NATURE | NEWS FEATURE

The quantum source of space-time

Many physicists believe that entanglement is the essence of quantum weirdness — and some now suspect that it may also be the essence of space-time geometry.

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Warner Bros. Entertainment/Paramount Pictures

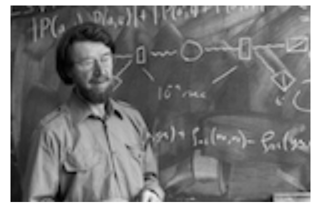
Black holes such as the one depicted in *Interstellar* (2014) can be connected by wormholes, which might have quantum origins.

In early 2009, determined to make the most of his first sabbatical from teaching, Mark Van Raamsdonk decided to tackle one of the deepest mysteries in physics: the relationship between quantum mechanics and gravity. After a year of work and consultation with colleagues, he submitted a paper on the topic to the *Journal of High Energy Physics*.

In April 2010, the journal sent him a rejection — with a referee's report implying that Van Raamsdonk, a physicist at the University of British Columbia in Vancouver, was a crackpot.

His next submission, to *General Relativity and Gravitation*, fared little better: the referee's report was scathing, and the journal's editor asked for a complete rewrite.

But by then, Van Raamsdonk had entered a shorter version of the paper into a prestigious annual essay contest run by the Gravity Research Foundation in Wellesley, Massachusetts. Not only did he win first prize, but he also got to savour a particularly satisfying irony: the honour included guaranteed publication in *General Relativity and Gravitation*. The journal published the shorter essay[1] in June 2010.



Quantum 'spookiness' passes toughest test yet

Still, the editors had good reason to be cautious. A successful unification of quantum mechanics and gravity has eluded physicists for nearly a century. Quantum mechanics governs the world of the small — the weird realm in which an atom or particle can be in many places at the same time, and can simultaneously spin both clockwise and anticlockwise. Gravity governs the Universe at large — from the fall of an apple to the motion of planets, stars and galaxies — and is described by Albert Einstein's general theory of relativity, announced 100 years ago this month. The theory holds that gravity is geometry: particles are deflected when they pass near a massive object not because they feel a force, said Einstein, but because space and time around the object are curved.

Both theories have been abundantly verified through experiment, yet the realities they describe seem utterly incompatible. And from the editors' standpoint, Van Raamsdonk's approach to resolving this incompatibility was strange. All that's needed, he asserted, is 'entanglement': the phenomenon that many physicists believe to be the ultimate in quantum weirdness. Entanglement lets the measurement of one particle instantaneously determine the state of a partner particle, no matter how far away it may be — even on the other side of the Milky Way.

Einstein loathed the idea of entanglement, and famously derided it as "spooky action at a distance". But it is central to quantum theory. And Van Raamsdonk, drawing on work by like-minded physicists going back more than a decade, argued for the ultimate irony — that, despite Einstein's objections, entanglement might be the basis of geometry, and thus of Einstein's geometric theory of gravity. "Space-time," he says, "is just a geometrical picture of how stuff in the quantum system is entangled."

"I had understood something that no one had understood before."

This idea is a long way from being proved, and is hardly a complete theory of quantum gravity. But independent studies have reached much the same conclusion, drawing intense interest from major theorists. A small industry of physicists is now working to expand the geometry–entanglement relationship, using all the modern tools developed for quantum computing and quantum information theory.

"I would not hesitate for a minute," says physicist Bartłomiej Czech of Stanford University in California, "to call the connections between quantum theory and gravity that have emerged in the last ten years revolutionary."


Einstein was no lone genius

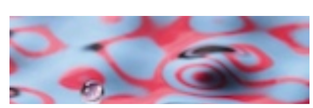
Gravity without gravity

Much of this work rests on a discovery[2] announced in 1997 by physicist Juan Maldacena, now at the Institute for Advanced Study in Princeton, New Jersey. Maldacena's research had led him to consider the relationship between two seemingly different model universes. One is a cosmos similar to our own. Although it neither expands nor contracts, it has three dimensions, is filled with quantum particles and obeys Einstein's equations of gravity. Known as anti-de Sitter space (AdS), it is commonly referred to as the bulk. The other model is also filled with elementary particles, but it has one dimension fewer and doesn't recognize gravity. Commonly known as the boundary, it is a mathematically defined membrane that lies an infinite distance from any given point in the bulk, yet completely encloses it, much like the 2D surface of a balloon enclosing a 3D volume of air. The boundary particles obey the equations of a quantum system known as conformal field theory (CFT).

