THE JOY OF WHY

What Is Quantum Field Theory and Why Is It Incomplete?

By STEVEN STROGATZ

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Quantum field theory may be the most successful scientific theory of all time, but there's reason to think it's missing something. Steven Strogatz speaks with theoretical physicist David Tong about this enigmatic theory.

Michael Driver for Quanta Magazine

Quantum field theory may be the most successful scientific theory of all time, predicting experimental results with stunning accuracy and advancing the study of higher dimensional mathematics. Yet, there's also reason to believe that it is missing something. Steven Strogatz speaks with David Tong, a theoretical physicist at the University of Cambridge, to explore the open questions of this enigmatic theory.

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Transcript

Steven Strogatz (00:03): I'm Steve Strogatz, and this is *The Joy of Why*, a podcast from quantum magazine that takes you into some of the biggest unanswered questions in math and science today.

(00:12) If you've ever wondered what are we actually made of, you probably found yourself going down a rabbit hole of discoveries. Just like other living things, of course, we're made of cells. And cells, in turn, are made of molecules and molecules are made of atoms. Dig even deeper and pretty soon you'll find yourself at the level of electrons and quarks. These are the particles that have traditionally been considered to be the end of the line, the fundamental building blocks of matter.

(00:39) But today, we know that's not really the case. Instead, physicists tell us that at the deepest level, everything is made up of mysterious entities, fluid-like substances that we call quantum fields. These invisible fields sometimes act like particles, sometimes like waves. They can interact with one another. They can even, some of them, flow right through us. The theory of quantum fields is arguably the most successful scientific theory of all time. In some cases, it makes predictions that agree with experiments to an astonishing 12 decimal places. On top of that, quantum field theory has also been shedding enormous light on certain questions in pure mathematics, especially in the study of four-dimensional shapes and even higher dimensional spaces. Yet, there's also reason to believe that quantum field theory is missing something. It seems to be mathematically incomplete, leaving us with many unanswered questions.

(01:38) Joining me now to discuss all this is Professor David Tong. David is a theoretical physicist at the University of Cambridge. His specialty is quantum field theory, and he's also renowned as an exceptionally gifted teacher and expositor. Among his many honors, he was awarded the Adams Prize in 2008, one of the most prestigious awards that the University of Cambridge bestows. He's also a Simons Investigator, an award from the Simons Foundation to scientists and mathematicians to study fundamental questions. The Simons Foundation also funds this podcast. David, thank you so much for joining us today.

David Tong

David Tong (02:15): Hi, Steve. Thanks a lot for having me.

Strogatz: I'm thrilled to have a chance to talk to you. I've enjoyed reading your lectures on the internet and watching some of your fantastic talks on YouTube. So this is a great treat. Let's start off with the basics. We're going to be talking about fields today. Tell us who originated them. Usually Michael Faraday gets the credit. What was his idea? And what did he discover?

Tong (02:37): It all goes back to Michael Faraday. Faraday was one of the great experimental physicists of all time, he was very much an experimental physicist, not a theorist. He left school at the age of 14. He knew essentially no mathematics. And yet rather wonderfully, he built up this intuition for the way the universe works. That meant he really made one of the most important contributions to theoretical physics. Over a period of about 25 years, he was playing with ideas of electricity and magnetism. He was getting magnets and wrapping copper wire around them. He did a couple of fairly important things like discover electromagnetic induction and invent the electric motor.

(03:19) And after about 20 years of this, he made the very bold proposal that pictures he had cooked up in his mind to explain the way things were working was actually the correct description of the universe that we live in.

(03:33) So let me give you an example. If you take a couple of bar magnets, and you push them together so that the two north poles approach each other — it's an experiment that we've all done. And as you push these magnets together, you feel this spongy force that's pushing them apart. Faraday made the very bold proposal that there was actually something in between the magnets. It's amazing because you look at the magnets, there — it's just thin air, there's clearly nothing there. But Faraday said there was something there, there was what we now call a magnetic field there, he called it a line of force. And that this magnetic field was every bit as real as the magnets themselves.

(04:11) So it was a very new way of thinking about the universe we live in. He suggested that not only are there particles in the universe, but in addition, there's this other kind of object, a very different kind of object, a field, which exists everywhere in space all at once. He said, we would now say in modern language, that at every single point in the universe, there are two vectors, two arrows. And these vectors tell us the direction and the magnitude of the electric and the magnetic field.

