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The unification of physics: the quest for a theory of everything

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The holy grail of physics has been to merge each of its fundamental branches into a unified "theory of everything" that would explain the functioning and existence of the universe. The last step toward this goal is to reconcile general relativity with the principles of quantum mechanics, a quest that has thus far eluded physicists. Will physics ever be able to develop an all-encompassing theory, or should we simply acknowledge that science will always have inherent limitations as to what can be known? Should new theories be validated solely on the basis of calculations that can never be empirically tested? Can we ever truly grasp the implications of modern physics when the basic laws of nature do not always operate according to our standard paradigms? These and other questions are discussed in this paper.

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Steve Paulson: Thank you. It is wonderful to be back here. We have a terrific evening ahead of us. The title of our panel is "The Unification of Physics: The Quest for a Theory of Everything," which is shorthand for asking, *Can* physics be unified? Can there really be a theory of everything?—and I don't just mean a movie about Stephen Hawking . . .

Should we even try to construct such an all-encompassing theory, or is this a fool's errand, an exercise in asking science to explain more than it really can? I think you all know we are living in a remarkable moment in the history of physics. So much has been discovered in recent years, from dark energy to the Higgs boson, and so many questions remain. What is dark energy? What is dark matter? Do we live in some sort of a multiverse? How do we reconcile the weirdness of quantum reality with the bigger stuff that we see in our everyday lives? And as physics has become more grounded in theory, is it becoming too removed from the empirical world of scientific experiment and testability?

We have a lot of big questions to consider this evening and we have a terrific panel to help us do it. Let me introduce our speakers.

Katherine Freese is a physicist at the University of Michigan. In September, she also became the director of NORDITA, the Nordic Institute for Theoretical Physics, based in Stockholm. She works on a wide range of topics in theoretical cosmology and astrophysics. Among other things, she specializes in dark matter. And she's the author of the new book, *The Cosmic Cocktail: Three Parts Dark Matter*.

Marcelo Gleiser is a professor of physics and astronomy at Dartmouth College. He's the cofounder of and a regular contributor to NPR's science and culture blog 13.7. He studies cosmic origins and the possibility of life elsewhere in the universe. He's written a number of books, including *A Tear at the Edge of the Universe* and, most recently, *The Island of Knowledge: The Limits of Science and The Search for Meaning*.

Max Tegmark is a physicist at MIT and the scientific director of the Foundational Questions Institute. His scientific interests include measurements of cosmic microwave background and galaxy clustering data and tests of inflation and gravitation theories. In a remarkable feat of symmetry, like the other panelists here, he has also published a new book this year, *Our Mathematical Universe: My Quest for the Ultimate Nature of Reality*.

Welcome to all of you.

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Paulson: Max, let me start with you. When physicists talk about a theory of everything, what do they mean?

Max Tegmark: What physicists generally see as our quest is to try to make sense of this extremely complicated reality that we find ourselves in. I feel that the two most spectacular good ideas that we humans have come up with so far in physics have been to (1) do experiments—in other words, go out and measure a bunch of things; and (2) try to look for mathematical patterns in the numbers, that is, to construct mathematical equations. Originally, these ideas worked well only for a very limited aspect of reality, namely the motions of stuff. Archimedes and Galileo, and others, noticed that everything moved in the same shape when thrown: a parabola. Later people realized the stuff in the sky always moves in the same shape: ellipses, and parabolas, which are just little pieces of ellipses approximately.

If we had Isaac Newton, for example, here on stage he could predict very accurately for you where the moon is going to be in 100 years or where it was 100 years ago, but he still had no idea about most other aspects of physics; such as, why the moon has the color that it does? Why are some things black and some things red? Why are some things hard and some things soft? Answers to such questions seemed to be beyond what you could access with the approach of doing experiments and looking for mathematical equations.

What we've seen since, however, is that science has gradually managed to describe more and more of the world around us with the same very approach. James Clerk Maxwell came up with the Maxwell equations, which could describe everything to do with light. Now we understand colors. Schrodinger came up with the Schrodinger equation, which lets us calculate all properties of atoms and why some things are soft and others are hard, and why some things actually look red. Little by little, this physics approach was able to describe more and more. And the quest for the theory of everything, which is what you're asking me to answer, is simply the quest to complete the job of explaining everything.

Paulson: Why don't we have a theory of everything? What are the main obstacles? Katie, let me turn to you.

Katherine Freese: In the universe, there are four fundamental forces that we know of: electromagnetic, strong nuclear, weak nuclear, and gravitational. We understand them.

We understand how electricity and magnetism work; we understand how electrons and protons are attracted to each other and how magnets stick on refrigerators. We also understand, to some degree, the strong force, which is what holds the nuclei together inside atoms. The other one, the weak force, is responsible for radioactivity and may also be responsible for dark matter. These three forces we understand, even going backwards in the history of the universe, as the universe gets hotter and hotter, these forces unify. There are theories about how they unify and accelerators show this unification, at least for electricity, magnetism, and the weak interactions; and we think we know how to also include the strong interactions, so we have some ideas how to unify everything in our existence. Except for gravity. That's a tough one. We don't know a whole lot more than Newton did: you drop an apple, it falls; but we don't have a fundamental understanding of why. And so trying to unify everything—all four forces—requires something really radically new.

That's where the unification of quantum mechanics and relativity would require some kind of theory of quantum gravity to get everything under one unified framework. That's something Einstein was trying to do.

Paulson: Is this a matter of needing more experiments, more tests, and somehow that'll get us this breakthrough? Or, are we talking about something conceptual, some new big idea that hasn't even been thought about yet . . . ?

Freese: Conceptual. I think we've got people working on string theory, which actually mathematically does unify all the four forces, and yet it's not making predictions for experiment.

Let me back up. We need both: we need something conceptual that we can then go and test. And we don't have that.

Paulson: Marcelo, what's your take on the theory of everything? Should it be the holy grail of physics?

Marcelo Gleiser: Just to rephrase, when physicists talk about the theory of everything, they don't mean they're going to predict what you're going to be doing tomorrow morning, or anything like that. Rather, they mean, in a very reductionist way, to develop a description of the world made of little bits of matter—the elementary particles, supposedly things that cannot be cut down into any smaller pieces, that are the building blocks of reality, so to speak—that interact, as Katie was saying, via four forces (as far as we know now) that ultimately can be understood as manifestations of a single force. In other words, what we see as electricity, magnetism, or the weak and strong interactions or even gravity would, if you put the right reductionist glasses on—which means looking at things at extremely high energies—behave as one single force. That's really the restricted domain, so to speak, of the theory of everything from a physicist's perspective. It's very important that people know that.

