Theory of Everything

Transcript

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How does the world work? What is the nature of reality? What are the ultimate governing principles of the universe? These are the foundational questions of physics that continue to fascinate and challenge us. Humans have come a long way on our quest to understand the world we live in. But the search is still on to find the ultimate answer, the single unified model that incorporates all of our knowledge of physics — a theory of everything.

A theory of everything is the holy grail of physics, the theory of all theories, the universe in a nutshell. But what exactly is a theory of everything? How close are we to developing a single unified theory, and what will happen after we've finally found it? These are challenging questions that help us to probe the nature of physics.

Let's start by thinking about what a theory of everything really is. In short, it's a single theory that describes how the universe works. At least in principle, a theory of everything explains all that there is to know about the fundamental mechanisms of physics. A theory of everything is the gold standard of reductionism — the idea that all of the complexity in the world can be reduced to simple underlying foundations. It might seem paradoxical that everything in the entire universe could be encapsulated by a single theory. Is it really possible to describe the entire universe on the back of an envelope? Well, yes and no. To understand what a theory of everything actually is, we need to explore the idea of emergence.

Emergence is the word we use to describe how complexity emerges from simple rules. This is a very abstract and nuanced concept that's central to the doctrine of reductionism. For example, the game of chess has some very simple rules; the playing pieces only have a few very basic moves. And yet chess is a game of seemingly infinite complexity. There are so many possible strategies and tactics in chess that all emerge from the basic rules of movement governing the game. The rules of chess don't list all of the possible arrangements of pieces on the board; they simply dictate the possible movements of different pieces on the board, and all of the game's complexity is an emergent result.

Similarly, a theory of everything doesn't catalogue the exact position of every single particle in the universe. But it does tell us the rules of the game, so to speak. A theory of everything describes how the universe works in the most fundamental sense. So having a theory of everything won't mean that we know all that there is to know — instead, it's a kind of boiled-down description of the truly essential and universal principles of reality. So how do we go about developing a theory of everything? What are the distinguishing qualities that a theory of everything must have?

Well, above all, a theory of everything has to meet the basic requirements of any theory. After all, if it's not a theory of anything, it certainly can't be a theory of everything. So what does it take to make a theory and how do we know if it's true?

In physics, a theory is a tool that we can use to make predictions. We can test our theories by performing experiments. For example, let's say I want to develop a simple theory of gravity. I notice that things fall when I drop them, and so my theory predicts that if I drop something, it will fall. Now I can perform an experiment to test my theory. I am going to drop an apple. If my theory is true, then the apple should fall. Sure enough, that's exactly what happens!

But that doesn't necessarily mean that my theory is true. After all, maybe apples fall, but bananas don't. Maybe things only fall on Wednesdays. I would have to perform more experiments to be sure. This type of extensive testing often reveals flaws in a theory. For example, if I try dropping a helium balloon, it won't fall as I had predicted; instead it will float away into the sky. That means that although my theory is very useful for certain circumstances, it sometimes makes incorrect predictions.

This process has repeated itself countless times in the history of physics. Many of the greatest discoveries have emerged out of the realization that our observations don't match our predictions. For example, the theory of quantum mechanics was developed in an attempt to explain the surprising results of many experiments including a particularly famous one called the double slit experiment, in which light can be seen to act as both a particle and a wave. In this sense, quantum mechanics was developed as a response to what physicists saw in the real world.

Sometimes, however, theories aren't inspired by physical events. New theories can also be created based off of previous theories. For example, Albert Einstein realized that the theories of electromagnetism and relative motion were in conflict. His theory of special relativity effectively resolved this conflict. Instead of doing laboratory experiments, Einstein did thought experiments, imagining what what it would be like to travel near the speed of light.

After a theory has been formulated, it needs to stand up to rigorous experimental testing before it can be generally accepted. Now, there are a few important caveats to this point. First of all, any experiment that we perform will have some amount of error in it. We can't test our theories with absolute precision. And even if we could perform infinitely accurate experiments, you could still make the argument that we will never be able to prove a theory to be true. It's always possible that a new experiment will prove the theory false, just as the balloon did away with my simple theory of gravity. But, by performing a large number of experiments under different circumstances and conditions, we can become very confident with the accuracy of our theories. Nevertheless, it's certainly a tall order for a theory to be completely accurate, since it only takes a single contradictory experiment to forever prove it incorrect.

And in addition to being accurate, a theory of everything also has to be all-encompassing — it needs to explain every single phenomenon in the universe. My theory of gravity was excellent for predicting what will happen if I drop an object, but it doesn't explain why magnets attract or what atoms are made of; I need to develop separate theories to describe those phenomena. A theory of everything, however, would, by its very definition, explain everything that we observe. Right now, we have a lot of theories that are excellent for predicting the behaviors of certain things, but we don't yet have a single theory that explains everything.

Towards this end, a general theme in the history of physics has been unification. Time and time again, physicists have been able to unify relatively specialized theories into more general ones. For example, Isaac Newton unified the theory of falling bodies and the theory of planetary orbits. He realized that these seemingly different concepts could be modeled with a single theory of gravity. Similarly, James Clerk Maxwell incorporated the electric force and the magnetic force into a unified theory of the electromagnetic force. A theory of everything would effectively unify all of our theories into a single all-encompassing model of the universe.

And when that happens, when the inner workings of the cosmos have been revealed, many physicist desire deeply to discover that underlying our experiences is a simple, elegant theory. Naturally, elegance is a very subjective quality, but searching for elegant explanations has proved to be a very successful strategy for many physicists in the past. It's a curious fact that our universe seems to have an inclination for beauty.

