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(00)- What Is Spacetime Really Made Of?

Spacetime may emerge from a more fundamental reality. Figuring out how could unlock the most urgent goal in physics—a quantum theory of gravity.AUTHOR

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Adam Becker is a science writer at Lawrence Berkeley National Laboratory and author of *What Is Real?*, about the sordid untold history of quantum physics. His writing has appeared in the *New York Times,* the BBC, and elsewhere. He earned a Ph.D. in cosmology from the University of Michigan. *Credit: Nick Higgins*

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(00)- What is spacetime really made of? Spacetime can emerge from a more fundamental reality. To find out how the most pressing goal in physics - the quantum theory of gravity - could be unlocked. AUTHOR **Adam Becker** adam@freelanceastro.com is a science writer at Lawrence Berkeley National Laboratory and author of What's Real? about the dirty, untold history of quantum physics. His writings have appeared in the New York Times, the BBC and elsewhere. He received his Ph.D. in cosmology from the University of Michigan. Credit: Nick Higgins

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(01)- Natalie Paquette spends her time thinking about how to grow an extra dimension. Start with little circles, scattered across every point in space and time—a curlicue dimension, looped back onto itself. Then shrink those circles down, smaller and smaller, tightening the loop, until a curious transformation occurs: the dimension stops seeming tiny and instead becomes enormous, like when you realize something that looks small and nearby is actually huge and distant. “We’re shrinking a spatial direction,” Paquette says. “But when we try to shrink it past a certain point, a new, large spatial direction emerges instead.”

Paquette, a theoretical physicist at the University of Washington, is not alone in thinking about this strange kind of dimensional transmutation. A growing number of physicists, working in different areas of the discipline with different approaches, are increasingly converging on a profound idea: space—and perhaps even time—is not fundamental. Instead space and time may be *emergent:* they could arise from the structure and behavior of more basic components of nature. At the deepest level of reality, questions like “Where?” and “When?” simply may not have answers at all. “We have a lot of hints from physics that spacetime as we understand it isn’t the fundamental thing,” Paquette says.

These radical notions come from the latest twists in the century-long hunt for a theory of quantum gravity. Physicists’ best theory of gravity is general relativity, Albert Einstein’s famous conception of how matter warps space and time. Their best theory of everything else is quantum physics, which is astonishingly accurate when it comes to the properties of matter, energy and subatomic particles. Both theories have easily passed all the tests physicists have been able to devise for the past century. Put them together, one might think, and you would have a “theory of everything.”

But the two theories don’t play nicely. Ask general relativity what happens in the context of quantum physics, and you’ll get contradictory answers, with untamed infinities breaking loose across your calculations. Nature knows how to apply gravity in quantum contexts—it happened in the first moments of the big bang, and it still happens in the hearts of black holes—but we humans are still struggling to understand how the trick is done. Part of the problem lies in the ways the two theories deal with space and time. While quantum physics treats space and time as immutable, general relativity warps them for breakfast.
Somehow a theory of quantum gravity would need to reconcile these ideas about space and time. One way to do that would be to eliminate the problem at its source, spacetime itself, by making space and time emerge from something more fundamental. In recent years several different lines of inquiry have all suggested that, at the deepest level of reality, space and time do not exist in the same way that they do in our everyday world. Over the past decade these ideas have radically changed how physicists think about black holes. Now researchers are using these concepts to elucidate the workings of something even more exotic: wormholes—hypothetical tunnel-like connections between distant points in spacetime. These successes have kept alive the hope of an even deeper breakthrough. If spacetime is emergent, then figuring out where it comes from—and how it could arise from anything else—may just be the missing key that finally unlocks the door to a theory of everything.
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(01)- Natalie Paquette spends her time thinking about how to get another dimension. Start with small circles, scattered across each point in space and time - the dimension of a curl that returns to itself. Then make these circles smaller, smaller and smaller, tightening the loop until a strange transformation occurs: the dimension ceases to appear tiny and becomes huge instead, like when you realize that something that looks small and nearby is actually huge and far away. "We're reducing spatial direction," says **Paquette**. "But if we try to shrink it past a certain point, a new, large spatial direction appears instead." **Paquette, a theoretical physicist at the University of Washington**, is not alone in thinking about this strange kind of dimensional transmutation. A growing number of physicists working in different areas of the discipline with different approaches are getting closer to deep to the idea : space - and perhaps not even time - are not essential. In the Czech Republic, they would be persecuted with insults for such crazy ideas... Instead one can discover space and time : could arise from the structure and behavior of more basic components of nature. At the deepest level of reality, questions like "Where?" and "When?" simply may not have answers at all. "We have many indications from physics that space-time as we understand it is not a fundamental thing," On the contrary, space-time is a basic commodity. And matter is made up of 3+3 dimensions in packages. I say. https://www.hypothesis-of-universe.com/index.php?nav=aa These radical views come from the latest twists in the century-long quest for a theory of quantum gravity. The best theory of gravity physicists is the general theory of relativity, Albert Einstein's famous concept of how matter distorts space and time. Length Their best theory of everything else is quantum physics, which is surprisingly accurate, interactions are essentially linear equations, and can be constructed using a new notation technique in two-character speech, like this http://www.hypothesis-of-universe.com/docs/aa/aa_078.pdf regarding the properties of matter, energy, and subatomic particles. Both theories have easily passed all the tests that physicists have been able to devise over the past century. It could be put together, he might think, and you'd have a "theory of everything." But these two theories do not play well. Ask general relativity what's going on in the context of quantum physics and you'll get conflicting answers, unleashing untamed infinities in your calculations. Nature knows how to apply gravity in quantum contexts—it happened in the first moments of the big bang, and it's still happening in the hearts of black holes—but we humans are still struggling to understand how the trick is done. Part of the problem lies in the ways the two theories deal with space and time. While quantum physics treats space and time as immutable, general relativity distorts them for breakfast. Somehow a theory of quantum gravity would need to reconcile these notions of space and time. One way to do this would be to eliminate the problem at its source, space-time itself, by making space and time emerge from something more fundamental. In recent years, several different lines of research have all suggested that at the deepest level of reality, space and time do not exist in the same way as they do in our everyday world. Over the past decade, these ideas have radically changed the way physicists think about black holes. Now researchers are using these concepts to shed light on the workings of something even more exotic: wormholes - hypothetical tunnel connections between distant points in space-time. These successes kept alive the hope of an even deeper breakthrough. If , then figuring out where it came from—and how it could come from anything else—may just be the missing key that finally unlocks the door to a theory of everything.