I wanted to pick up on something here that Katie mentioned. Electromagnetism, which is a beautiful theory that was developed from work by Maxwell and Faraday, supposedly unifies with the weak force, resulting in the electroweak theory. This unification—it's almost a unification because within that theory you still have components of the two forces; they don't merge into a single thing—however, the expectation is that, when one keeps going to higher energies and further back into the history of the universe, the strong force would eventually join in. I just want to make sure that it's understood that we do not have even a unified theory of these three forces yet.

In fact, in order for the three forces—the electromagnetic, the weak, and the strong—to be unified requires bringing in something called *supersymmetry*, which is yet another component, a wonderful idea that I'm sure we'll talk a lot about here tonight but one which we're still not sure about. So the unification of the three forces only happens if supersymmetry is brought in, as far as we know now.

And then trying to bring in gravity becomes yet another problem . . . .

Paulson: Let me jump in here. You've given the theory of everything from the perspective of the physicists. I'm not a physicist. I'm a journalist and I'm trying to make sense of this. Isn't there an underlying question here which is, Can science and, specifically, can physics really come up with foundation laws that explain the universe, that explain the way everything works? Isn't that really the question that we're grappling with here?

Tegmark: I think that's a wonderful question that we honestly don't know the answer to yet. What's the best way to find an answer? It is to try to answer it, and if we succeed, then yes. We're never going to know if it's impossible unless we actually try. The easiest way to fail at something is to convince oneself that it won't work, and therefore not try.

There is also some difference of opinion in the physics community for how ambitious physics should be. You mentioned something everybody agrees with, that reductionism, looking at the ultimate Lego-like building blocks, is at a minimum central to the theory of everything.

You mentioned a lot of other things we care about that we don't understand today. Like what about consciousness? Why are we having conscious experience right now? Why are these 10^{28} quarks in this "blob" in my skull having a subjective experience? Some physicists feel that that's not the kind of question that physics should ask. My personal view is that's also something we don't understand.

Paulson: Maybe you could if the question was, Can physics ever come up with an answer?

Tegmark: My guess is that it actually can, but there are some people who would disagree. To me, consciousness is a science question. Some people might say the reason that some things are conscious and some aren't is because you need something beyond quarks and electrons—maybe there's some sort of life force or *élan vital* or a soul? Then there are people who think it's just a matter of putting the particles together in a very special and beautifully complex pattern. Until we try to see if we can actually understand it with just particles, we'll never really make progress.

Neuroscientists today are trying very hard to do exactly this kind of thing. If there actually is some sort of thing (force) beyond physics that is having an effect on me by pushing my particles around, then, if you measure my particles accurately enough, you could see this thing (force) and study this "soul field," or whatever it is, just like we looked for the Higgs boson by seeing new forces on the particles. If we find that actually, no, our quarks are moving just like Katie and Marcelo's equations say that they should move, then there is no outside effect pushing them.

I don't think this is beyond what we physicists should at least allow ourselves to think about.

Paulson: Let's get a response here.

Freese: We told you what the physicist's definition of the theory of everything is. It is reductionist, and we want to explain everything in terms of one single force acting on fundamental objects, whether they be particles or strings or membranes.

Max is talking about questions that go beyond the narrow reductionist goal. I'm going to talk about things that are maybe in between the two, namely questions that physicists are actively working on now. Even if you were to have a theory of everything—a unification of forces—that's not enough to explain (. . . or is it?) the evolution of the universe from a very bizarre (to us) initial state to its expanded current state: what kicked that off? Maybe in the search for a theory of the unified force we can find some hints for an answer to that? For example, string theory takes us into extra dimensions. And maybe our universe is a three-dimensional surface sitting inside these dimensions and these could collide, or . . . .who knows? These are very, very interesting ideas.

While such issues are a notch down from understanding consciousness, they are still very interesting, fun problems. As another example, the arrow of time. These are tough issues to understand, but we are actively trying to pursue them.

Paulson: I just want to follow up on something you said. You're saying that even if we come up with a more sophisticated view of these various forces of Nature, that's not going to get us back to the very first moment of the Big Bang? It stops before then?

Freese: This ties into what Marcelo was saying. In accelerators now, we see the unification of electromagnetism and weak interactions, and maybe someday we could build a really, really giant accelerator that would allow us to see the unification of the four forces. And since, in principle, the higher energies required for such a giant accelerator correspond to the higher temperatures of the Big Bang, these questions are definitely related. But I don't know if in answering the unification question we'll answer what happened at, or before, the Big Bang.

Tegmark: We've been getting by quite successfully with a sort of "schizophrenic swindle," as it were, in physics, where for some problems we can just ignore gravity and calculate everything wonderfully with quantum field theory and predict what's going to happen with, for example, the Large Hadron Collider, and it works great. This basically works for everything really small.

Then, for other problems, we can ignore quantum mechanics and do general relativity theory; this works great for black holes and large things in the universe.

But then there are some pesky problems, very few—for example, the origin of the universe is one—that actually need both: general relativity, because things are very heavy because we're talking about a whole universe, and quantum mechanics, because things are very small when we run time backwards and everything is scrunched together. To figure out what really happened requires use of both theories at the same time. To do that we have to—as both Marcelo and Katie said—find a mathematical theory that incorporates all of this consistently.

I, for one, do not think that this is a problem with Nature. I think instead it's a problem with us and our understanding. I think Nature knows exactly what it's doing and how it's supposed to evolve from one day to the next. The reason that our two theories won't talk to each other is because we haven't yet found the correct description.

Gleiser: The problem with constructing a physical theory that describes the origin of the universe is that this is one of the oldest *religious* questions as well. All different religions of the world throughout history have come up with narratives of creation of the universe—the creation myths. There are lots of them. We know of a few that are very popular in the West.

Freese: We have the best one, the Big Bang! . . . [*laughing*]

Gleiser: You don't want to call it a creation myth do you? [*laughing*]. That won't get you a grant . . . !