(04:43) So he left us with this picture of the universe in which there's kind of a dichotomy that there's two very, very different objects. There's particles, which are setting up electric and magnetic fields. And then these electric and magnetic fields themselves are waving and evolving and in turn telling the particles how to move. So there's this sort of intricate dance between what particles are doing, and what fields are doing. And really, his big contribution was to say these fields are real, they're really every bit as real as the particles.

Strogatz (05:12): So how then did the concept of fields change once quantum mechanics was discovered?

Tong (05:18): So by the time quantum mechanics came around, this is now 1925. And we have this sort of peculiar view of the world. So we know that there are electric and magnetic fields. And we know that the ripples of these electromagnetic fields are what we call light. But in addition, because of the quantum revolution, we know that light itself is made of particles, photons.

(05:41) And so there's kind of a question that emerges, which is, how should you think of this relationship between the fields on the one hand and the photons on the other. And I think there's two logical possibilities for the way this could work, It could be that you should think of electric and magnetic fields as comprised of lots and lots of photons, rather like a fluid is comprised of lots and lots of atoms, and you think the atoms are the fundamental object. Or alternatively, it could be the other way around, it could be that the fields are the fundamental thing. And the photons come from little ripples of the fields. So they were the two logical possibilities.

(06:18) And the big development in, well, it sort of starts in 1927. But it takes a good 20 or 30 years until this is fully appreciated. The big appreciation, then, is that it's the fields that are really fundamental, that the electric and magnetic field is at the basis of everything. And little ripples of the electric and magnetic field get turned into little bundles of energy that we then call photons due to the effects of quantum mechanics.

(06:44) And the wonderful big step, one of the great unifying steps in, in the history of physics, is to understand that that same story holds for all other particles. That the things we call electrons and the things we call quarks are not themselves the fundamental objects. Instead, there is spread throughout the entire universe something called an electron field, exactly like the electric and magnetic fields. And the particles that we call electrons are little ripples of this electron field. And the same is true for any other particle you care to mention. There's a quark field — in fact, there are six different quark fields throughout the universe. There are neutrino fields, there are fields for gluons and *W* bosons. And whenever we discover a new particle, the most recent being the Higgs boson, we know that associated to that is a field which underlies it, and the particles are just ripples of the field.

Strogatz (07:33): Is there a particular name that we should associate with this way of thinking?

Tong (07:36): There is one person and he's a, he's been almost erased from the history books, because he was a very key member of the Nazi Party. And he was a member of the Nazi Party way before it was cool to be a member of the Nazi Party. His name is Pascal Jordan. And he was one of the founders of quantum mechanics. He was on the original papers with Heisenberg and others. But he was really the person that first appreciated that if you start with a field, and you apply the rules of quantum mechanics, you end up with a particle.

Strogatz (08:06): Okay, well, very good. Now, you mentioned all these different — the electron field, quark, *W* and *Z* bosons and the rest. Tell us a little about the Standard Model that we hear so much about.

Tong (08:18): The Standard Model is our current best theory of the universe we live in. It's an example of a quantum field theory. It's basically all the particles that we've already listed. Each of those has a field associated to it. And the Standard Model is a formula that describes how each of those fields interacts with the others. The fields at play are three force fields. And sort of depending how you count 12 matter fields in, in a way that I will explain. So the three force fields are electricity and magnetism — we since, actually in large part due to Faraday, realize that the electric field and the magnetic field are sort of two sides of the same coin, you can't have one without the other. So we, we count those just as one. And then there are two nuclear force fields, one called the gluon field that's associated to the strong nuclear force. This holds the nuclei together inside atoms, and the other fields associated to the weak nuclear force. They're called the *W* boson or the *Z* boson fields. So we have three force fields.

(09:20) And then we have a bunch of matter fields, they come in three groups of four. The most familiar ones are an electron field, two quark fields associated to the up and the down quark. The proton contains — oh man, I hope we get this right — two up and down and the neutron contains two down and an up, I think, I've got that the right way around.

Strogatz (09:41): You could fool me either way. I can never remember.

Tong (09:43): Yeah, but the listeners are gonna know. And then a neutrino field. So there's this collection of four particles interacting with three forces. And then for a reason that we really do not understand, the universe decided to repeat those matter fields twice over. So there is a second collection of four particles called the muon, the strange the charm and another neutrino. We sort of ran out of good names for neutrinos, so we just call it the muon neutrino. And then you get another collection of four: the tau, the top quark, the bottom quark and, again, a tau neutrino. So nature has this way of repeating itself. And no one really knows why. I think that remains one of the big mysteries. But those collections of 12 particles interacting with three forces comprises the Standard Model.

(09:43) Oh, and I missed one. The one I missed is important. It's the Higgs boson. The Higgs boson sort of ties everything together.