But in the end, it's not our job to project our own visions of beauty onto the universe. The goal of physics is to understand how the universe really works, and to do that, we must have an open mind to surprising possibilities.

It’s also important to remember that a theory of everything won’t reveal the “meaning of life, the universe, and everything,” if such a thing even exists. A theory of everything isn’t a philosophical statement about why we exist or our role in the universe. Nevertheless, it’s certainly a very exciting prospect. We are closer than ever to having a true theory of everything and physicists around the world are working hard to advance our knowledge even further.

So how close are we to having a theory of everything? Well, our current theories are very good, but there’s still a lot of work to do. One theory that is very close to being a theory of everything is the Standard Model of particle physics, which describes the properties and interactions of all of the fundamental particles that make up everything that we see. The Standard Model explains everything from the chemistry of life to the nuclear fusion in the sun’s core to the radioactive decay of uranium. And the predictions of the Standard Model match our observations with astonishing accuracy.

But although it is a very successful theory, the Standard Model still isn’t universal — there are phenomena that the Standard Model just doesn’t cover. Particularly, the Standard Model doesn’t explain gravity. We have an excellent theory of gravity, Albert Einstein’s theory of General Relativity, but we don’t yet have a theory that encompasses both the Standard Model and General Relativity. One reason that these two theories are so incompatible is that they rely on fundamentally different mathematical constructs. The Standard Model is a quantum field theory involving discrete, quantized states and particles of matter and energy; General Relativity, on the other hand, is a theory about the intrinsic curvature of the smooth four-dimensional space-time continuum. Developing a unified theory of quantum gravity will be a significant hurdle to conquer before a theory of everything is finally achieved. Another major conundrum left to be resolved is the nature of the mysterious dark energy and dark matter that appear to make up the vast majority of the universe and aren’t explained by either the Standard Model or General Relativity.

One leading contender for a theory of everything is String Theory. The central idea of String Theory is that the fundamental particles described by the Standard Model are actually tiny vibrating strings. String Theory postulates that the different vibrational patterns of these strings result in the different properties of the particles. String Theory has attracted a great deal of attention because it may be able to finally unify gravity and quantum mechanics. Furthermore, the ideas of String Theory have a certain elegance about them, which is very appealing to its devotees.

However, the mathematics of String Theory have proven very difficult to analyze. It takes some of the most advanced mathematical tools available to explore the theory and it still isn't completely understood. In fact, there are several different versions of String Theory, each making different predictions. Some speculate that all of these different string theories may someday be unified into an all-encompassing theory, called M-Theory, but the road ahead is still very foggy.

And in addition to these mathematical difficulties, String Theory also includes some extra implications that some physicists aren't prepared to accept. Most notably, String Theory requires the existence of extra dimensions. In addition to the three spatial dimensions and one time dimension that we are accustomed to, String Theory predicts that there could be six or more additional dimensions that are curled up in tiny manifolds so that we can't observe them.

Inventing extra invisible dimensions sounds more like science fiction than science and a common criticism of String Theory is that it doesn't really fit the job, kind of like smashing a square peg into a round hole. But then again, the idea that the earth is round seemed unimaginable at first; we need to be open-minded to these strange possibilities.

However, regardless of its idiosyncrasies, String Theory in many ways still fails to meet the basic requirements of any physical theory — it doesn't make any testable predictions. In other words, there isn't any experiment that we can perform to test whether String Theory is actually true. Right now at least, String Theory is an interesting mathematical idea, but it isn't a real theory of physics yet. Nonetheless, the mathematical foundations of String Theory are very powerful. Even if String Theory doesn't turn out to be the ultimate theory of everything, it seems likely that much of the work being done to develop it will be reused for some other purpose.

String Theory also isn't the only contender for a theory of everything. Another theory called loop quantum gravity proposes that space and time are actually composed of a discrete network, in an attempt to make General Relativity more compatible with the ideas of quantum mechanics. It may be that someone with a brilliantly creative insight into the universe will come up with an entirely new explanation. Like a great mystery, we have collected many of the necessary clues. Now it's time to figure out how to put them all together to solve the puzzle.

Once we finally have a theory of everything, will that mean that we are finished with science? Will it mean that we know everything there is to know about how the universe works? The answer is a resounding "no!" Just as knowing the rules of chess doesn't make you a grandmaster, knowing the fundamental laws of our universe won't automatically solve all of the scientific challenges facing humanity. In fact, the precision of a theory of everything would actually be a major hinderance in modeling a complex system. For example, if you want to predict how an airplane will behave if it hits a pocket of turbulent air, it would be impossible to model every single subatomic particle exactly, because the computational power required would be unimaginably enormous. Instead, we need to develop approximate models that are designed to work well for that specific case.

Indeed, a theory of everything will probably look completely unlike anything that we observe in our daily lives. It will be a distant and unusual mathematical construct with seemingly no bearing at all on our experiences. But although it may be difficult to comprehend, a theory of everything is a very important and exciting prospect. Truly understanding the way our world works will be a major accomplishment and will open the door to many new inquiries about the boundaries of physical possibility. Knowing what's really going on under the hood — figuring out the rules to the game of the universe — will mark a turning point in the history of physics and will spark countless new questions to explore.

This is a very exciting time to study physics because we are closer than ever before to finally solving the mystery of the ages, finally finding a universal theory of everything. We are closing in on the ultimate intellectual goal that has eluded humanity since we first walked the planet. And the end will only be the beginning.