The point, though, is that there's an issue in philosophy called the problem of the first cause, which is something that, for example, Aristotle was worried about. The first cause, the cause that started all subsequent causes in our case we call "the initial conditions" or the Big Bang.

Aristotle came up with the notion of the *unmoved mover*, which was the thing, entity, that could move without itself moving. It was a deity, some sort of divine force that would impact motion in his cosmos from the outside in.

The problem is that we have been dealing with this issue of first cause forever. Modern cosmology made this question scientific. We now actually have a scientific way of asking this question. Can we come up with a model where we can describe the beginning of the universe? People have done that. There are several different kinds of boundary conditions, meaning the beginning of everything started with some assumption that can trigger the universe out of nothing, and this nothing is extremely qualified. In other words, there's no such thing as nothing in physics.

The point I'm trying to make is that, even if we come up with a theory, a physical theory, that describes the beginning of the universe, that theory will have been built upon a whole conceptual framework—energy, conservation laws, maybe general relativity and quantum physics—and these theories are taken for granted in order for us to begin to be able to talk about the beginning of the universe.

Paulson: Let me just see if I understand. Are you suggesting that this modern scientific effort to explain everything is basically a new version of what religious thinkers used to do? Is this just religion 2.0 in the gods of physics?

Gleiser: I love that. In a certain sense yes, with a very fundamental difference. The impetus to try to understand everything and to explain everything is very human. I think the reason why people buy more books about cosmology than about laser physics is because we want to understand, we want to share this knowledge somehow.

In physics, ultimately, Nature is the judge. You can come up with any crazy idea you want. If it is confirmed by a series of experiments and it is reproducible, then we rubber stamp it and say, "Yes, this is good, as long as it doesn't get broken down later on."

Paulson: Max, do you see a connection between the religious impulse and the scientific impulse?

Tegmark: I completely agree with Marcelo that the basic impetus for asking all of these questions, which led to the creation myths and all these religious stories, was of course the same very curiosity that makes every kid want to think about these things, and that's the scientific spirit.

I think the key difference is what you [Marcelo] said so nicely. The way I would put it as a scientist is, it's better to have questions that you can't answer than to have answers that you can't question.

Freese: That's a good one . . .

Tegmark: We are allowed to question everything. That's very much the point of science. Coming back to your question and the point about the unmoved mover, there have always been questions we couldn't answer in science. There's always been a frontier to our knowledge. Some distance away we didn't know what was farther, then we explored more. We found that we live in a solar system in the galaxy, etc. Similarly, there was a frontier of our knowledge in time. Isaac Newton could figure out, again, as I mentioned, where planets were 100 years ago, but he had no idea what made the planets.

We shouldn't sit here and be smart alecks and lampoon religious people 1000 years ago who thought the best explanation was that someone made the planets, because that was the most plausible explanation available at the time. Today, when we simulate on our computer that when you put a gas cloud and gravity together it makes a planet, we feel we truly understand where planets come from. But then we could ask, where did the gas cloud come from?

Similarly, in cosmology we also simulate carefully in our computers that if you start with everything we see around us in our universe and then squish it together into an extremely dense and hot state, so it's hotter than the core of the sun, it will fly apart so fast that it doubles its size in under a second and then evolve into everything we see around here.

So yes, we've pushed the frontier of our knowledge now back to a second after the Big Bang. And if the theory of inflation turns out to be correct, which we will have to just wait and see, we will have pushed our frontier of knowledge back maybe to the first hundredth of a trillionth of a trillionth of a trillionth of a second after the Big Bang, which is progress, but that's still not the very beginning because, finally, is there an unmoved mover that started it all?

Maybe not. Because we've discovered that a lot of things we thought were fundamental—like the continuum nature of water, that it's actually made out of some fundamental molecules—are in fact made of more fundamental blocks, we're starting to suspect, indeed, that actually it's probably the same with space—maybe even with space and time: that it's actually ultimately not continuous but made out of some quantum building blocks of some sort.

It might very well be, as it is in some of this early wave function stuff that Marcelo mentioned, that if you go really far back, time as we know it time doesn't exist anymore. Instead, there is some sort of quantum fuzz where time doesn't have any meaning. That beautifully gets us off the hook because we can't ask what caused it or what happened before if there was no before.

Paulson: There's also the problem of what the beginning is. You've said our modern creation myth—maybe myth is not the right word—is the Big Bang.

Gleiser: Creation *narrative*. . . .

Paulson: Creation narrative.

Freese: This is a slight shift of subject to the human world view. So 100 years ago, Albert Einstein was writing down the theories of relativity. Yet, on the observational side, scientists thought that every star out there is part of one galaxy, the Milky Way galaxy. So our knowledge of the universe, from an observational point of view, was extremely limited. That was resolved in 1929. Edwin Hubble, the same guy who discovered that the universe is expanding, proved that things are too far away for there to be only the Milky Way: there have to be other galaxies. If we fast forward 100 years, consider the stupendous improvements in our knowledge of cosmology.

The specific advances I'm talking about have nothing to do with religion, but they certainly affect our more general worldview. Hundreds of years ago, the earth was thought to be the center of the universe; it took a long while to accept that the sun was at the center. Likewise, it was thought that there is only one galaxy, and then more than. And then island universes. Or that there are galaxies and galaxies. The amount that we know of now is huge. There's something we call the edge of the observable universe, the horizon, which is as far out as anything can come from that we can see—14 billion light years away, that's the distance beyond which nothing can have reached us in the age of the universe.

Paulson: It's possible that there could be other stuff further away, but we'll never know because we can't see that.

Freese: The point I was going to make is that, while we don't know what dark matter and dark energy are, we pretty much have an understanding of the basic physics all the way out to the edge of the observable universe. Our understanding is remarkable. For me, it's not really about religion, but about the *level* of understanding we have.

Paulson: There's a famous quote from Stephen Weinberg; he said years ago, "The more the universe seems comprehensible, the more it also seems pointless." What do you think?

Tegmark: I strongly disagree with that pessimistic spirit. I think that if we've learned anything by studying the cosmos it's that the universe gives meaning to us. Rather, we give meaning to the universe. Raise your hand if you think galaxies are beautiful [*to the audience*]. Why are they beautiful? They're beautiful because some people with telescopes looked at them and took pictures, and people who are conscious perceive them and behold them. That's what gives them their beauty. If there weren't conscious beings in the universe or telescopes to observe with, galaxies would not be beautiful. They would just be a giant waste of space, as far as I'm concerned.