Strogatz (10:37): All right, that's tantalizing. Maybe we should say a little what the Higgs boson does, what role does it play in the Standard Model.

Tong (10:43): It does something rather special. It gives a mass to all the other particles. I would love to have a good analogy to explain how it gives mass. I can give a bad analogy, but it really is a bad analogy. The bad analogy is that this Higgs field is spread throughout all of space, that's a true statement. And the bad analogy is it acts a little like treacle or molasses. The particles sort of have to push their way through this, this Higgs field to make any progress. And that sort of slows them down. They would naturally travel at the speed of light, and they get slowed down by the presence of this Higgs field. And that is responsible for the phenomenon that we call mass.

(11:22) A large part of what I just said is basically a lie. I mean, it sort of suggests that there's some friction force at play. And that's not true. But it's one of those things where the equations are actually surprisingly easy. But it's rather hard to come up with a compelling analogy that captures those equations.

Strogatz (11:36): It's an amazing statement that you made, that without the Higgs field or some, I guess, some analogous mechanism, everything would be moving at the speed of light. Did I hear you right?

Tong (11:47): Yes, except, as always, these things, it's yes, with a caveat. The "but" is if the Higgs field turned off, the electron would move at the speed of light. So you know, atoms would not be particularly stable. The neutrino, which is almost massless anyway, would travel at the speed of light. But the proton or neutron, it turns out, would have basically the same masses that they have now. You know, the quarks inside them would be massless. But the mass of the quarks inside the proton or neutron, are totally trivial compared to the proton or neutron — 0.1%, something like that. So the proton or neutron actually get their mass from a part of quantum field theory that we understand least, but wild fluctuations of quantum fields, is what's going on inside the proton or neutron and giving them their mass. So the elementary particles would become massless — quarks, electrons — but the stuff we're made of —neutrons and protons — would not. They get their mass from this other mechanism.

Strogatz (12:42): You're just full of interesting things. Let's see if I can say what I'm thinking in response to that. And you can correct me if I've got it completely wrong. So I've got these strongly interacting quarks inside, say, a proton. And I keep in my mind guessing there's some $E = mc^2$ connection going on here, that the powerful interactions are associated with some large amount of energy. And that's somehow translating into mass. Is it that, or is that there's virtual particles being created and then disappearing? And all of that is creating energy and therefore mass?

Tong (13:16): It's both of the things you just said. So we tell this lie when we're in high school — physics is all about telling lies when you're young and realizing that things are a bit more complicated as you grow older. The lie we tell, and I already said it earlier, is that there are three quarks inside each proton and each neutron. And it's not true. The correct statement is that there are many hundreds of quarks and antiquarks and gluons inside a proton. And statement that there are really three quarks, the proper way of saying it is that at any given time, there are three more quarks than there are antiquarks. So there's sort of an additional three. But it's an extraordinarily complicated object, the proton. It, it's nothing nice and clean. It contains these hundreds, possibly even thousands of different particles interacting in some very complicated way. You could think about these quark-antiquark pairs as being, as you say, virtual particles, things that just pop out of the vacuum and pop back in again inside the proton. Or another way of thinking about it is just the fields themselves are excited in some complicated fashion inside the proton or neutron thrashing around and that's what's giving them their mass.

Strogatz (14:20): Earlier, I hinted that this is a very successful theory and mentioned something about 12 decimal places. Can you tell us about that? Because that is one of the great triumphs, I would say not just of quantum field theory, or even physics, but all of science. I mean, humanity's attempt to understand the universe, this is probably the best thing we've ever done. And from a quantitative standpoint, we as a species.

Tong (14:42): I think that's exactly right. It's kind of extraordinary. I should say that there's a few things we can calculate extraordinarily well, when we know what we're doing, we can really do something spectacular.

Strogatz (14:42): It's enough to get you sort of in a philosophical mood, this question of the unreasonable effectiveness of mathematics.

Tong (14:52): So, the particular object or the particular quantity, that is the poster boy for quantum field theory, because we can calculate it very well albeit taking many, many decades to do these calculations, they're not easy. But also importantly, we can measure it experimentally very well. So it's a number called g-2 , it's not particularly important in the grand scheme of things, but the number is the following. If you take an electron, then it has a spin. The electron spins about some axis not dissimilar to the way the Earth spins about its axis. It's more quantum than that, but it's not a bad analogy to have in mind.