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(02)- The World in a String Duet

Today the most popular candidate theory of quantum gravity among physicists is string theory. According to this idea, its eponymous strings are the fundamental constituents of matter and energy, giving rise to the myriad fundamental subatomic particles seen at particle accelerators around the world. They are even responsible for gravity—a hypothetical particle that carries the gravitational force, a "graviton," is an inevitable consequence of the theory. But string theory is difficult to understand—it lives in mathematical territory that has taken physicists and mathematicians decades to explore. Much of the theory's structure is still uncharted, expeditions still planned and maps left to be made. Within this new realm, the main technique for navigation is through mathematical dualities—correspondences between one kind of system and another.

One example is the duality from the beginning of this article, between tiny dimensions and big ones. Try to cram a dimension down into a little space, and string theory tells you that you will end up with something mathematically identical to a world where that dimension is huge instead. The two situations are the same, according to string theory—you can go back and forth from one to the other freely and use techniques from one situation to understand how the other one works. "If you carefully keep track of the fundamental building blocks of the theory," Paquette says, "you can naturally find sometimes that ... you might grow a new spatial dimension."

Credit: Elena Hartley

A similar duality suggests to many string theorists that space itself is emergent. The idea began in 1997, when Juan Maldacena, a physicist at the Institute for Advanced Study, uncovered a duality between a kind of well-understood quantum theory known as a conformal field theory (CFT) and a special kind of spacetime from general relativity known as anti–de Sitter space (AdS). The two seem to be wildly different theories—the CFT has no gravity in it whatsoever, and the AdS space has all of Einstein's theory of gravity thrown in. Yet the same mathematics can describe both worlds. When it was discovered, this AdS/CFT correspondence provided a tangible mathematical link between a quantum theory and a full universe with gravity in it.

Curiously, the AdS space in the AdS/CFT correspondence had one more dimension in it than the quantum CFT had. But physicists relished this mismatch because it was a fully worked-