I think it's completely silly for people to get an inferiority complex just because we weigh less than a galaxy or take up fewer cubic feet than a galaxy. On the contrary, the fact is that our brains are the most remarkably, beautifully complex structure in the universe. That our brains can be conscious and see things as beautiful, that's the whole point. That's where meaning comes from.

Paulson: Marcelo?

Gleiser: I agree 100%, but I think what Weinberg meant is that, the more we understand the universe, the less purpose there seems to be in the universe. There is no grand designer behind the scene. The universe just happens to evolve in different ways, and a bunch of accidents eventually led to our being. I think that's what he meant.

The point, I'm interpreting his words, the point is that there was no point. We're here just because it so happens that, on this little planet, the conditions were such for life to evolve. There was a whole big history about that.

Yet, what *is* really remarkable are the transitions that life had to go through, beginning from the jump from no life to life, from non-living chemistry to living chemistry. How that occurred is a huge mystery, and now is a scientific question that lots of people are trying to figure out. How on earth do you get dead atoms to combine into living molecules? Somehow groups of molecules began to "behave" as a living organism, in the sense that it could feed from the environment and reproduce. This jump from non-living to living is amazing, but then that's just the beginning of the story. Next is the jump to unicellular life; then multicellular organisms. Each one of these jumps in the history of life is tremendously complex and improbable.

Paulson: We as humans, in the grand scheme of things, would seem to be a rather insignificant speck in the cosmos. Does this help in the search for meaning, knowing this?

Gleiser: Absolutely. This is just what Max was talking about. Because the fact that we are molecular machines that have self-awareness is remarkable. We talk about the "Copernicanism" of science, which basically means that, the more we learn about the universe, the less important humans become. The idea in the beginning was that humans are the center of everything, and then the sun became the center; and then from one galaxy there were many galaxies; and then we understood that the universe is expanding; and now we believe humans are not even made of the most important thing [dark matter]. It has been one indignation for humanity after another. [*Audience laughter*]

What is the point of all this? On the one hand, it can seem very depressing. Yet, the important point is precisely the opposite: it is that, because we are molecular machines capable of self-awareness, capable of thinking, we have a very fundamental role in the universe, which is to create meaning. I actually call this *humancentrism.* The idea that we humans are actually, in a metaphorical sense obviously, the "center" of the universe, because as far as we know, even if there are other intelligences out there, they are so far away physically that we are all there is. And because of this, everything that we do has tremendous meaning to our existence. Neil deGrasse Tyson wants to startle people on the streets by telling them they're made of stardust that can think. I agree. That notion is truly remarkable and it's where you begin to find meaning.

Paulson: Katie, what about you? Where do you look for meaning? Or do you even look for meaning in the world of physics?

Freese: I think not only are we remarkable molecular machines, but we *understand* most of what's out there. I think we're better off because of that. Our self-awareness has only grown without understanding of the universe.

But the idea that we are the best thing in the universe is, I think, is hubris. We don't know that. There could be plenty of intelligent species out there.

Tegmark: I think it's interesting to combine the optimism in Marcelo's words with the optimism in Katie's words. Katie pointed out eloquently that it's not just that we discovered that our cosmos is much larger than we thought, that we had simply underestimated the size of our cosmos, that we're part of a solar system in a galaxy in a vast universe, etc., but, importantly, we also didn't appreciate the power of our minds to *understand* our cosmos. That, I think, is an incredibly inspiring idea. If you combine that with what Marcelo said, that we create meaning in our universe, you realize that, contrary to what humanity has believed of itself throughout much of history, life can be even better. And, indeed, there's nothing in the laws of physics that contradicts this. What I mean is, there's absolutely nothing in the laws of physics that says that quarks can't be arranged into even more amazing flourishing societies than on earth, or even beyond.

Paulson: Wait, what are you suggesting here?

Tegmark: I'm suggesting that, as we heard here from Marcelo and from Katie, humanity has come a very long way from no life to more and more complex life. Yet, humanity [likely] has billions of years left to make things even better. **I**t's quite possible in the future that life will flourish even more than it does now here on earth, and maybe even in much of our observable universe.

I think it's extremely significant what humanity does now, today. In fact, I feel we've reached a fork in the road. We now have technologies that are so powerful that we can wipe ourselves out with them. Yet, we also have technologies that can make things much better. All this knowledge, which Katie talked about, helps us not only understand but it helps us, in principle, to make things better. We're at a sort of this fork in the road where if we get our act together and don't do stupid things, we can create even more meaning. I think that's a very inspiring challenge to rise to.

Paulson: Marcelo, you were going to jump in?

Gleiser: Yeah, I was just going to stress this realization of our uniqueness in the grand scheme of things and how rare our planet is. Right now we're looking for other earths out there. Maybe we're going to find something. The point is that, for now, we are here and we're stuck here. What we have found is that this planet is truly unique in many, many ways. It's not just that it has water and it's warm. It's about its magnetic field, it's about plate tectonics, it's about the mass of the moon. All these different factors contribute to making earth a beautiful place for life, not just to exist, but to exist for a very long time so that it has had time to evolve into more complex forms.

Freese: I was just reading about—and I'm not an expert on Mars—but I understand that they're now saying from the latest probes and Curiosity that there may have been water on Mars for billions of years, with comets bringing organic molecules. So past life was possible, and nobody knows why it got wiped out. But Mars may have even had intelligent life . . . ?

Gleiser: Nobody has said that . . .

Tegmark: I agree with your point Marcelo, that even if there are other intelligent life forms out there who are more advanced than us, it's very likely they're very far away from earth.

Having said that, we should not take for granted, just because we saw it on Star Trek, that there are other civilizations that are out there who could keep meaning going in our universe if we mess up our home here on earth. It might take away from what Marcelo was saying, but I think we're saying the same thing here. All of us should be very grateful for the amazing planet we have here and should be very, very good stewards of it.

To be candid, however, I believe we're doing a terrible job.

Freese: I *am* disagreeing. I am saying that I think that it's very likely that even in our own galaxy at least half the stars have a solar system around them. Some of those are looking pretty good for life as we know it. Not something Star Treky . . . . I think even in our own galaxy that it's likely that there is life as intelligent as we are.