(14:59) And if you take the electron, and you put it in a magnetic field, the direction of that spin precesses over time, and this number g-2 just tells you how fast it precesses, the -2 is slightly odd. But you would naively think that this number would be 1. And [Paul] Dirac won the Nobel Prize in part for showing that actually this number is 2 to first approximation. Then [Julian] Schwinger won the Nobel Prize, together with [Richard] Feynman and [Sin-Itiro] Tomonaga, for showing that, you know, it's not 2, it's 2-point-something-something-something. Then over time, we've made that something-something-something with another nine somethings afterwards. As you said, it's something that we now know extremely well theoretically and extremely well experimentally. And it's just astonishing to see these numbers, digit after digit, agreeing with each other. It's something rather special.

(15:21) This is one of the things that pushes you in that direction is that it's so good. It's so good that this isn't a model for the world, this is somehow much closer to the actual world, this equation.

Strogatz (16:31): So having sung the praises of quantum field theory, and it does deserve to be praised, we should also recognize that it's an extremely complicated, and in some ways, problematic theory or set of theories. And so in this part of our discussion, I wonder if you could help us understand what reservation should we have? Or where the frontier is. Like, the theory is said to be incomplete. What is incomplete about it? What are the big remaining mysteries about quantum field theory?

Tong (17:01): You know, it really depends on what you subscribe to. If you're a physicist and you want to compute this number *g*-2, then there's nothing incomplete about quantum field theory. When the experiment gets better, you know, we calculate or we do better. You can really do as well as you want to. There's several axes to this. So let me maybe focus on one to begin with.

(17:22) The problem comes when we talk to our pure mathematician friends, because our pure mathematician friends are smart people, and we think that we have this mathematical theory. But they don't understand what we're talking about. And it's not their fault, it's ours. That the mathematics we're dealing with is not something that's on a rigorous footing. It's something where we're playing sort of fast and loose with various mathematical ideas. And we're pretty sure we know what we're doing as this agreement with experiments shows. But it's certainly not at the level of rigor that, well, certainly mathematicians would be comfortable with. And I think increasingly that we physicists are also growing uncomfortable with.

(17:22) I should say that this isn't a new thing. It's always the case whenever there are new ideas, new mathematical tools, that often the physicists take these ideas and just run with them because they can solve things. And the mathematicians are always — they like the word "rigor," maybe the word "pedantry" is better. But now, they're kind of going slower than us. They dot the i's and cross the T's. And somehow, with quantum field theory, I feel that, you know, it's been so long, there's been so little progress that maybe we're thinking about it incorrectly. So that's one nervousness is that it can't be made mathematically rigorous. And it's not through want of trying.

Strogatz (18:33): Well, let's try to understand the nub of the difficulty. Or maybe there are many of them. But you spoke earlier about Michael Faraday. And at each point in space, we have a vector, a quantity that we could think of as an arrow, it's got a direction and a magnitude, or if we prefer, we could think of it as three numbers maybe like an x, y and z component of each vector. But in quantum field theory, the objects defined at each point are, I suppose, more complicated than vectors or numbers.

Tong (18:33): They are. So the mathematical way of saying this is that at every single point, there is an operator — some, if you like, infinite dimensional matrix that sits at each point in space, and acts on some Hilbert space, that itself is very complicated and very hard to define. So the mathematics is complicated. And in large part, it's because of this issue that the world is a continuum, we think that space and time, space in particular, is continuous. And so you have to define really something at each point. And next to one point, infinitesimally close to that point is another point with another operator. So there's an infinity that appears when you look on smaller and smaller distance scales, not an infinity going outwards, but an infinity going inwards.

(19:44) Which suggests a way to get around it. One way to get around it is just to pretend for these purposes, that space isn't continuous. In fact, it might well be that space isn't continuous. So you could imagine thinking about having a lattice, what mathematicians call a lattice. So rather than have a continuous space, you think about a point, and then some finite distance away from it, another point. And some finite distance away from that, another point. So you discretize space, in other words, and then you think about what we call the degrees of freedom, the stuff that moves as just living on these lattice points rather than living in some continuum. That's something that mathematicians have a much better handle on.

(19:44) But there's a problem if we try to do that. And I think it's one of the deepest problems in theoretical physics, actually. It's that some quantum field theories, we simply cannot discretize in that way. There is a mathematical theorem that forbids you from writing down a discrete version of certain quantum field theories.

Strogatz (20:41): Oh, my eyebrows are raised at that one.

Tong (20:43): The theorem is called the Nielsen-Ninomiya theorem. Among the class of quantum field theories that you cannot discretize is the one that describes our universe, the Standard Model.

Strogatz (20:52): No kidding! Wow.