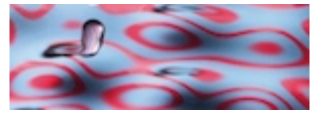
Maldacena discovered that the boundary and the bulk are completely equivalent. Like the 2D circuitry of a computer chip that encodes the 3D imagery of a computer game, the relatively simple, gravity-free equations that prevail on the boundary contain the same information and describe the same physics as the more complex equations that rule the bulk.

"It's kind of a miraculous thing," says Van Raamsdonk. Suddenly, he says, Maldacena's duality gave physicists a way to think about quantum gravity in the bulk without thinking about gravity at all: they just had to look at the equivalent quantum state on the boundary. And in the years since, so many have rushed to explore this idea that Maldacena's paper is now one of the most highly cited articles in physics.

Among the enthusiasts was Van Raamsdonk, who started his sabbatical by



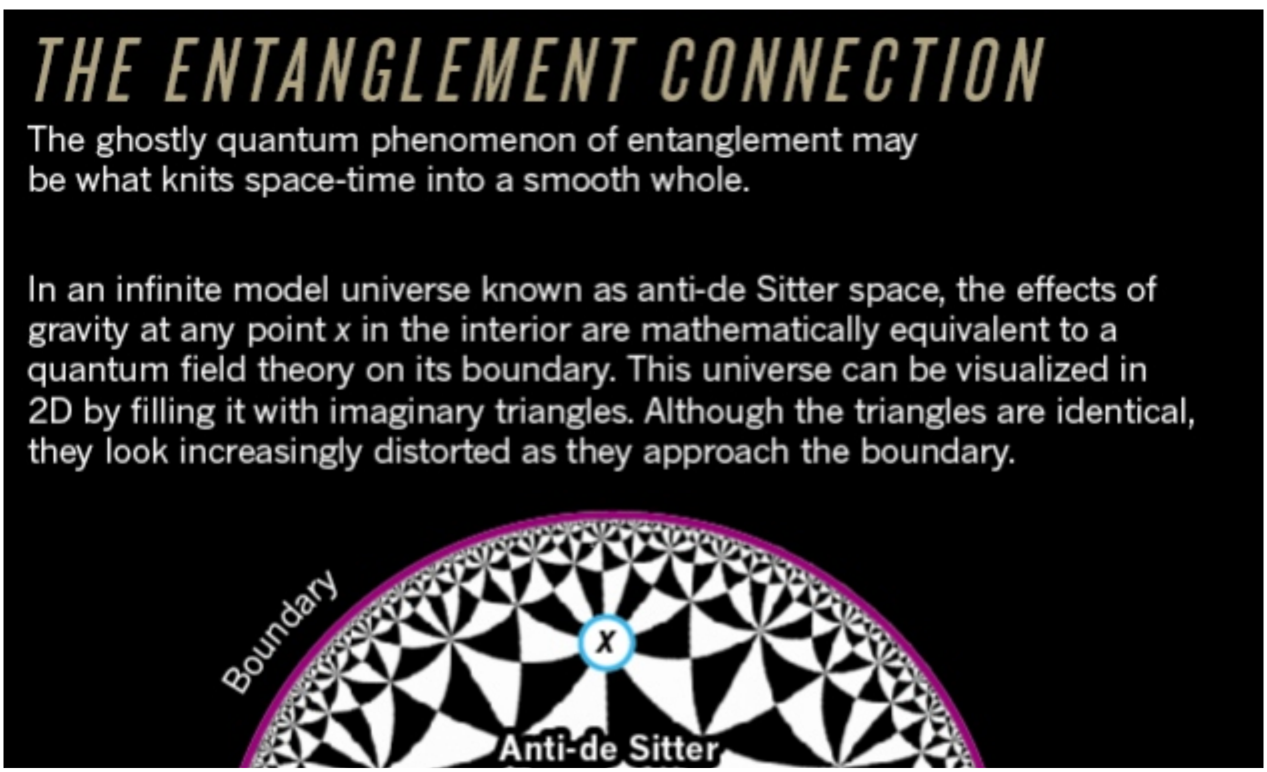
pondering one of the central unsolved questions posed by Maldacena's discovery: exactly how does a quantum field on the boundary produce gravity in the bulk? There had already been hints[3] that the answer might involve some sort of relation between geometry and entanglement. But it was unclear how significant these hints were: all the earlier work on this idea had dealt with special cases, such as a bulk universe that contained a black hole. So Van Raamsdonk decided to settle the matter, and work out whether the relationship was true in general, or was just a mathematical oddity.

