THE ORIGINS OF SPACE AND TIME

BY ZEEYA MERALI

Many researchers believe that physics will not be complete until it can explain not just the behaviour of space and time, but where these entities come from.

"Imagine waking up one day and realizing that you actually live inside a computer game," says Mark Van Raamsdonk, describing what sounds like a pitch for a science-fiction film. But for Van Raamsdonk, a physicist at the University of British Columbia in Vancouver, Canada, this scenario is a way to think about reality. If it is true, he says, "everything around us — the whole three-dimensional physical world — is an illusion born from information encoded elsewhere, on a two-dimensional chip". That would make our Universe, with its three spatial dimensions, a kind of hologram, projected from a substrate that exists only in lower dimensions.

This 'holographic principle' is strange even by the usual standards of theoretical physics. But Van Raamsdonk is one of a small band of researchers who think that the usual ideas are not yet strange enough. If nothing else, they say, neither of the two great pillars of modern

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physics — general relativity, which describes gravity as a curvature of space and time, and quantum mechanics, which governs the atomic realm — gives any account for the existence of space and time. Neither does string theory, which describes elementary threads of energy.

Van Raamsdonk and his colleagues are convinced that physics will not be complete until it can explain how space and time emerge from something more fundamental — a project that will require concepts at least as audacious as holography. They argue that such a radical reconceptualization of reality is the only way to explain what happens when the infinitely dense 'singularity' at the core of a black hole distorts the fabric of space-time beyond all recognition, or how researchers can unify atomic-level quantum theory and planet-level general relativity — a project that has resisted theorists' efforts for generations.

"All our experiences tell us we shouldn't have two dramatically different conceptions of reality — there must be one huge overarching theory," says Abhay Ashtekar, a physicist at Pennsylvania State University in University Park.

Finding that one huge theory is a daunting challenge. Here, *Nature* explores some promising lines of attack — as well as some of the emerging ideas about how to test these concepts (see 'The fabric of reality').

GRAVITY AS THERMODYNAMICS

One of the most obvious questions to ask is whether this endeavour is a fool's errand. Where is the evidence that there actually is anything more fundamental than space and time?

A provocative hint comes from a series of startling discoveries made in the early 1970s, when it became clear that quantum mechanics and gravity were intimately intertwined with thermodynamics, the science of heat.

In 1974, most famously, Stephen Hawking of the University of Cambridge, UK, showed that quantum effects in the space around a black hole will cause it to spew out radiation as if it was hot. Other physicists quickly determined that this phenomenon was quite general. Even in completely empty space, they found, an astronaut undergoing acceleration would perceive that he or she was surrounded by a heat bath. The effect would be too small to be perceptible for any acceleration achievable by rockets, but it seemed to be fundamental. If quantum theory and general relativity are correct — and both have been abundantly corroborated by experiment — then the existence of Hawking radiation seemed inescapable.

A second key discovery was closely related. In standard thermodynamics, an object can radiate heat only by decreasing its entropy, a measure of the number of quantum states inside it. And so it is with black holes: even before Hawking's 1974 paper, Jacob Bekenstein, now at the Hebrew University of Jerusalem, had shown that black holes possess entropy. But there was a difference. In most objects, the entropy is proportional to the number of atoms the object contains, and thus to its volume. But a black hole's entropy turned out to be proportional to the surface area of its event horizon — the boundary out of which not even light can escape. It was as if that surface somehow encoded information about what was inside, just as a two-dimensional hologram encodes a three-dimensional image.

In 1995, Ted Jacobson, a physicist at the University of Maryland in College Park, combined these two findings, and postulated that every point in space lies on a tiny 'black-hole horizon' that also obeys the entropy–area relationship. From that, he found, the mathematics yielded Einstein's equations of general relativity — but using only thermodynamic concepts, not the idea of bending space-time[1].

"This seemed to say something deep about the origins of gravity," says Jacobson. In particular, the laws of thermodynamics are statistical in nature — a macroscopic average over the motions of myriad atoms and molecules — so his result suggested that gravity is also statistical, a macroscopic approximation to the unseen constituents of space and time.

In 2010, this idea was taken a step further by Erik Verlinde, a string theorist at the University of Amsterdam, who showed[2] that the statistical thermodynamics of the space-time constituents — whatever they turned out to be — could automatically generate Newton's law of gravitational attraction.