out example of another kind of correspondence conceived a few years earlier, from physicists Gerard ’t Hooft of Utrecht University in the Netherlands and Leonard Susskind of Stanford University, known as the holographic principle. Based on some of the peculiar characteristics of black holes, ’t Hooft and Susskind suspected that the properties of a region of space might be fully “encoded” by its boundary. In other words, the two-dimensional surface of a black hole would contain all the information needed to know what was in its three-dimensional interior—like a hologram. “I think a lot of people thought we were nuts,” Susskind says. “Two good physicists gone bad.”
Similarly, in the AdS/CFT correspondence, the four-dimensional CFT encodes everything about the five-dimensional AdS space it is associated with. In this system, the entire region of spacetime is built out of interactions between the components of the quantum system in the conformal field theory. Maldacena likens this process to reading a novel. “If you are telling a story in a book, there are the characters in the book that are doing something,” he says. “But all there is is a line of text, right? What the characters are doing is inferred from this line of text. The characters in the book would be like the bulk [AdS] theory. And the line of text is the [CFT].”
But where does the space in the AdS space come from? If this space is emergent, what is it emerging from? The answer is a special and strangely quantum kind of interaction in the CFT: entanglement, a long-distance connection between objects, instantaneously correlating their behavior in statistically improbable ways. Entanglement famously troubled Einstein, who called it “spooky action at a distance.”
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(02)- The world in a string duet. Today, the most popular candidate theory of quantum gravity among physicists is string theory. According to this idea, its eponymous strings are the fundamental components of matter and energy that have given rise to the countless fundamental subatomic particles seen at particle accelerators around the world. They are even responsible for gravity - the hypothetical particle that carries the gravitational force, the "graviton", is an inevitable consequence of this theory. But string theory is hard to understand - it lives in mathematical territory that has taken physicists and mathematicians decades to explore. Much of the structure of the theory is still uncharted, expeditions are still planned, and maps remain to be made. In this new field, the main technique is to navigate through mathematical dualities – correspondences between one kind of system and another. One example is the duality from the beginning of this article, between small and large dimensions. Try to cram a dimension into a small space, and string theory tells you that you end up with something mathematically identical to a world where that dimension is huge instead. The two situations are the same according to string theory - you can freely go back and forth from one to the other and use techniques from one situation to understand how the other works. "If you look carefully at the basic building blocks of the theory," says Paquette, "sometimes you naturally find that... you can grow a new spatial dimension." Credit: Elena Hartley Similar duality suggests to many string theorists that space by itself arises. My idea is that the curvatures of the dimensions, which were "squished" into foam after the Big Bang, are "unwrapped" and therefore new points on the segment (whether it is 10^{27} m from us to the big-bang) do not have to "emerge", only the line stretches by unwrapping The idea began in 1997, when **Juan Maldacena**, a physicist at the Institute for Advanced Study, discovered a duality between a kind of well-understood quantum theory known as conformal field theory (CFT) and a special kind of spacetime ??? from general relativity, as anti–de Sitter space (AdS). It seems that the two theories are completely different theories - CFT has no gravity in

it and AdS space contains all of Einstein's theory of gravity. Yet the same mathematics can describe both worlds. When discovered, this AdS/CFT correspondence provided a tangible mathematical link between quantum theory and a complete universe with gravity. Curiously, the AdS space in the AdS/CFT correspondence had one more dimension in it than the quantum CFT did. Physicists relished the discrepancy, however, because it was a fully fleshed-out example of another kind of correspondence made a few years earlier by physicists **Gerard 't Hooft** of Utrecht University in the Netherlands and **Leonard Susskind** of Stanford University, known as the holographic principle. Based on some special characteristics of black holes, 't Hooft and Susskind suspected that the properties of a region of space could be fully "encoded" by its boundaries. In other words, the two-dimensional surface of a black hole would contain all the information needed to know what's in its three-dimensional interior—like a hologram. "I think a lot of people thought we were crazy," Susskind says. "Two good physicists gone wrong." Similarly, in the AdS/CFT correspondence, the four-dimensional CFT encodes everything about the five-dimensional AdS space with which it is associated. In this system, the entire region of spacetime is built from the interactions between the components of the quantum system in conformal field theory. Maldacena compares the process to reading a novel. "If you're telling a story in a book, there are characters in the book who are doing something," he says. "But it's just a line of text, right?" What the characters do is inferred from that line of text. The characters in the book would be mass theory [AdS]. And the line of text is [CFT]." But where does the space in AdS space come from? If does this space emerge, what does it emerge from? The answer is a strange and strangely quantum kind of interaction in CFT: entanglement, the connection between objects at great distances, instantly correlating their behavior in statistically implausible ways. The entanglement famously worried Einstein, who called it "spooky action at a distance."
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(03)- Will we ever know the real nature of space and time?

Yet despite its spookiness, entanglement is a core feature of quantum physics. When any two objects interact in quantum mechanics, they generally become entangled and will stay entangled so long as they remain isolated from the rest of the world—no matter how far apart they may travel. In experiments, physicists have maintained entanglement between particles more than 1,000 kilometers apart and even between particles on the ground and others sent to orbiting satellites. In principle, two entangled particles could sustain their connection on opposite sides of the galaxy or the universe. Distance simply does not seem to matter for entanglement, a puzzle that has troubled many physicists for decades.

But if space is emergent, entanglement's ability to persist over large distances might not be terribly mysterious—after all, distance is a construct. According to studies of the AdS/CFT correspondence by physicists Shinsei Ryu of Princeton University and Tadashi Takayanagi of Kyoto University, entanglement is what produces distances in the AdS space in the first place. Any two nearby regions of space on the AdS side of the duality correspond to two highly entangled quantum components of the CFT. The more entangled they are, the closer together the regions of space are.