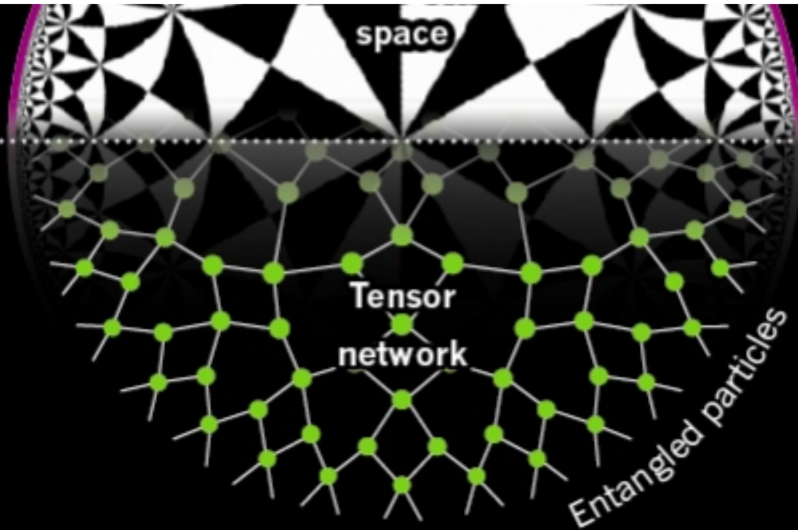


Quantum weirdness: What's really real?

He first considered an empty bulk universe, which corresponded to a single quantum field on the boundary. This field, and the quantum relationships that tied various parts of it together, contained the only entanglement in the system. But now, Van Raamsdonk wondered, what would happen to the bulk universe if that boundary entanglement were removed?

He was able to answer that question using mathematical tools[4] introduced in 2006 by Shinsei Ryu, now at the University of Illinois at Urbana–Champaign, and Tadashi Takanagi, now at the Yukawa Institute for Theoretical Physics at Kyoto University in Japan. Their equations allowed him to model a slow and methodical reduction in the boundary field's entanglement, and to watch the response in the bulk, where he saw space-time steadily elongating and pulling apart (see 'The entanglement connection'). Ultimately, he found, reducing the entanglement to zero would break the space-time into disjointed chunks, like chewing gum stretched too far.



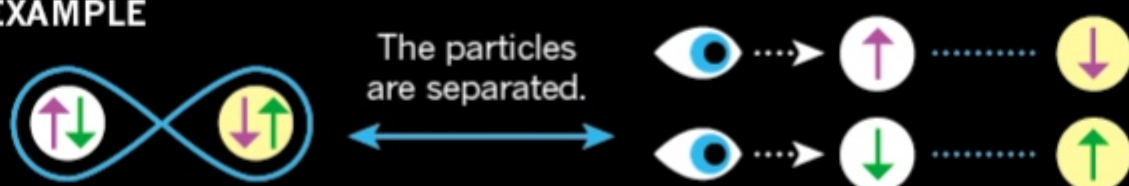


Physicists noticed that this pattern resembled diagrams called tensor networks, which were invented to show connections between quantum particles on a massive scale. These connections are known as quantum entanglement.

What is quantum entanglement?

In 1935, Albert Einstein, Boris Podolsky and Nathan Rosen (EPR) pointed out that a connection can exist between widely separated quantum systems: a measurement of one will determine the state of the other.