Paulson: I'm going to do a little quiz here. Katie, you think there's intelligent life elsewhere. What about the two of you?

Gleiser: It's a completely unanswerable question.

Paulson: What's your hunch?

Gleiser: So let's be very precise here. The fact that there *could* be life elsewhere . . .

Freese: Carbon based . . . .

Gleiser: Carbon based . . . like things that we are used to . . . it is highly probable that there is some sort of microbial life elsewhere, just because of the sheer number of other earth-like planets. I'm being very earth-centric, in a sense. But intelligent life is a completely different ball game because of all the little hoops that life has to go through to go from amoeba-based to more advanced life. Just to give an important example, the dinosaurs were here for 150 million years and they were pretty stupid. They didn't build radio telescopes, but they were happy. But an asteroid came 65 million years ago, hit the Yucatan peninsula in Mexico, and wiped out all the cold-blooded reptiles.

The point is that evolution does not necessarily lead to intelligence. Evolution is about adaption, is about being okay in your environment. It's not as if life begins somewhere and with enough time out pops an intelligent creature . . .

Freese: I don't know, I think the smart ones win . . . . We are speculating here, actually . . .

Gleiser: No, no, I'm not actually. This is evolution theory. It's natural selection. All you need to survive is to have a hierarchy where whoever is better adapted survives until there is a major cataclysm, and then the whole soup gets mixed up again, so to speak. This is punctuated equilibrium; a cataclysm occurs, things change, they stabilize, there's another cataclysm, etc. It's not necessary that life leads to intelligence. That's a very important point.

Paulson: Max, what's your best guess?

Tegmark: My best guess—I might be the most extreme on the opposite side of Katie, which is perfect, as I'm sitting on the opposite side of her . . . My guess is that the nearest planet where there's something as advanced as the New York Academy of Science's evening discussion going on is so far away that it's even outside of our observable universe. So it doesn't matter for us. That's my guess.

The reason I'm guessing that is because—I agree with all the things you said Marcelo—there's absolutely nothing automatic about intelligent life. We shouldn't laugh at the dinosaurs for being losers, for going extinct, by the way; we haven't been around for 150 million years. We've been around for 150,000 years tops. Moreover, there's the famous Fermi paradox that says if it's so inevitable that you get life and it's pretty easy to invent space ships, etc., we should have been contacted already by intelligent life; but we haven't been. And since no one has yet been here, the nearest intelligent neighbor is probably pretty far away.

Guess what, Fermi's paradox has gotten worse in the last five years, as we've discovered that there are actually billions of planets in our galaxy even that are pretty earth-like, as you mentioned. Many of them are two billion years older than our planet. And so if it's so automatic that intelligent life develops, then that means there would be a lot of civilizations relatively nearby in our galaxy that have had two billion years of R&D to get here, and yet they haven't.

My guess is that actually the nearest intelligent neighbors are probably outside of our observable universe. If we want there to be meaning in the part of space that we know exists, it's up to us.

Paulson: We've been talking about mysteries, the big mysteries in physics, the big mysteries in science. I'm curious: if each of you could pick the biggest mystery, the thing that you're most curious about, that you'd most like to get an answer to, what would it be? Marcelo?

Gleiser: To me, the biggest mystery is the origin of time, how things got started. Honestly, I don't even know if we can provide a fully scientific answer to that question simply because of the way science works. Science operates within a conceptual framework, and any answer that we give to this question uses that framework.

The question then becomes, Where did this framework for science come from, and how is science even going to deal with that? We're really stuck with that sort of paradox. That to me is the hardest question you can ask.

Paulson: Katie, what about you?

Freese: There are many, but the one that has occupied me is, What is the universe made of? Take everything in this room, your body, the air, the walls, and then add the planets, stars, and everything that we know about in our experience—which is all made of atoms—all of this adds up to only 5% of the content of the universe. I want to know about the other 95%, the dark matter and dark energy that make up the rest, the bulk of the universe.

Paulson: I've been reading your book. You think we might have an answer relatively soon to dark matter, at least?

Freese: Yeah. So, 25% of this cosmic cocktail is dark matter, and that's what makes up, for example, most of our galaxy. The Milky Way has a flattened central region, it's shaped like a pinwheel, and you go out along one of the arms you get to our sun. The arms are where all the stars are.

In addition, there's a giant spherical object that we call a *halo*, which is made of dark matter. We think dark matter is made of some new kind of fundamental particle. We think it might have the weak interactions that I was talking about before. Among other things, this means that it's possible to build detectors underground and then wait for them to be hit by dark matter particles. People are doing this right now, and there are a number of experiments that are seeing something, though they're currently in disagreement with one another. We have to wait and see, but this is a problem that's well defined, soluble, and there's a good chance we'll have this one in the next decade.

Paulson: Max, what's your biggest mystery?

Tegmark: I first of all agree with you that there are a lot of good ones here to pick from. You both picked good ones that I'm very excited about. Let me pick a third one I'm fascinated by, which is the physics of consciousness. This is something that philosophers have pondered for thousands of years. It seemed for thousands of years like a pretty hopeless problem, that you can speculate about it over some alcoholic beverage and then go home because there's nothing you can do about it.

The reason people kept thinking it was hopeless was because you have privileged access to your own conscious experience. You know you are aware of these things subjectively and that you're experiencing these colors and sounds, but for most of human history nobody else could know what you were thinking about.

That's changing now. We have this revolution in neuroimaging technology where you can put yourself in an fMRI machine or use magnetoencephalography. By just looking at that data and plugging it into a computer, you can figure out in real time a lot of things about what they're actually thinking and experiencing. You can show them pictures and then the computer can say, "Ah, that was Halle Berry you're thinking about." You say, "Yes, how did you know that?" What's so cool about that is it takes this old metaphysical thing which seemed hopeless, much like cosmology.

What I think is so exciting about this is—Katie was excited about dark matter because there is a potential to actually do something concrete about it—I'm excited about this for the same reason, because if you put yourself in a scanner, which is observing from the outside all the information processing that the "computer" in your head is doing, then you can, at the same time, observe subjectively from inside what of the information you are processing you are conscious of; you can compare the two.

Paulson: But the problem is that doesn't explain causation. Yes, you could match the brain imaging and the thoughts, but it doesn't explain *why* those thoughts pop into our mind.