In recent years physicists have come to suspect that this relation might apply to our universe as well. "What is it that holds the space together and keeps it from falling apart into separate subregions? The answer is the entanglement between two parts of space," Susskind says. "The continuity and the connectivity of space owes its existence to quantum-mechanical entanglement." Entanglement, then, may undergird the structure of space itself, forming the warp and weft that give rise to the geometry of the world. "If you could somehow destroy the entanglement between two parts [of space], the space would fall apart," Susskind says. "It would do the opposite of emerging. It would dis-emerge."

If space is made of entanglement, then the puzzle of quantum gravity seems much easier to solve: instead of trying to account for the warping of space in a quantum way, space itself emerges out of a fundamentally quantum phenomenon. Susskind suspects this is why a theory of quantum gravity has been so difficult to find in the first place. "I think the reason it never worked very well is because it started with a picture of two different things, [general relativity] and quantum mechanics, and put them together," he says. "And I think the point is really that they're much too closely related to pull apart and then put back together again. There's no such thing as gravity without quantum mechanics."

Yet accounting for emergent space is only half the job. With space and time so intimately linked in relativity, any account of how space emerges must also explain time. "Time must also emerge somehow," says Mark van Raamsdonk, a physicist at the University of British Columbia and a pioneer in the connection between entanglement and spacetime. "But this is not well understood and is an active area of research."

Another active area, he says, is using models of emergent spacetime to understand wormholes. Previously many physicists had believed that sending objects through a wormhole was impossible, even in theory. But in the past few years physicists working on the AdS/CFT correspondence and similar models have found new ways to construct wormholes. "We don't know if we could do that in our universe," van Raamsdonk says. "But what we now know is that certain kinds of traversable wormholes are theoretically possible." Two papers—one in 2016 and one in 2018—led to an ongoing flurry of work in the area. But even if traversable wormholes could be built, they would not be much use for space travel. As Susskind points out, "you can't go through that wormhole faster than it would take for [light] to go the long way around."

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(03)- Will we ever know the true nature of space and time? Despite its creepiness, entanglement is a fundamental feature of quantum physics. When any two objects interact in quantum mechanics, they usually become entangled and remain entangled as long as they remain isolated from the rest of the world—no matter how far apart they may travel. In experiments, physicists maintained entanglement between particles more than 1,000 kilometers apart and even between particles on the ground and other particles beamed to orbiting satellites. In principle, two entangled particles could maintain their connection on opposite sides of a galaxy or universe. Distance just doesn't seem to play a role in entanglement, a puzzle that has plagued many physicists for decades. But if space appears, the ability of entanglement to persist over great distances need not be too mysterious—after all, distance is a construct. According to studies of the AdS/CFT correspondence by physicists **Shinsei Ryu** of Princeton University and **Tadashi Takayanagi** of Kyoto University takayana@yukawa.kyoto-u.ac.jp , entanglement is what creates distances in AdS space in the first place. Any two nearby regions of space on the AdS side of the duality correspond to two highly coupled quantum components of the CFT. The more intertwined they are, the closer the regions of the universe are to each other. In recent years, physicists have come to suspect that this relationship might also apply to our universe. "What holds space together and prevents it from breaking up into separate sub-regions? The answer is an entanglement between two parts of the universe," says Susskind. "The continuity and connectivity of the universe owes its existence to quantum-mechanical entanglement." Thus, entanglement can support the structure of space itself and create the warp and weft that give rise to the geometry of the world. "If you could somehow destroy the entanglement between the two parts [of the universe], space would fall apart," says Susskind. "It would do the opposite of emergence." It would emerge." If space consists of entanglement, then it seems much easier to solve the puzzle of quantum gravity: instead of trying to explain the deformation of space in a quantum way, space itself emerges from a fundamentally quantum phenomenon. Susskind believes , that's why it was so difficult to find a theory of quantum gravity. "I think the reason it never worked well is that it started with a picture of two different things, [general relativity] and quantum mechanics, and gave they're together," he says. "And I think the point is that they're really too related to be torn apart and then put back together again. There's no such thing as gravity without quantum mechanics." However, accounting for urgent space is only half the job. Since space and time are so closely related in relativity, any account of how space comes into existence must also explain time. "Time also has to appear somehow," says **Mark van Raamsdonk**, mav@phas.ubc.ca a physicist at the University of British Columbia and a pioneer in the connection between entanglement and space-time. "But this is not well understood and is an active area of research." Another active area, he says, is using models of emerging spacetime to understand wormholes. Previously, many physicists believed that sending objects through a wormhole was impossible, even in theory. But in the last few years, physicists working on the AdS/CFT correspondence and similar models have found new ways to construct wormholes. "We don't know if we could do that in our universe," says van Raamsdonk. "However, we now know that certain kinds of traversable wormholes are theoretically possible." Two papers – one in 2016 and one in 2018 – have led to a continued flurry of work in this area. But even if passable wormholes could be built, they wouldn't be very useful for space travel. As Susskind points out, "you can't go through that wormhole any faster than it would take [light] to go a long way around."