Tong (20:54): You know, if you take this theorem at face value, it's telling us we're not living in the Matrix. The way you simulate anything on a computer is by first discretizing it and then simulating. And yet there's a fundamental obstacle seemingly to discretizing the laws of physics as we know it. So we can't simulate the laws of physics, but it means no one else can either. So if you really buy this theorem, then we're not living in the Matrix.

Strogatz (21:18): I'm really enjoying myself, David. This is so, so interesting. I never had a chance to study quantum field theory. I did get to take quantum mechanics from Jim Peebles at Princeton. And that was wonderful. And I did enjoy that very much, but never continued. So quantum field theory, I'm just in the position of many of our listeners here, just looking in agog at all the wonders that you're describing,

Tong (21:41): I can tell you a little more about the exact aspect of the Standard Model that makes it hard or impossible to simulate on a computer. There's a nice tagline, I can add like a Hollywood tagline. The tagline is, "Things can happen in the mirror that cannot happen in our world." In the 1950s, Chien-

Shiung Wu discovered what we call parity violation. This is the statement that when you look at something happening in front of you, or you look at its image in a mirror, you can tell the difference, you can tell whether it was happening in real world or happening in the mirror. It's this aspect of the laws of physics, that what happens reflected in a mirror is different from what happens in reality, that turns out to be problematic. It's that aspect that's difficult or impossible to simulate, according to this theory.

Strogatz (22:28): It's hard to see why I mean, because the lattice itself wouldn't have any problem coping with the parity. But anyway, I'm sure it's a subtle theorem.

Tong (22:36): I can try to tell you a little bit about why every particle in our world — electrons, quarks. They split into two different particles. They're called left-handed and right-handed. And it's basically to do with how their spin is changing as they move. The laws of physics are such that the left-handed particles feel a different force from the right-handed particles. This is what leads to this parity violation.

(22:59) Now, it turns out that it's challenging to write down mathematical theories that are consistent and have this property that left-handed particles and right-handed particles, experienced different forces. There are sort of loopholes that you have to jump through. It's called anomalies, or anomaly cancellation in quantum field theory. And these subtleties, these loopholes they come from, at least in certain ways of calculating the fact that space is continuous, you only see these loopholes when spaces, or these requirements when space is continuous. So the lattice knows nothing about this. The lattice knows nothing about these fancy anomalies.

(23:36) But you can't write down an inconsistent theory on the lattice. So somehow, the lattice has to cover its ass, it has to make sure that whatever it gives you is a consistent theory. And the way it does that is just by not allowing theories where left-handed and right-handed particles feel different forces.

Strogatz (23:50): All right, I think I get the flavor of it. It's something like that topology allows for some of the phenomena, these anomalies that are required to see what we see in the case of the weak force, that a discrete space would not permit. That something about the continuum is key.

Tong (24:06): You said it better than me, actually. It's all to do with topology. That's exactly right. Yeah.

Strogatz (24:11): All right. Good. That's a very nice segue for us actually, into where I was hoping we could go next, which is to talk about what quantum field theory has done for mathematics, because that is another one of the great success stories. Although, you know, for physicists who care about the universe, that's maybe not a primary concern, but for people in, in mathematics, we're very grateful and also mystified at the great contributions that have been made by thinking about purely mathematical objects, as if they were informing them with insights from quantum field theory. Could you just tell us a little about some of that story starting, say, in the 1990s?

Tong (24:48): Yeah, this is really one of the wonderful things that come out of quantum field theory. And there's no small irony here. You know, the irony is that we're using these mathematical techniques that mathematicians are extremely suspicious about because they don't think that, that they're, they're not rigorous. And yet at the same time, we're sort of somehow able to leapfrog mathematicians and almost beat them at their own game in certain circumstances, where we can turn around and hand them results that they're interested in, in their own area of specialty, and results that in some circumstances have utterly transformed some areas of mathematics.

(25:22) So I can try to give you some sense about how this works. The kind of area of mathematics that this has been most useful in is ideas to do with geometry. It's not the only one. But it's, I think it's the one that we've made most progress in thinking about as physicists. And of course, geometry has always been close to the heart of physicists. Einstein's theory of general relativity is really telling us that space and time are themselves some geometric object. So that what we do is we take what mathematicians call a manifold, it's some geometric space. In your mind, you can think, firstly, of the surface of a soccer ball. And then maybe if the surface of a doughnut, where there's a hole in the middle. And then generalize to the surface of a pretzel, where there's a few holes in the middle. And then the big step is to take all of that and push it to some higher dimensions and think of some higher dimensional object with wrapped around on itself with higher dimensional holes, and, and so on.