EXAMPLE

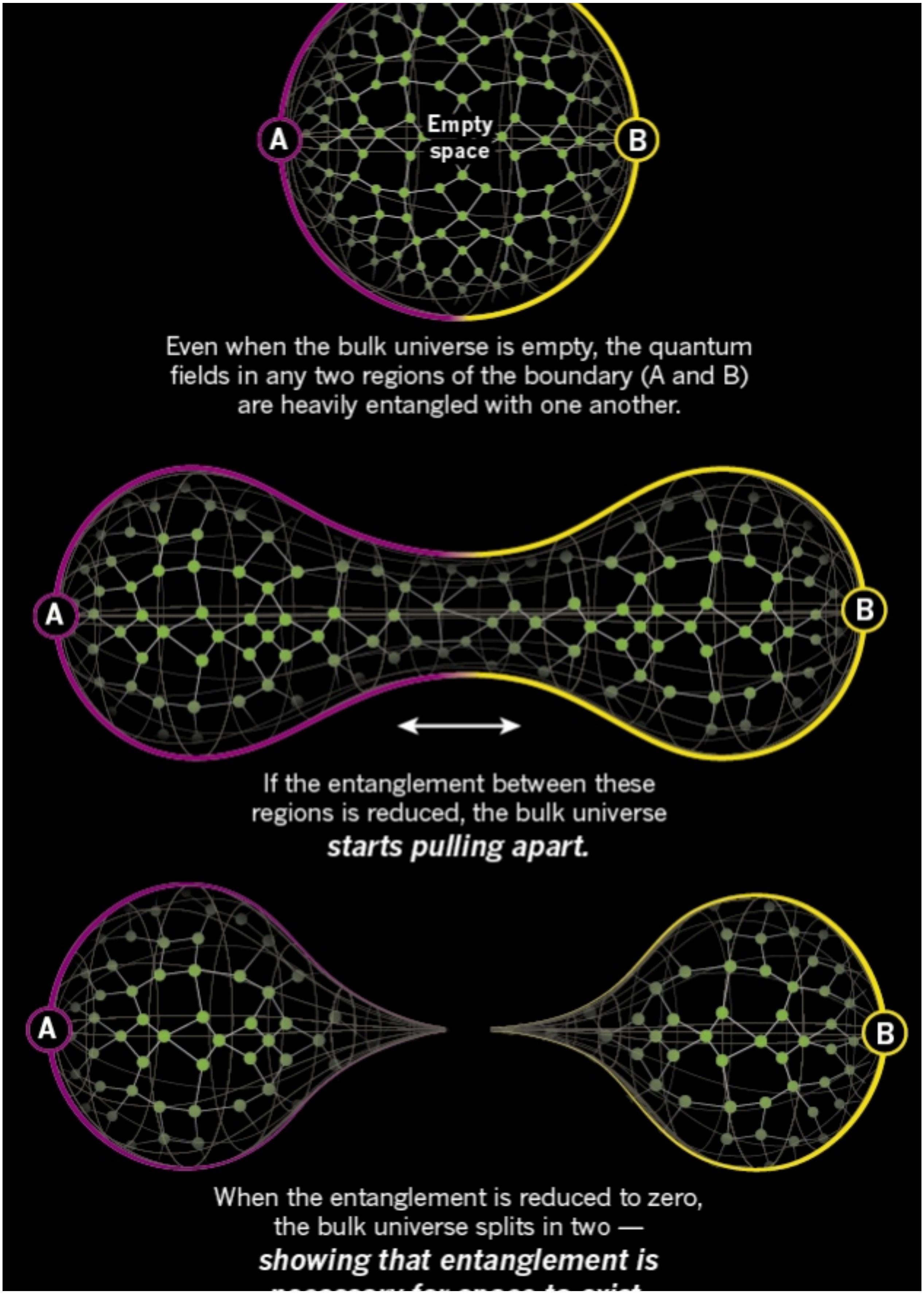


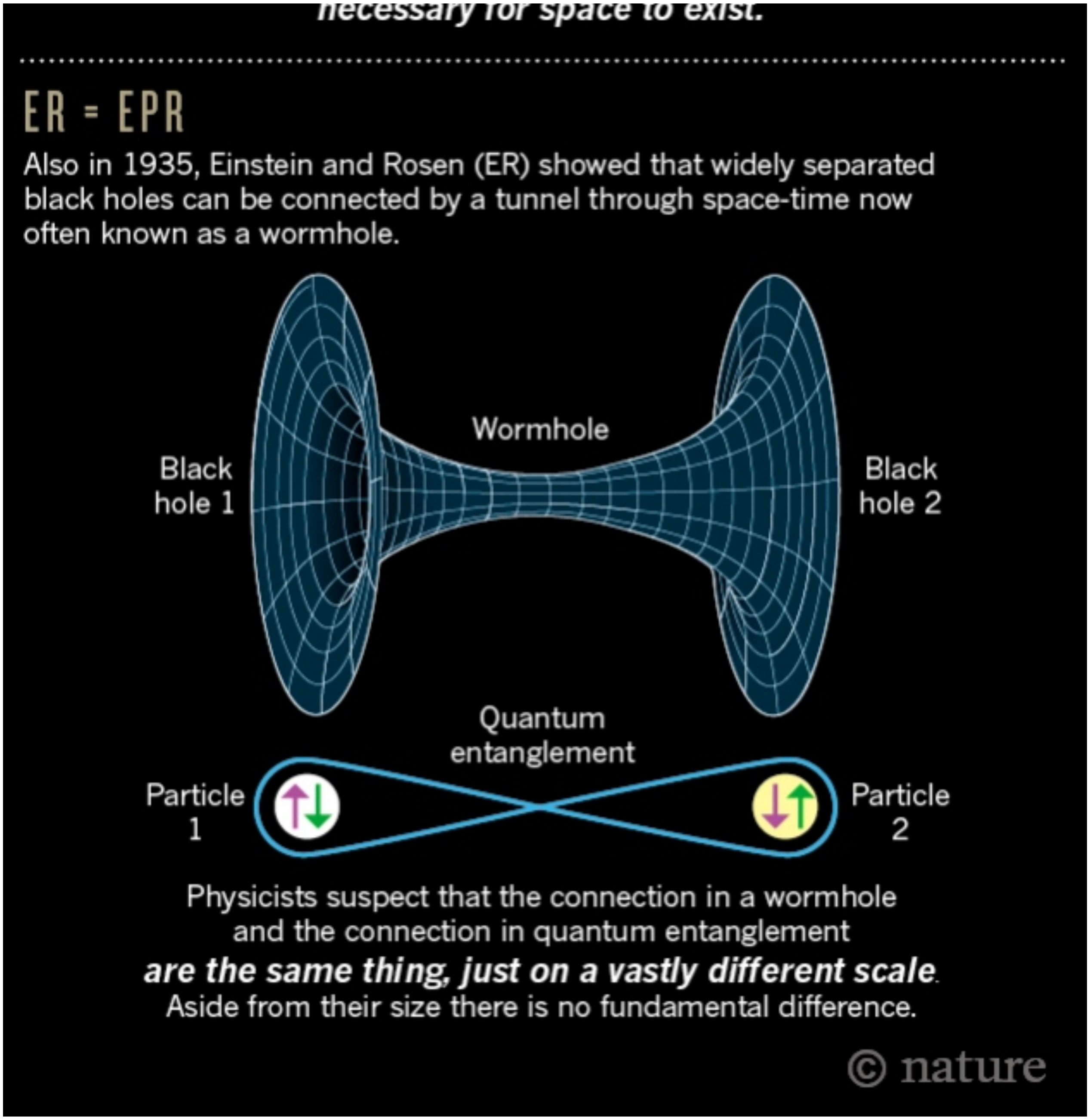
Entangled spins: if one particle is spinning up, the other spins down, and vice versa.

Observation of one particle instantaneously reveals the state of the other.

DISENTANGLEMENT

The bulk–boundary correspondence implies that space on the inside is built from quantum entanglement around the outside.


A
Empty space
B
Even when the bulk universe is empty, the quantum fields in any two regions of the boundary (A and B) are heavily entangled with one another.
A
B
If the entanglement between these regions is reduced, the bulk universe *starts pulling apart.*
A
B
When the entanglement is reduced to zero, the bulk universe splits in two —
showing that entanglement is

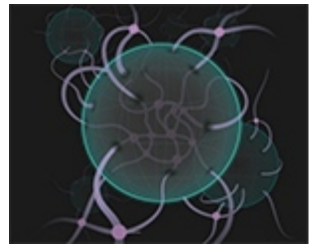


NIK SPENCER/NATURE

The geometry–entanglement relationship was general, Van Raamsdonk realized. Entanglement is the essential ingredient that knits space-time together into a smooth whole — not just in exotic cases with black holes, but always.