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(04)- Space to Think

If the string theorists are correct, then space is built from quantum entanglement, and time might be as well. But what would that really mean? How can space be "made of" entanglement between objects unless those objects are themselves somewhere? How can those objects become entangled unless they experience time and change? And what kind of existence could things have without inhabiting a true space and time?

These are questions verging on philosophy—and indeed, philosophers of physics are taking them seriously. "How the hell could spacetime be the kind of thing that could be emergent?" asks **Eleanor Knox**, a philosopher of physics at King's College London. Intuitively, she says, that seems impossible. But Knox doesn't think that is a problem. "Our intuitions are terrible sometimes," she says. They "evolved on the African savanna interacting with macro objects and macro fluids and biological animals" and tend not to transfer to the world of quantum mechanics. When it comes to quantum gravity, " 'Where's the stuff?' and 'Where does it live?' aren't the right questions to be asking," Knox concludes.

It is certainly true that objects live in places in everyday life. But as Knox and many others point out, that does not mean that space and time have to be fundamental—just that they have to reliably emerge from whatever is fundamental. Consider a liquid, says Christian Wüthrich, a philosopher of physics at the University of Geneva. "Ultimately it's elementary particles, like electrons and protons and neutrons or, even more fundamental, quarks and leptons. Do quarks and leptons have liquid properties? That just doesn't make sense, right?... Nevertheless, when these fundamental particles come together in sufficient numbers and show a certain behavior together, collective behavior, then they will act in a way that is like a liquid."

Space and time, Wüthrich says, could work the same way in string theory and other theories of quantum gravity. Specifically, spacetime might emerge from the materials we usually think of as living in the universe—matter and energy itself. "It's not [that] we first have space and time and then we add in some matter," Wüthrich says. "Rather something material may be a necessary condition for there to be space and time. That's still a very close connection, but it's just the other way from what you might have thought originally."

But there are other ways to interpret the latest findings. The AdS/CFT correspondence is often seen as an example of how spacetime might emerge from a quantum system, but that might not actually be what it shows, according to **Alyssa Ney**, a philosopher of physics at the University of California, Davis. "AdS/CFT gives you this ability to provide a translation manual between facts about the spacetime and facts of the quantum theory," **Ney** says. "That's compatible with the claim that spacetime is emergent, and some quantum theory is fundamental." But the reverse is also true, she says. The correspondence could mean that quantum theory is emergent and spacetime is fundamental—or that neither is fundamental and that there is some even deeper fundamental theory out there. Emergence is a strong claim to make, Ney says, and she is open to the possibility that it is true. "But at least just looking at AdS/CFT, I'm still not seeing a clear argument for emergence."

An arguably bigger challenge to the string theory picture of emergent spacetime is hidden in plain sight, right in the name of the AdS/CFT correspondence itself. "We don't live in anti–de Sitter space," Susskind says. "We live in something much closer to de Sitter space." De Sitter space describes an accelerating and expanding universe much like our own. "We haven't got the vaguest idea how [holography] applies there," Susskind concludes. Figuring out how to set up this kind of correspondence for a space that more closely resembles the actual universe is one of the most pressing problems for string theorists. "I think we're going to be able to understand better how to get into a cosmological version of this," van Raamsdonk says.

Finally, there is the news—or lack thereof—from the latest particle accelerators, which have not found any evidence for the extra particles predicted by supersymmetry, an idea that string theory relies on. Supersymmetry dictates that all known particles would have their own "superpartners," doubling the number of fundamental particles. But CERN's Large Hadron Collider near Geneva, designed in part to search for superpartners, has seen no sign of them. "All of the really precise versions of [emergent spacetime] that we have are in supersymmetric theories," Susskind says. "Once you don't have supersymmetry, the ability to mathematically follow the equations just evaporates out of your hands."