(26:13) And so the kinds of questions mathematicians are asking us to classify objects like this, to ask what's special about different objects, what kind of holes they can have, the structures they can have on them, and so forth. And as physicists, we sort of come with some extra intuition.

(26:28) But in addition, we have this secret weapon of quantum field theory. We sort of have two secret weapons. We have quantum field theory; we have a willful disregard for rigor. Those two combine quite, quite nicely. And so we will ask questions like, take one of these spaces, and put a particle on it, and ask how does that particle respond to the space? Now with the particles or quantum particles, something quite interesting happens because it has a wave of probability which spreads over the space. And so because of this quantum nature, it has the option to sort of know about the global nature of the space. It can sort of feel out all of the space at once and figure out where the holes are and where the valleys are and where the peaks are. And so our quantum particles can do things like get stuck in certain holes. And in that way, tell us something about the topology of the spaces.

(27:18) So there's been a number of very major successes of applying quantum field theory to this one of the biggest ones was in the early 1990s, something called mirror symmetry, which revolutionized an area called symplectic geometry. A little later [Nathan] Seiberg and [Edward] Witten solved a particular four-dimensional quantum field theory, and that gave new insights into topology of four-dimensional spaces. It's really been a wonderfully fruitful program, where what's been happening for several decades now is physicists will come up with new ideas from quantum field theory, but utterly unable to prove them typically, because of this lack of rigor. And then mathematicians will come along, but it's not just dotting eyes and crossing T's, they typically take the ideas and they prove them in their own way, and introduce new ideas.

(28:02) And those new ideas are then feeding back into quantum field theory. And so there's been this really wonderful harmonious development between mathematics and physics. As it turns out, that we're often asking the same questions, but using very different tools, and by talking to each other have made much more progress than we otherwise would have done.

Strogatz (28:18): I think the intuitive picture that you gave is very helpful that somehow thinking about this concept of a quantum field as something that is delocalized. You know, rather than a particle that we think of as point-like, you have this object that spreads over the whole of space and time, if there's time in the theory, or if we're just doing geometry, I guess we're just thinking of it as spreading over the whole of the space. These quantum fields are very neatly suited to detecting global features, as you said.

(28:47) And that's not a standard way of thinking in math. We're used to thinking a point and the neighborhood of a point, the infinitesimal neighborhood of a point. That's our friend. We're like the most myopic creatures as mathematicians, whereas the physicists are so used to thinking of these automatically global sensing objects, these fields that can, as you say, sniff out the contours, the valleys, the peaks, the wholes of surfaces of global objects.

Tong (29:14): Yeah, that's exactly right. And part of the feedback into physics has been very important. So appreciating that topology is really underlying a lot of our ways of thinking in quantum field theory that we should think globally in quantum field theory as well as in, in geometry. And, you know, there are programs, for example, to build quantum computers and one of the most, well, perhaps it's one of the more optimistic ways to build quantum computers.

(29:34) But if it could be made to work, one of the most powerful ways of building a quantum computer is to use topological ideas of quantum field theory, where information isn't stored in a local point but it's stored globally over a space. The benefit being that if you nudge it somewhere at a point, you don't destroy the information because it's not stored at one point. It's stored everywhere at once. So as I said, there's this really this wonderful interplay between mathematics and physics that It's happening as we speak.

Strogatz (30:01): Well, let's shift gears one last time back away from mathematics toward physics again, and maybe even a little bit of cosmology. So with regard to the success story of the physical theory, more of the constellation of theories that we call quantum field theory, we've had these experiments fairly recently at CERN. Is this, that's where the Large Hadron Collider is, is that right?

Tong (30:01): That's right. It's in Geneva.

Strogatz (30:04): Okay. You mentioned about the discovery of the Higgs long predicted something like 50, 60 years ago, but it's my understanding that physicists have been — well, what's the right word? Disappointed, chagrined, puzzled. That some of the things that they'd hoped to see in the experiments at the Large Hadron Collider have not materialized. Supersymmetry, say, being one. Tell us a little about that story. Where are we hoping to see more from those experiments? How should we feel about not seeing more?

Tong (30:53): We were hoping to see more. I have no idea how we should feel though, that we haven't seen. I could, I can tell you the story.