“I felt that I had understood something about a fundamental question that perhaps nobody had understood before,” he recalls: “Essentially, what is space-time?”

Entanglement and Einstein



The origins of space and time

Quantum entanglement as geometric glue — this was the essence of Van Raamsdonk's rejected paper and winning essay, and an idea that has increasingly resonated among physicists. No one has yet found a rigorous proof, so the idea still ranks as a conjecture. But many independent lines of reasoning support it.

In 2013, for example, Maldacena and Leonard Susskind of Stanford published[5] a related conjecture that they dubbed ER = EPR, in honour of two landmark papers from 1935. ER, by Einstein and American-Israeli physicist Nathan Rosen, introduced[6] what is now called a wormhole: a tunnel through space-time connecting two black holes. (No real particle could actually travel through such a wormhole, science-fiction films notwithstanding: that would require moving faster than light, which is impossible.) EPR, by Einstein, Rosen and American physicist Boris Podolsky, was the first paper to clearly articulate what is now called entanglement[7].

Maldacena and Susskind's conjecture was that these two concepts are related by more than a common publication date. If any two particles are connected by entanglement, the physicists suggested, then they are effectively joined by a wormhole. And vice versa: the connection that physicists call a wormhole is equivalent to entanglement. They are different ways of describing the same underlying reality.

No one has a clear idea of what this underlying reality is. But physicists are increasingly convinced that it must exist. Maldacena, Susskind and others have been testing the ER = EPR hypothesis to see if it is mathematically consistent with everything else that is known about entanglement and wormholes — and so far, the answer is yes.

Hidden connections

Theoretical physics: Complexity on the horizon

Other lines of support for the geometry–entanglement relationship have come from condensed-matter physics and quantum information theory: fields in which entanglement already plays a central part. This has allowed researchers from these disciplines to attack quantum gravity with a whole array of fresh concepts and mathematical tools.

Tensor networks, for example, are a technique developed by condensed-matter physicists to track the quantum states of huge numbers of subatomic particles. Brian Swingle was using them in this way in 2007, when he was a graduate student at the Massachusetts Institute of Technology (MIT) in Cambridge, calculating how groups of electrons interact in a solid material. He found that the most useful network for this purpose started by linking adjacent pairs of electrons, which are most likely to interact with each other, then linking larger and larger groups in a pattern that resembled the hierarchy of a family tree. But then, during a course in quantum field theory, Swingle learned about Maldacena's bulk–boundary correspondence and noticed an intriguing pattern: the mapping between the bulk and the boundary showed exactly the same tree-like network.

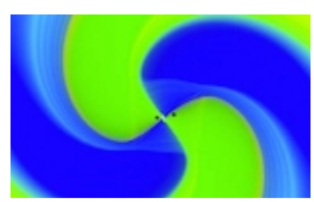
"You can think of space as being built from entanglement."

Swingle wondered whether this resemblance might be more than just coincidence. And in 2012, he published[8] calculations showing that it was: he had independently reached much the same conclusion as Van Raamsdonk, thereby adding strong support to the geometry–entanglement idea. "You can think of space as being built from entanglement in this very precise way using the tensors," says Swingle, who is now at Stanford and has seen tensor networks become a frequently used tool to explore the geometry–entanglement correspondence.

Another prime example of cross-fertilization is the theory of quantum error-correcting codes, which physicists invented to aid the construction of quantum computers. These machines encode information not in bits but in 'qubits': quantum states, such as the up or down spin of an electron, that can take on values of 1 and 0 simultaneously. In principle, when the qubits interact and become entangled in the right way, such a device could perform calculations that an ordinary computer could not finish in the lifetime of the Universe. But in practice, the process can be incredibly fragile: the slightest disturbance from the outside world will disrupt the qubits' delicate entanglement and destroy any possibility of quantum computation.