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(04)- Space for reflection

If the string theorists are right, then space is made of quantum entanglement of what with what? and time might be too. Involved? But what would that actually mean? How can space be "created" from the entanglement between objects, if these objects themselves are nowhere? Ha-ha How can these objects become entangled unless they experience time and change? Ha-ha. And what kind of existence could things have without inhabiting actual space and time? These are questions bordering on philosophy - and philosophers of physics do take them seriously. He wants to study HDV. "How the hell could spacetime be the kind of thing that can emerge?" asks **Eleanor Knox**, eleanor.knox@kcl.ac.uk a philosopher of physics at King's College London. Intuitively, she says, it seems impossible. But Knox doesn't think that's a problem. "Our intuitions are sometimes terrible," he says. They "evolved on the

African savanna interacting with macro objects and macro fluids and biological animals" and do not tend to carry over into the world of quantum mechanics. When it comes to quantum gravity, 'Where is the stuff?' and 'Where does it live?' are not the right questions," Knox concludes. It is certainly true that objects live in places in everyday life. But as Knox and many others point out, it doesn't mean that space and time have to be fundamental - they just have to be reliably derived from whatever is fundamental. A mistake, a fundamental mistake. Take a liquid, says **Christian Wüthrich**, a philosopher of physics at the University of Geneva. : Christian.Wuthrich@unige.ch "Ultimately they are elementary particles like electrons and protons and neutrons or even more fundamental quarks and leptons. Do quarks and leptons have liquid properties? That just doesn't make sense, does it?... However, when these fundamental particles come together in sufficient numbers and exhibit a common behavior, a collective behavior, they will behave in a way that is like a liquid." Space and time, says Wüthrich, could work the same way way in string theory and other theories of quantum gravity. Specifically, space-time can emerge from the materials we usually think of as living in space—matter and energy itself. Fundamental mistake. Matter is constructed from spacetime, not the other way around. "It's not like we first have space and time and then add some matter," says Wüthrich. No, first we have spacetime and then we make matter out of it. "Something material may be more of a necessary condition for space and time to exist. That's still a very close connection, but it's just a different path than you originally thought." But there are other ways to interpret the latest findings.The AdS/CFT correspondence is often seen as an example of how spacetime might emerge from a quantum system, but according to **Alyssa Ney**, aney@ucdavis.edu a philosopher of physics at the University of California, Davis, it may not to be what it shows. "AdS/CFT gives you a translation manual between the facts of spacetime and the facts of quantum theory. This is consistent with the claim that spacetime arises and some quantum theory is essential." is true, he says. This correspondence could mean that quantum theory is emerging and spacetime is fundamental - or that neither is fundamental and that there is an even deeper fundamental theory. HDV Emergence is a strong claim, Ney says. and she is open to the possibility that it is true. "But at least looking at AdS/CFT, I still don't see a clear case for emergence. Arguably the bigger challenge to the string theory picture of emerging spacetime is hidden in plain sight, right in the name of the AdS/CFT correspondence itself. "We don't live in an anti-de Sitter space," says Susskind. "We live in something much closer to de Sitter space. De Sitter space describes an accelerating and expanding universe similar to our own. "We don't have the foggiest idea how [holography] applies there," Susskind concludes. Figuring out how to set up this kind of correspondence for a space that more closely resembles the real universe is one of the most pressing problems for string theorists. "I think we'll be able to better understand how to get into the cosmological version of this," says van Raamsdonk. Finally, there are reports—or lack thereof—from the latest particle accelerators that have found no evidence for the extra particles predicted by supersymmetry, the idea behind string theory. Supersymmetry dictates that all known particles will have their own "superpartners", doubling the number of fundamental particles. But CERN's Large Hadron Collider near Geneva, designed in part to search for superpartners, has seen no sign of them. "All the really accurate versions [of emerging spacetime] that we have are in supersymmetric theories," says Susskind. "Once you don't have supersymmetry, the ability to follow the equations mathematically just evaporates from your hands."

(05)- Atoms of Spacetime

String theory is not the only idea that suggests spacetime is emergent. String theory has "failed to live up to [its] promise as a way to unite gravity and quantum mechanics," says Abhay Ashtekar, a physicist at Pennsylvania State University. "The power of string theory now is in providing an extremely rich set of tools, which has been used widely across the whole spectrum of physics." Ashtekar is one of the original pioneers of the most popular alternative to string theory, known as loop quantum gravity. In loop quantum gravity, space and time are not smooth and continuous the way they are in general relativity—instead they are made of discrete components, what Ashtekar calls "chunks or atoms of spacetime." These atoms of spacetime are connected in a network, with one- and two-dimensional surfaces joining them together into what practitioners of loop quantum gravity call a spin foam. And despite that foam being limited to two dimensions, it gives rise to our four-dimensional world, with three dimensions of space and one of time. Ashtekar likens it to a piece of clothing. "If you look at your shirt, it looks like a two-dimensional surface," he says. "If you just take a magnifying glass, you will immediately see that it's all one-dimensional threads. It's just that those threads are so densely packed that for all practical purposes, you can think of the shirt as being a two-dimensional surface. So, similarly, the space around us looks like a three-dimensional continuum. But there is really a crisscross by these [atoms of spacetime]."