Tong (31:00): So the LHC was built. And it was built with the expectation that it would discover the Higgs boson, which it did. The Higgs boson was the last part of the Standard Model. And there were reasons to think that once we completed the Standard Model, the Higgs boson would also be the portal that led us to what comes next, the next layer of reality that what comes afterwards. And there are arguments that you can make, that when you discover the Higgs, you should discover sort of around in the same neighborhood, the same energy scale as the Higgs, some other particles that somehow stabilize the Higgs boson. The Higgs boson is special. It's the only particle in the Standard Model that doesn't spin. All other particles, the electron spins, the photon spins, it's what we call the polarization. The Higgs boson is the only particle that doesn't spin. In some sense, it's the simplest particle in the Standard Model.

(31:00) But there are arguments theoretical arguments that say that a particle that doesn't spin should have a very heavy mass. Very heavy means pushed up to the highest energy scale possible. These arguments are good arguments. We could use quantum field theory in many other situations, in materials described by quantum field theory. It's always true that if a particle doesn't spin, it's called a scalar particle. And it's got a light mass. There's a reason why it's masses light.

(32:25) And so we expected there to be a reason why the Higgs boson had the mass that it has. And we thought that reason would come with some extra particles that will sort of appear once the Higgs appeared. And maybe it was supersymmetry and maybe it was something called technicolor. And there were many, many theories out there. And we discovered the Higgs and the LHC — I think this is important to add — has exceeded all expectations when it comes to the operation of the machine and the experiments and the sensitivity of the detectors. And these people are absolute heroes who are doing the experiment.

(32:56) And the answer is there's just nothing else there at the energy scale that we're currently exploring. And that's a puzzle. It's a puzzle to me. And it's a puzzle to many others. We were clearly wrong; we were clearly wrong about the expectation that we should discover something new. But we don't know why we're wrong. You know, we don't know what was wrong with those arguments. They still feel right, they still feel right to me. So there's something that we're missing about quantum field theory, which is exciting. And you know, it's good to be wrong in this area of science, because it's only when you're wrong, you can finally be pushed in the right direction. But it's fair to say that we're not currently sure why we're wrong.

Strogatz (33:32): That's a good attitude to have, right, that so much progress has been made from these paradoxes, from what feels like disappointments at the time. But to be living through it and to be in a generation — I mean, well, I don't want to say you could be washed up by the time this is figured out, but it's a scary prospect.

Tong (33:50): Washed up would be fine. But I'd like to be alive.

Strogatz (33:56): Yeah, I felt bad even saying that.

Going from the small to the big, why don't we think about some of the cosmological issues. Because some of the other great mysteries, things like dark matter, dark energy, the early universe. So you study as one of your own areas of great interest, the time right after the Big Bang, when we didn't really have particles yet. We just had, what, quantum fields?

Tong (34:22): There was a time after the Big Bang called inflation. So it was a time at which the universe expanded very, very rapidly. And there were quantum fields in the universe when this was happening. And what I think is really one of the most astonishing stories in all of science is that these quantum fields had fluctuations. They're always bouncing up and down, just because of quantum jitters, you know. Just as the Heisenberg uncertainty principle says a particle can't, can't be in a specific place because it will have infinite momentum, so you know, it's always some uncertainty there. That the same is true for these fields. These quantum fields can't be exactly zero or exactly some value. They're always jittering up and down through quantum uncertainty.

(35:02) And what happened in these first few seconds — seconds is way too long. First few 10^{-30} seconds, let's say, of the Big Bang is the universe expanded very rapidly. And these quantum fields sort of got caught in the act, that they were fluctuating, but then the universe dragged them apart to vast scales. And those fluctuations got stuck there. They couldn't fluctuate anymore, basically, because of causality reasons, because now they were spread so far that, you know, one part of the fluctuation didn't know what the other one was doing. So these fluctuations get stretched across the whole universe, way back in the day.

(35:43) And the wonderful story is that we can see them, we can see them now. And we've taken a photograph of them. So the photograph has a terrible name. It's called the cosmic microwave background radiation. You know this photograph, it's the blue and red ripples. But it's a photograph of the fireball that filled the universe 13.8 billion years ago, and there's ripples in there. And the ripples that we can see were seeded by these quantum fluctuations in the first few fractions of a second after the Big Bang. And we can do the calculation, you can calculate what the quantum fluctuations look like. And you can experimentally measure the fluctuations in the CMB. And they just agree. So it's an astonishing story that we can take a photograph of these fluctuations.

(36:30) But there's also a level of disappointment here as well. The fluctuations that we see are fairly vanilla, they're just those that you would get from free fields. And it would be nice if we could get more information, if we could see — the statistical name is that the fluctuations are Gaussian. And it would be nice to see some non-Gaussianity, which will be telling us about the interactions between the fields back in the very, very early universe. And so again, the Planck satellite has, has flown and it has taken a snapshot of the CMB in ever clearer detail, and the non-Gaussianities that are there, if there are any there at all, are just smaller than, than the Planck satellite can detect.