Tegmark: Let me get to that. In physics, first of all, we're not mainly focused on the why question. We're very interested in how. If you want to know what is a fire, it's just some arrangement of atoms. You try this arrangement, that's not fire, this one is. Then you look for patterns and you say, "Oh, whenever these equations are obeyed, that's what we call a fire." You see a pattern.

We can start to do something similar here. David Chalmer, who's moving to New York now, articulated your question famously as the hard problem of consciousness. He said "Why is it that you put a quark blob together and there's a subjective experience in it sometimes, but not other times?"

From a physics perspective, and from my perspective, you can transform that instead by saying that you start not with a hard question, but with a hard fact: that some quark blobs are conscious, like each of us, and some are not, like the food we eat.

Then you can say, "Okay, what is different about those patterns?" What I was getting at with all the neuroimaging is that you can start to look. Okay, of all the information you can measure from outside that's flying around in your head, which of that information is the part that you're conscious of, and which of that are you not conscious of, such as what's controlling your heartbeat and a gazillion other things?

Then you can start looking at what it is that's so special about the conscious part. What equations does it obey? Is there some simple idea? Is there some pattern here? Is there some principle? My gut tells me that there is some principle there to be discovered. My guess is that conscious subjective experience is the way information *feels* when it's being processed in certain complex ways. I think we now are on the verge of being able to scientifically ask, What are those complex ways? That's a question I'm very excited about.

Paulson: Marcelo, I have to turn to you because I know you have also written about science and consciousness. Do you agree? Do you think physics will crack the consciousness problem at some point?

Gleiser: I don't, but I admire Max's optimism. [*Audience laughter*]. That's the spirit!

Tegmark: Just to add to that, it's the same with the hunt for dark matter and understanding the origin of our cosmos. You don't have to be 100% sure you're going to succeed to really want to try. We all agree that the best recipe for failure in any endeavor in life is to convince oneself that something is impossible and therefore not to try. We just have to feel we have a good shot at it and then try our best.

Paulson: Aren't we really asking *how much* can science explain our world, the universe that we live in? The other possibility that might be put forward is that, while science can take us pretty far, there will always be some things about our world that science just will never be able to explain.

Freese: That's good, that's what keeps us employed. [*Audience laughter*]

Tegmark: I don't think we're going to run out of mysteries anytime soon. I wouldn't worry about our paychecks . . .

But look in history. There have been so many times when a famous physicist stood up and said, "Physics is basically over; there are things we can never figure out." I'll just mention one example; the famous physicist Ernest Rutherford, one of the greatest atomic physicists ever, said in the 1930s that nuclear energy was never going to work. That was only about a decade before there were nuclear weapons, nuclear reactors, and so on.

Whenever someone says, "This is impossible," I say, "I see an opportunity."

Paulson: Marcelo, you have written exactly on this question.

Gleiser: I think, again, I admire Max's optimism. The point being the following—I think it's totally true that we should pursue very hard questions. But we also have to be aware of El Dorado, the fabled city of gold. There is a difference between pursuing El Dorado because you believe El Dorado exists and simply learning along the way of trying to find it.

I think that's a very important distinction because we have to go back to how we humans make sense of reality. We make sense of reality by measuring it. The way we measure things is always limited by the technologies that we have at our disposal. We can only see so far. We can only see so small because of our telescopes and our particle accelerators, which are basically glorified microscopes. What we have seen over the last three or four centuries has changed dramatically because of the evolution in technology, in instrumentation. That's always going to be true. I think technology is going to keep evolving. We're going to keep seeing more and more.

However, we can never see everything there is to see because of the myopic nature of *how* we acquire knowledge of reality.

That's not necessarily a bad thing. I think we will keep on seeing, but to have the hope that we will be able to encompass all of reality through our knowledge is, I think, against the whole way in which we do physics and the way we acquire knowledge with tools and our intuitions, of course.

For example, just to go back to your main theme, a unified theory of everything. When people talk about the four forces of nature and solving a theory of everything, I think we have to be very careful because it is very possible that 20, 50, or 100 years from now maybe physicists will say there's yet another force. There'll be a completely different effect . . . .

Freese: In the subject of dark energy, people are playing around with the potential for a fifth force . . . .

Gleiser: There you go. You have to be careful. Any theory of everything now is a theory given what we know now, not a final theory. The idea of final absolute truth in the pursuit of knowledge in Nature is, to me, a fallacy. In fact, it's called the Ionian fallacy because of the first pre-Socratic philosophers, the Ionians, who wanted to understand the ultimate substance that the universe is made of. That was the first philosophical question ever, by Thales, 650 years BCE: he wanted to know what the world is made of. And his theory of everything was that the world is ultimately made of water.

Tegmark: Actually, it's interesting. All three of us picked our answer to the question about a great mystery to solve using exactly the same method, if you think about it. We asked, What is it we still don't understand? We looked at the list of all the cool big things and then whittled it down by each picking one of those things for which there was a revolution and new data on the horizon.

Marcelo picked the origin of our universe because we're getting all this spectacular data in particle physics, in cosmology with the Planck satellite, etc. Katie picked the make-up of the universe because there's a revolution and new data for looking for dark matter in various ways. I picked consciousness because there's a revolution of data coming in neuroscience.

Freese: I wanted to say something about the experience of being a scientist. We really get to have fun. We're at the forefront of technology. That means we get to make stuff up; we invent stuff. Then we hope—at least from the point of view of a theorist—we hope that those experiments are going to come along very soon and we hope that Nature matches up with our ideas. The odds are long that what we're doing will succeed; it may be well motivated, we may be doing the math correctly, we're doing nothing wrong, but Nature just doesn't work that way, in which case any of us could spend most of his/her life on science fiction.

Predicting what will come in the future is awfully difficult . . . . When new data come in and all of a sudden the paradigm changes, you've got to ask different questions, head in a different direction.

Paulson: We need to bring our audience into this discussion. I'm willing to bet there might be some questions or comments in response to all of this.

Audience question: Why isn't there much discussion about the connection between theories of quantum mechanics and actuality?

Gleiser: I think you're conflating the *use* of quantum mechanics and the *interpretation* of quantum mechanics. You can spend your whole professional life as a physicist using quantum mechanics all the time with tremendous success, and we have all our digital gadgets to prove it, without having a clue what it really means.