Although string theory and loop quantum gravity both suggest that spacetime is emergent, the kind of emergence is different in the two theories. String theory suggests that spacetime (or at least space) emerges from the behavior of a seemingly unrelated system, in the form of entanglement. Think of how traffic jams emerge from the collective decisions of individual drivers. The cars are not made of traffic—the cars *make* the traffic. In loop quantum gravity, on the other hand, the emergence of spacetime is more like a sloping sand dune emerging from the collective motion of sand grains in wind. The smooth familiar spacetime comes from the collective behavior of tiny "grains" of spacetime; like the dunes, the grains are still sand, even though the chunky crystalline grains do not look or act like the undulating dunes.

Despite these differences, both loop quantum gravity and string theory suggest spacetime emerges from some underlying reality. Nor are they the only proposed theories of quantum gravity that point in this direction. Causal set theory, another contender for a theory of quantum gravity, posits that space and time are made of more fundamental components as well. "It's really striking that for most of the plausible theories of quantum gravity that we have, in some sense their message is, yeah, general relativistic spacetime isn't in there at the fundamental level," Knox says. "People get very excited when different theories of quantum gravity agree on at least something."

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The Future of Space at the Edge of Time

Modern physics is a victim of its own success. Because quantum physics and general relativity are both so phenomenally accurate, quantum gravity is needed only to describe extreme situations, when enormous masses are stuffed into unfathomably tiny spaces. Those conditions exist in only a few places in nature, such as the center of a black hole—and notably not in physics laboratories, not even the largest and most powerful ones. It would take a particle accelerator the size of a galaxy to directly test the behavior of nature under conditions where quantum gravity reigns. This lack of direct experimental data is a large part of the reason why scientists' search for a theory of quantum gravity has been so long.

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(05)- Atoms of space-time.

String theory isn't the only idea that suggests spacetime is emerging. String theory "has fallen short of its promise of unifying gravity and quantum mechanics," says **Abhay Ashtekar**, a physicist at Pennsylvania State University. "The strength of string theory is now in providing an extremely rich set of tools that have been widely used across the spectrum of physics." Ashtekar is one of the original pioneers of the most popular alternative to string theory, known as loop quantum gravity. In loop quantum gravity space and time are not smooth and continuous as they are in general relativity - instead they are made of discrete componenta, and those "components" are what ? of what ? which Ashtekar calls "chunks or atoms of space-time". These space-time atoms are connected in a network, with one- and two-dimensional surfaces connecting them into what practitioners of loop quantum gravity call spin foam. Packaging dimensions of lengths and times. And although this foam is limited to two dimensions, it gives birth to our four-dimensional world with three dimensions of space and one dimension of time. The foam cp will be 3+3 dimensional and those manifestations of "quantization" are essentially those "packages" that will present themselves with their properties and behavior as elementary particles of matter. Ashtekar likens it to a piece of clothing. "When you look at your shirt, it looks like a two-dimensional surface," he says. “When you take a magnifying glass, you immediately see that these are all one-dimensional fibers. It's just that these threads are so densely packed that for all practical purposes you can think of the shirt as a two-dimensional surface. Similarly, the space around us looks like a three-dimensional continuum. But these [atoms of space-time] are indeed crossed.” Although string theory and loop quantum gravity suggest that space-time emerges, the kind of emergence differs in the two theories. String theory indicates, every theory suggests something, that is not the prerogative of string theory, and certainly not the invention with strings from Nothing. That space-time (or at least space) arises from the behavior of a seemingly unrelated system in the form of entanglement. Nonsense. Think about how traffic jams arise from the collective decisions of individual drivers. Cars are not made from traffic - cars create traffic. And therefore space-time is not created-made from some "entanglement" (particles of matter), but on the contrary: matter is made by "entanglement" of space-time dimensions. In loop quantum gravity, on the other hand, the genesis of spacetime is more like a sloping sand dune emerging from the collective movement of grains of sand in the wind. Nonsense. The smooth known space-time comes from the collective behavior of tiny "grains" of space-time these are wrongly formulated concepts. Of course, a smooth sea surface seen from an airplane as smooth is a strongly undulating view from near the surface. Smoothness does not "come" from grains...!! Why should she? what is this nonsense?! http://www.hypothesis-of-universe.com/docs/c/c_425.jpg ; http://www.hypothesis-of-universe.com/docs/c/c_418.jpg ; http://www.hypothesis-of-universe.com/docs/c/c_411.jpg ; http://www.hypothesis-of-universe.com/docs/c/c_171.jpg like dunes, the grains are still sand, although the massive crystalline grains do not look or behave like rolling dunes. Despite these differences, both loop quantum gravity and string theory suggest that spacetime emerges from some underlying reality. This is a faulty reasoning, rather nonsense. Because, on the other hand, space-time is the basic reality and it is subsequently realized = matter is created. Nor are these the only proposed theories of quantum gravity that point in this direction. Causal set theory, another contender for the theory of quantum gravity, assumes that space and time are also composed of basic components. Which ones, do you think? "It's really striking that for most of the plausible theories of quantum gravity that we have, in some sense their message is, yes, general relativistic spacetime is not there at the fundamental level," says **Knox**. "People get very excited when the different theories of quantum gravity agree on something." The future of the universe at the edge of time Modern physics is a victim of its own success. Because quantum physics and general relativity are so phenomenally accurate, quantum gravity is only needed to describe extreme situations where huge masses are crammed into incredibly small spaces. These conditions exist only in a few places in nature, such as the center of a black hole - and especially not in physics laboratories, even the largest and most powerful ones. A galaxy-sized particle accelerator would be needed to directly test the behavior of nature under conditions where quantum gravity rules. This lack of direct experimental data is a large part of the reason scientists have sought a theory of quantum gravity for so long.

