one with higher dimensions.

Maldacena's ideas have helped Sachdev get a better understanding of phase transitions of certain materials - the temperature at which a solid changes to a superconducting state.

SS: So, at that point, there is a phase transition in the quantum nature of the electrons. And what we've realized in the last few years is that these critical points are exactly the type of quantum state that's easily described by Maldacena's duality. And somewhat amazingly, this dual description allows you to get at certain properties of this critical point that you couldn't get at by the traditional methods.

These phase transitions involve strong interactions between particles that are extremely difficult to calculate. But mapping this system without gravity to a system with gravity surprisingly makes things easier.

JUAN MALDACENA: So in physics, it's useful many times to simplify your systems. The nature of the duality is such that when the particles on the boundary are very strongly interacting, the gravity description is relatively simple. So, you can use this duality to be able to solve or to understand how at least certain cases of strongly interacting particles behave.

Along with Sachdev, there are a variety of research groups using the AdS/CFT correspondence to provide insights into unanswered questions in diverse areas of physics.

IGOR KLEBANOV: Somehow this subject has had a lot more spin-offs than I think anyone had the right to anticipate, particularly these rather effective connections with nuclear physics, with other types

of physical systems, condensed matter physics, and cosmology - it goes way beyond I think what I could dream of.

In the past, science has not been able to successfully explain the beginning of our universe or black holes. But both Henry Tye and Juan Maldacena have used string theory and extra dimensions to gain a better understanding of the physics of our universe.