That is indeed the very big challenge, the interpretation of quantum mechanics, but all the theories that we use to describe the fundamental forces of nature, which are called quantum field theories, are very, very functional. They talk about the probabilities they are referring to, but in a very concrete way, and we don't really worry so much about the interpretation of quantum mechanics. But yes, understanding quantum mechanics, even what *nonlocality* means in physics, is still pretty much an open question.

Tegmark: I just wanted to add to that that there certainly are a lot of people who have thought a lot about the questions you asked, because it's not the case that it's something being ignored. There's a wide spectrum of views and interpretations of quantum mechanics. I talked a lot about them, for example, in my book. There are some different versions of this that even make different predictions for where, for example, quantum computers in the future will work. This is a particularly exciting field that even connects to some things we can test.

Freese: I guess the one thing I would disagree with is the statement that we're not experimentally testing quantum mechanics. Transistors are based on quantum mechanics. I guess that gets back to what you're saying: there are fundamental, very difficult questions that people *do* work on. But we're [*the panelists*] just not those people.

Audience question: It doesn't seem like a theory of everything can be approached through reductionism. Don't we need to consider emergence?

Tegmark: I'm glad you brought this up. There's a lot of wonderfully elegant work you're referring to. I don't see reductionism and emergent phenomena as in any way being incompatible with one another. Often, we discover the emergent phenomena first, before we have a clue what they're emerging from. For example, we discovered the Navier–Stokes equation that describes the motion of water molecules before we knew that there were quarks. Later on, when we understood quantum field theory, we could derive from a solution corresponding to water, and see that it's going to obey the Navier–Stokes equation. We have this beautiful emergence. Then, later on, we can forget about the quarks in good conscience when we study water because we know that we don't need to worry about what these water waves are made of to study the wave behavior.

Same thing with Boltzmann's work. Now you can derive all of the statistical mechanics from quantum statistical mechanics and ground it in quantum field theory. That's not the way it happened historically, but in the end we see that it all hangs together beautifully, that everything is resting very solidly on these reductionist principles. But in our everyday life, it's very convenient to just look at the emergent phenomena and the rules they follow.

When you speak with one of your friends and you think they look a little bit sad and you wonder what might have happened, you don't need to go back to thinking about what their quarks were doing yesterday. You think of higher-level phenomena, and that's quite fine.

Audience question: Given the cost of research equipment, like the Large Hadron Collider, will there be a point at which doing science will become too expensive?

Gleiser: Depends where you want to go. A B2 bomber costs about two billion dollars. How many B2 bombers do you need to guarantee the safety of a country?

Tegmark: The U.S. ordered 46 . . .

Gleiser: There you go; that's a lot of particle accelerators right there . . .

I think that, yes, science does become more expensive, just because the technology becomes more complex and bigger. But that does not mean that we should stop asking questions because, for sure, if we stop asking these questions, we'll stagnate as a species and we won't be able to build a B3 bomber.

Tegmark: Just to add to that, we also have to remember that there is a lot of science you can do without building CERN or very expensive facilities. For example, there was a recent Nobel Prize for the discovery of graphene, a single layer of carbon. When Andre Geim and Kostya Novoselov discovered this, they had very, very expensive lab equipment: a lead pencil and scotch tape. That's it.

Freese: Just to make another point. Take CERN; what is the biggest societal impact of that? Was that worth it? A computer scientist named Tim Berners-Lee was a product of CERN and he did something absolutely brilliant: he created the World Wide Web in 1989. So, was CERN worth it? Has it changed your life? Yes! I challenge you to go through a day without the web . . . .

Paulson: There's another question that comes out of this: Are we at the point in science, especially in physics, where we need all of this technology? Despite the example you just gave. For the big conceptual breakthroughs, have we left the era where an Einstein—the solitary genius—could totally revolutionize our thinking, just within one man's head?

Gleiser: I don't think so . . .

Freese: Yes, we need them . . .

Gleiser: You can still have theorists, lone wolves who come up with great ideas, but then you have to test them . . .

Freese: Dark energy might need a solitary genius. The theory of everything might need someone of this caliber . . .

Gleiser: It's different. The difference being that, when Einstein came up with his theory 100 years ago, the tests for the theory, at least the bending of starlight, required only a few astronomers and some telescopes; it didn't take billions of dollars to test. Today, if you come up with some revolutionary theory in fundamental science, meaning very high-energy physics or something like that, it will probably take big equipment or some very precise underground detectors to test. That seems inevitable to me.

Freese: They're actually cheap, Marcelo. The entire U.S. budget for dark matter experiments, until recently, was two million dollars a year.

Gleiser: So some fundamental research is not expensive, I agree.

Tegmark: The entire American budget from the National Science Foundation for all of physics—and throw in math, too, for good measure—is four stealth bombers per year. I think the most important piece of lab equipment we need to invest in is our *children*, because I agree there's plenty of room for brilliant minds to make a huge difference.

Freese: Especially our daughters! [*audience and panelists clapping*]

Tegmark: It's wonderful that the New York Academy of Science is doing its share to get people fired up about science, to get our kids fired up about science. We live in a country right now where 46% of the population, in a recent poll, thinks that Earth is less than 10,000 years old. That is not the kind of thing our daughters need to hear, especially not from their schoolteachers, when we want to inspire them to go and do science. We live also in a society where it's very fashionable, whenever a scientist says something that some powerful person doesn't want to hear, for them to just dismiss the science and say the scientist is a loser.

That's also not something we want our daughters to hear, or our sons, if we want to inspire them to go and be the people who are going to solve dark energy in the future. Let's keep inspiring our kids.

Audience question: Are there theories about whether quantum gravity becomes probabilistic?

Gleiser: There are theories of quantum gravity that treat the wave function of the gravitational field. There's a whole tradition of that dating back to the early 1960s, where you can write something called the wave function of the universe and quantize gravity in that way.

Then there's a whole other approach, which is a more recent one, called loop quantum gravity, where you basically break down space into little chunks, which are basically fluctuations of the metric that you use to measure distances and timeframes. Yes, people have been trying to do that. They've been partially successful.