And in separate work, Thanu Padmanabhan, a cosmologist at the Inter-University Centre for Astronomy and Astrophysics in Pune, India, showed[3] that Einstein's equations can be rewritten in a form that makes them identical to the laws of thermodynamics — as can many alternative theories of gravity. Padmanabhan is currently extending the thermodynamic approach in an effort to explain the origin and magnitude of dark energy: a mysterious cosmic force that is accelerating the Universe's expansion.

Testing such ideas empirically will be extremely difficult. In the same way that water looks perfectly smooth and fluid until it is observed on the scale of its molecules — a fraction of a nanometre — estimates suggest that space-time will look continuous all the way down to the Planck scale: roughly 10^{-35} metres, or some 20 orders of magnitude smaller than a proton.

But it may not be impossible. One often-mentioned way to test whether space-time is made of discrete constituents is to look for delays as high-energy photons travel to Earth from distant cosmic events such as supernovae and γ-ray bursts. In effect, the shortest-wavelength photons would sense the discreteness as a subtle bumpiness in the road they had to travel, which would slow them down ever so slightly. Giovanni Amelino-Camelia, a quantum-gravity researcher at the University of Rome, and his colleagues have found[4] hints of just such delays in the photons from a γ-ray burst recorded in April. The results are not definitive, says Amelino-Camelia, but the group plans to expand its search to look at the travel times of high-energy neutrinos produced by cosmic events. He says that if theories cannot be tested, "then to me, they are not science. They are just religious beliefs, and they hold no interest for me."

Other physicists are looking at laboratory tests. In 2012, for example, researchers from the University of Vienna and Imperial College London proposed[5] a tabletop experiment in which a microscopic mirror would be moved around with lasers. They argued that Planck-scale granularities in space-time would produce detectable changes in the light reflected from the mirror (see *Nature* http://doi.org/njf; 2012).

LOOP QUANTUM GRAVITY

Even if it is correct, the thermodynamic approach says nothing about what the fundamental constituents of space and time might be. If space-time is a fabric, so to speak, then what are its threads?

One possible answer is quite literal. The theory of loop quantum gravity, which has been under development since the mid-1980s by Ashtekar and others, describes the fabric of space-time as an evolving spider's web of strands that carry information about the quantized areas and volumes of the regions they pass through[6]. The individual strands of the web must eventually join their ends to form loops — hence the theory's name — but have nothing to do with the much better-known strings of string theory. The latter move around in space-time, whereas strands actually are space-time: the information they carry defines the shape of the space-time fabric in their vicinity.