That need inspired quantum error-correcting codes, numerical strategies that repair corrupted correlations between the qubits and make the computation more robust. One hallmark of these codes is that they are always 'non-local': the information needed to restore any given qubit has to be spread out over a wide region of space. Otherwise, damage in a single spot could destroy any hope of recovery. And that non-locality, in turn, accounts for the fascination that many quantum information theorists feel when they first encounter Maldacena's bulk–boundary correspondence: it shows a very similar kind of non-locality. The information that corresponds to a small region of the bulk is spread over a vast region of the boundary.

"Anyone could look at AdS–CFT and say that it's sort of vaguely analogous to a quantum error-correcting code," says Scott Aaronson, a computer scientist at MIT. But in work published in June[9], physicists led by Daniel Harlow at Harvard



University in Cambridge and John Preskill of the California Institute of Technology in Pasadena argue for something stronger: that the Maldacena duality is itself a quantum error-correcting code. They have demonstrated that this is mathematically correct in a simple model, and are now trying to show that the assertion holds more generally.

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“People have been saying for years that entanglement is somehow important for the emergence of the bulk,” says Harlow. “But for the first time, I think we are really getting a glimpse of how and why.”

Beyond entanglement

That prospect seems to be enticing for the Simons Foundation, a philanthropic organization in New York City that announced in August that it would provide US$2.5 million per year for at least 4 years to help researchers to move forward on the gravity–quantum information connection. “Information theory provides a powerful way to structure our thinking about fundamental physics,” says Patrick Hayden, the Stanford physicist who is directing the programme. He adds that the Simons sponsorship will support 16 main researchers at 14 institutions worldwide, along with students, postdocs and a series of workshops and schools. Ultimately, one major goal is to build up a comprehensive dictionary for translating geometric concepts into quantum language, and vice versa. This will hopefully help physicists to find their way to the complete theory of quantum gravity.

Still, researchers face several challenges. One is that the bulk–boundary correspondence does not apply in our Universe, which is neither static nor bounded; it is expanding and apparently infinite. Most researchers in the field do think that calculations using Maldacena’s correspondence are telling them something true about the real Universe, but there is little agreement as yet on exactly how to translate results from one regime to the other.

Another challenge is that the standard definition of entanglement refers to particles only at a given moment. A complete theory of quantum gravity will have to add time to that picture. “Entanglement is a big piece of the story, but it’s not the whole story,” says Susskind.

He thinks physicists may have to embrace another concept from quantum information theory: computational complexity, the number of logical steps, or operations, needed to construct the quantum state of a system. A system with low complexity is analogous to a quantum computer with almost all the qubits on zero: it is easy to define and to build. One with high complexity is analogous to a set of qubits encoding a number that would take aeons to compute.

Susskind's road to computational complexity began about a decade ago, when he noticed that a solution to Einstein's equations of general relativity allowed a wormhole in AdS space to get longer and longer as time went on. What did that correspond to on the boundary, he wondered? What was changing there? Susskind knew that it couldn't be entanglement, because the correlations that produce entanglement between different particles on the boundary reach their maximum in less than a second[10]. In an article last year[11], however, he and Douglas Stanford, now at the Institute for Advanced Study, showed that as time progressed, the quantum state on the boundary would vary in exactly the way expected from computational complexity.

Quantum quest: Reinventing quantum theory

"It appears more and more that the growth of the interior of a black hole is exactly the growth of computational complexity," says Susskind. If quantum entanglement knits together pieces of space, he says, then computational complexity may drive the growth of space — and thus bring in the elusive element of time. One potential consequence, which he is just beginning to explore, could be a link between the growth of computational complexity and the expansion of the Universe. Another is that, because the insides of black holes are the very regions where quantum gravity is thought to dominate, computational complexity may have a key role in a complete theory of quantum gravity.

Despite the remaining challenges, there is a sense among the practitioners of this field that they have begun to glimpse something real and very important. "I didn't know what space was made of before," says Swingle. "It wasn't clear that question even had meaning." But now, he says, it is becoming increasingly apparent that the question does make sense. "And the answer is something that we understand," says Swingle. "It's made of entanglement."

As for Van Raamsdonk, he has written some 20 papers on quantum entanglement since 2009. All of them, he says, have been accepted for publication.

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Corrections

Corrected: The original text of this article stated that Leonard Susskind began to think about computational complexity about a decade ago. In fact it was closer to three years ago. The text has been corrected to reflect that.

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