Tegmark: Just to add to that also: all the questions you're asking can certainly be tackled. Yes, there is a problem of getting good experimental data on it, because you need to do extremely violent things to the fabric of space-time for these effects to become strong. So, to learn more about them from Nature, since we can't do such violent things with our technology, we have to look at the most violent places in Nature. That's why it's so interesting to look really hard at what black holes are doing. If we can catch a black hole in the final stages of its evaporation—Hawking evaporation, for example—we would learn so much from this.

Another extremely violent place, of course, is our Big Bang that we heard about. That's why it's very, very interesting to look in more detail than we have so far about what radiation actually came from the Big Bang, because encoded in that might again be some of the best clues available to answer your questions.

Paulson: We're running very short of time. I'm actually going to take the last few minutes to ask a question of each of you here. We've been talking as if everything did start with the Big Bang. We haven't even really talked about the multiverse and I feel like I'm remiss here without . . .

Tegmark: Yes we have, just not in this particular universe . . . . [*audience and panelist laughter*]

Paulson: Do you think we just have this one universe that started 13.8 billion years ago? Or are there actually other universes? Maybe really the origin isn't 13.8 billion years?

Max, what's your guess? Do you think there are many universes out there?

Tegmark: Before we talk about other universes, we should probably define what we mean by ours. When we say our universe, or our observable universe, we don't in physics or astronomy mean everything that exists, because then, by definition, we would all have to say no, no, no. We mean simply the spherical region of space from which light has had time to reach us so far, or, as Katie called it, the horizon volume. The question you're asking then is are there more, are there other regions of that same size somewhere else.

If space is actually much bigger than the part of space we can see, if, for example, as Euclid thought, that it goes on forever, then certainly yes, there are lots of other places, other galaxies. Even though we can't see those things . . . .

Freese: Oh no, I'm already defining *universe* differently than you are . . . [*laughter*]

Tegmark: Just made sure you redefine it before you answer!

Anyway, I just was going to say that what's interesting is that, first of all, we have no evidence whatsoever that space ends magically exactly at the edge of what we can see. In fact, every hour we wait, light reaches us from still farther away.

Moreover, more seriously, the most popular theory we have for what created this space and stretched it out and made it so big, namely inflation, actually predicts that space is vastly bigger than what we can see, so that there is much more.

To me, this is not particularly surprising at all, since we've again and again discovered, as we talked about, that everything we thought existed was part of something even bigger. The planet, the solar system, the galaxy, our observable universe . . . . so if it happens once again, not such a big deal. So yes, to the multiverse.

Paulson: So, yes to the multiverse.

Katie?

Freese: I'm responding to something, not exactly this question, but actually the part of the universe we can access, the amount of it is going *down* because the universe is accelerating. As time goes on, we can see less and less of it.

I would define universe a little differently, would be motivated rather by inflation or string theory. I'll talk about the inflation one. During the very, very early accelerating period of the universe, you can think of a ball rolling down a hill, only in some places of the universe that ball gets kicked back up. We may be from a part of the universe that rolled down and we got to the bottom because we have to be at the bottom for us to exist. That happened here, but somewhere else in a distant region that ball kept getting kicked up and maybe rolled down at a different time. This is similar to your definition of a universe—

Tegmark: Actually, you are talking about what I call the level-two parallel universe, while I was talking about the level one. I even talk about four kinds in my book, if people want to get really confused, but I'm with you. I'm with you on your level two . . .

Freese: These are real physics questions as to how different these regions are. I'm not sure that I'm convinced. I don't know, but I am also not sure I care, because we'll never talk to other universes. We'll never communicate with them. They are so far away that we'll never know about them.

I don't think it's fair to say that there are questions about physics we don't have to answer. We can say, "Well, obviously we don't have to worry about the strength of electromagnetism in this universe because otherwise we wouldn't exist: if it were a little bit different, then the nuclei would fly apart. We don't have to explain it because somewhere else they have a different value and humans can't exist there."

I'm not satisfied. I want to explain it in our universe now. Of course, there must be other universes no matter how you define them, but the question is the impact they have on us as physicists, and I don't want their existence to affect the way we think about solving problems within our universe.

It's a complicated answer.

Paulson: Marcelo.

Gleiser: I don't think this is a yes or no question; it's unfair to set it up like that . . . .

Paulson: That's my job, to ask unfair questions . . . [*laughter*]

Gleiser: Max said something that we all have experience of: if you're standing at the beach and you see the horizon where the sky and the ocean touch, you know that that's not the end of the earth. You know it goes on, but you cannot see it. What you call level one is basically whatever is beyond our observable bubble, because like a fish in a bowl we have this little bubble of information we can cover. The universe will probably continue after that, just like the ocean continues beyond what we see at the beach. That's pretty much okay.

However, the notion of having a multiverse, not just our bubble universe being the only universe but having some entity where you have eternally bubbling universes that go into existence, that is based on extrapolations of current theories—that is something we really can't be sure of.

If you say, "I believe in the multiverse," that is a subjective statement, not a *scientific* statement. I think you have to make that differentiation. The point is, I am agnostic with respect to this. If there are multiverses, then that's awesome.

My main concern is what Katie raised, which is, Can we test the hypothesis? That is a really complicated issue. Actually, Matt Klebhan from NYU and Anthony Aguirre from Santa Cruz have this idea that, if there are other universes out there, they may have collided with ours in the past, which would have left some kind of "scar" (radiation) that we can see in the sky. There will be evidence perhaps of a past collision with our neighbor.

Freese: That is *the* only prediction of multiverses.

Tegmark: Well . . . .perhaps not.

Gleiser: That is the best one. Unfortunately, so far it hasn't really panned out. People have looked at the data, but it's not working. And even if it were to be the case, that would only mean that we may have a neighbor universe; it doesn't mean there is an infinite number of universes—a multiverse—out there.

It is a very complicated question from an epistemological point of view because we can never be sure that an infinite multiverse exists. In fact, we can never be sure, from an experimental perspective, that *anything* infinite exists, because even if we measure the curvature of space and it looks flat plus or minus marginal error, that plus or minus margin of error, which is how science is done, kills the idea that we can ever be sure that universe is infinitely flat.

Paulson: We have many more questions that we could ask, but we have no more time. Thank you all.

Acknowledgments

Steve Paulson, executive producer and one of the founders of *To the Best of Our Knowledge*, moderated the panel of experts. The is an edited transcript of the discussion from December 10, 2014, 7:00PM–8:30PM, at the New York Academy of Sciences in New York City.

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