(36:52) So there's hope for the future that there's other CMB experiments, there's also a hope that these non-Gaussianities might show up in the way that galaxies form, the statistical distribution of galaxies through the universe also holds a memory of these fluctuations that much we know is true, but that perhaps we might get more information from there. So it really is incredible that you can trace these fluctuations for 14 billion years, from the very earliest stages to the way the galaxies are distributed in the universe now,

Strogatz (37:36): Well, that's given me a lot of insight that I didn't have before about the imprint of these quantum fluctuations on the cosmic microwave background. I'd always wondered. You mentioned that it's the free theory, meaning —what, tell us what's "free" means exactly? There's no nothing right? I mean, it's just, it's the vacuum itself?

Tong (37:45): It's not just the vacuum, because these fields get excited as the universe expands. But it's just a field that isn't interacting with any other fields or even with itself, it's just bouncing up and down like a harmonic oscillator, basically. Each point is bouncing up and down like a spring. So it's kind of the most boring field that you could imagine.

Strogatz (38:11): And so that means we didn't have to postulate any particular quantum field at the beginning of the universe. It's just, that's what you say, vanilla.

Tong (38:19): It's vanilla. So it would have been nice to get a better handle that these interactions are happening, or these interactions are happening, or the field had this particular property. And that doesn't seem — maybe in the future, but at the moment, we're not there yet.

Strogatz (38:32): So maybe we should then close with your personal hopes. Is there one, if you had to single out one thing that you would like to see solved personally, in the next few years, or for the future of research in quantum field theory, what would be your favorite? If you could dream.

Tong (38:48): There are so many —

Strogatz: You can pick more.

Tong: There's things on the mathematical side. So I would, I would love to understand, on the mathematical side, more about this Nielsen-Ninomiya theorem, the fact that you cannot discretize certain quantum field theories. And are there loopholes in the theorem? Are there assumptions we can throw out and somehow succeed in doing it?

(39:07) You know, theorems in physics, they're usually called "no-go" theorems. You can't do this. But they're often signposts about where you should look, because a mathematical theorem is, obviously it's true, but therefore, it comes with very strict assumptions. And so maybe you can throw out this assumption or that assumption and, and make progress on that. So it's on the mathematical side, I would love to see progress on that.

(39:28) On the experimental side, any of the things that we've spoken about — some new particle, new hints of what lies beyond. And we are seeing hints fairly regularly. The most recent one is that the mass of the *W* boson on your side of the Atlantic is different from the mass of the *W* boson on my side of the Atlantic and that, that seems weird. Hints about dark matter, or dark matter. Whatever it is, is made of quantum fields. There's no doubt about that.

(39:53) And the dark energy that you alluded to that there are predictions is too strong a word but there are suggestions from quantum field theory. at all those fluctuations of quantum fields should be driving the expansion of the universe. But in a way that's way, way bigger than we're actually seeing.

(40:07) So, so the same puzzle that's there with the Higgs. Why is the Higgs so light? It's also there with dark energy. Why is the cosmological acceleration of the universe so small compared to what we, we think it is. So it's a slightly odd situation to be in. I mean, we have this theory. It's completely amazing. But it's also clear there are things we really don't understand.

Strogatz (40:26): I just want to thank you, David Tong, for this really wide-ranging and fascinating conversation. Thanks a lot for joining me today.

Tong (40:33): My pleasure. Thanks very much.

Announcer (40:39): If you like *The Joy of Why*, check out the *Quanta Magazine Science Podcast*, hosted by me, Susan Valot, one of the producers of this show. Also tell your friends about this podcast and give us a like or follow where you listen. It helps people find *The Joy of Why* podcast.

Steve Strogatz (41:03): *The Joy of Why* is a podcast from *Quanta Magazine*, an editorially independent publication supported by the Simons Foundation. Funding decisions by the Simons Foundation have no influence on the selection of topics, guests, or other editorial decisions in this podcast or in *Quanta Magazine*. *The Joy of Why* is produced by Susan Valot and Polly Stryker. Our editors are John Rennie and Thomas Lin, with support by Matt Carlstrom, Annie Melchor and Leila Sloman. Our theme music was composed by Richie Johnson. Our logo is by Jackie King, and artwork for the episodes is by Michael Driver and Samuel Velasco. I'm your host, Steve Strogatz. If you have any questions or comments for us, please email us at quanta@simonsfoundation.org. Thanks for listening.