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(06)- Faced with the lack of evidence, most physicists have pinned their hopes on the sky. In the earliest moments of the big bang, the entire universe was phenomenally small and dense—a situation that calls for quantum gravity to describe it. And echoes of that era may remain in the sky today. “I think our best bet [for testing quantum gravity] is through cosmology,” Maldacena says. “Maybe something in cosmology that we now think is unpredictable, that maybe can be predicted once we understand the full theory, or some new thing that we didn’t even think about.”

Laboratory experiments may come in handy, however, for testing string theory, at least indirectly. Scientists hope to study the AdS/CFT correspondence not by probing spacetime but by building highly entangled systems of atoms and seeing whether an analogue to spacetime and gravity shows up in their behavior. Such experiments might “have some features of gravity, though, perhaps not all the features,” Maldacena says. “It also depends on exactly what you call gravity.”

Will we ever know the real nature of space and time? The observational data from the skies may not be forthcoming any time soon. The lab experiments could be a bust. And as philosophers know well, questions about the true nature of space and time are very old indeed. What exists “is now all together, one, continuous,” said the philosopher Parmenides 2,500 years ago. “All is full of what is.” Parmenides insisted that time and change were illusions, that everything everywhere was one and the same. His pupil Zeno created famous paradoxes to prove his teacher’s point, purporting to show that motion over any distance was impossible. Their work raised the question of whether time and space are somehow illusory, an unsettling prospect that has haunted Western philosophy for over two millennia.

“The fact that the ancient Greeks asked things like, ‘What is space?’ ‘What is time?’ ‘What is change?’ and that we still ask versions of these questions today means that they were the right questions to ask,” Wüthrich says. “It’s by thinking about these kinds of questions that we have learned a lot about physics.”

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(06)- Faced with a lack of evidence, most physicists are pinning their hopes on the sky. In the earliest moments of the big bang, the entire universe was phenomenally small and dense—a situation that requires quantum gravity to describe. And the echoes of that time can remain in the sky even today. "I think our best solution [to test quantum gravity] is through cosmology," says Maldacena. "Maybe something in cosmology that we now think is unpredictable that maybe can be predicted once we understand the whole theory, or some new thing that we haven't even thought about." However, laboratory experiments can be useful for testing string theory, at least indirectly. The researchers hope to study the AdS/CFT correspondence not by probing through space-time, but by building highly entangled systems of atoms and seeing if their behavior shows analogies between space-time and gravity. Such experiments may have "some features of gravity, but maybe not all," says Maldacena. “It also depends on what exactly you mean by gravity. Will we ever know the true nature of space and time? Maybe not, but I have shown physicists another new stage of knowledge in HDV. Sky observation data may not be available anytime soon. Laboratory experiments could fail. And as philosophers well know, questions about the true nature of space and time are very old indeed. That which exists "is now all together, one, continuous," said the philosopher Parmenides 2,500 years ago. "Everything is full of what it is." Parmenides insisted that time and change are illusions, that everything everywhere is one and the same. His pupil Zeno created the famous paradoxes to prove his teacher's point and wanted to show that motion over any distance was impossible. Their work raised the question of whether time and space are somehow illusory, a troubling prospect that has haunted Western philosophy for more than two millennia. "The fact that the ancient Greeks asked things like, 'What is space?', 'What is change?' says **Wüthrich**. "We've learned a lot about physics by thinking about these types of questions."

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