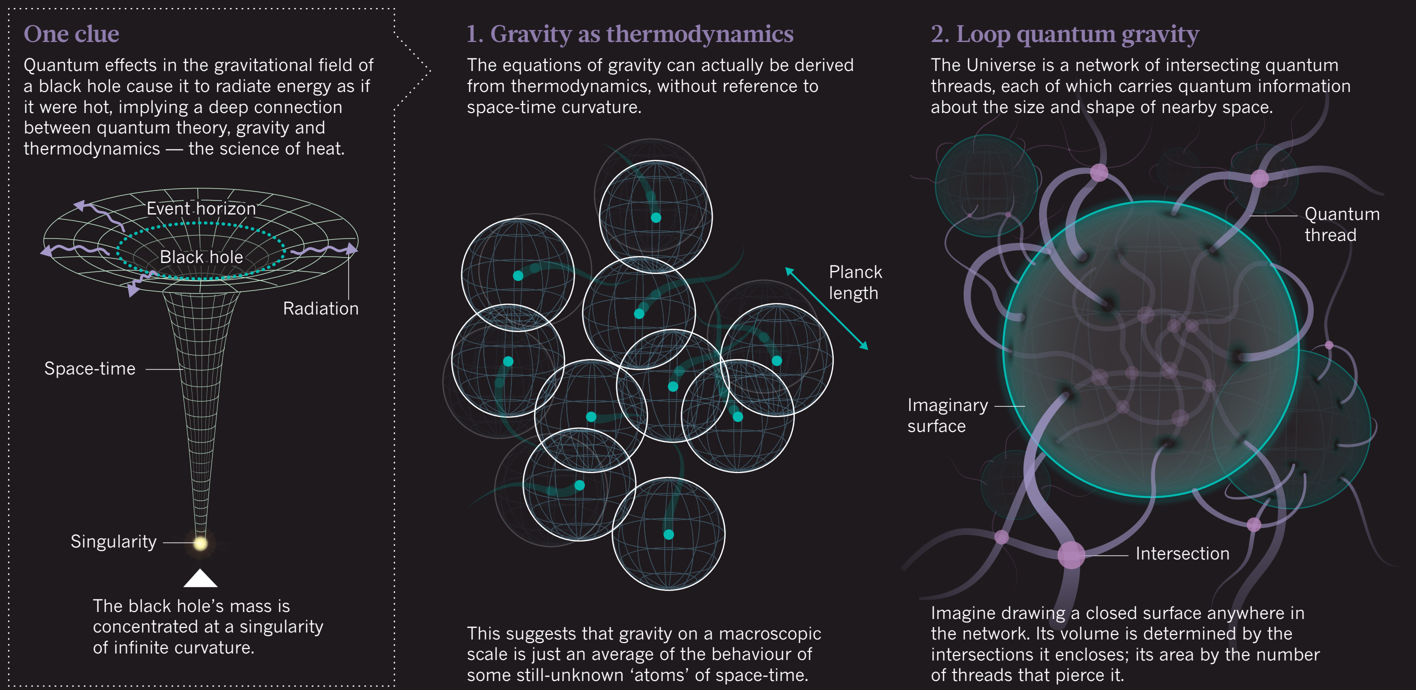
Because the loops are quantum objects, however, they also define a minimum unit of area in much the same way that ordinary quantum mechanics defines a minimum ground-state energy for an electron in a hydrogen atom. This quantum of area is a patch roughly one Planck scale on a side. Try to insert an extra strand that carries less area, and it will simply disconnect from the rest of the web. It will not be able to link to anything else, and will effectively drop out of space-time.

One welcome consequence of a minimum area is that loop quantum gravity cannot squeeze an infinite amount of curvature onto an infinitesimal point. This means that it cannot produce the kind of singularities that cause Einstein's equations of general relativity to break down at the instant of the Big Bang and at the centres of black holes.

In 2006, Ashtekar and his colleagues reported[7] a series of simulations that took advantage of that fact, using the loop quantum gravity

THE FABRIC OF REALITY

If space and time are not fundamental, then what is? Theoretical physicists are exploring several possible answers.



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version of Einstein's equations to run the clock backwards and visualize what happened before the Big Bang. The reversed cosmos contracted towards the Big Bang, as expected. But as it approached the fundamental size limit dictated by loop quantum gravity, a repulsive force kicked in and kept the singularity open, turning it into a tunnel to a cosmos that preceded our own.

This year, physicists Rodolfo Gambini at the Uruguayan University of the Republic in Montevideo and Jorge Pullin at Louisiana State University in Baton Rouge reported[8] a similar simulation for a black hole. They found that an observer travelling deep into the heart of a black hole would encounter not a singularity, but a thin space-time tunnel leading to another part of space. "Getting rid of the singularity problem is a significant achievement," says Ashtekar, who is working with other researchers to identify signatures that would have been left by a bounce, rather than a bang, on the cosmic microwave background — the radiation left over from the Universe's massive expansion in its infant moments.

Loop quantum gravity is not a complete unified theory, because it does not include any other forces. Furthermore, physicists have yet to show how ordinary space-time would emerge from such a web of information. But Daniele Oriti, a physicist at the Max Planck Institute for Gravitational Physics in Golm, Germany, is hoping to find inspiration in the work of condensed-matter physicists, who have produced exotic phases of matter that undergo transitions described by quantum field theory. Oriti and his colleagues are searching for formulae to describe how the Universe might similarly change phase, transitioning from a set of discrete loops to a smooth and continuous space-time. "It is early days and our job is hard because we are fishes swimming in the fluid at the same time as trying to understand it," says Oriti.

CAUSAL SETS

Such frustrations have led some investigators to pursue a minimalist programme known as causal set theory. Pioneered by Rafael Sorkin, a physicist at the Perimeter Institute in Waterloo, Canada, the theory postulates that the building blocks of space-time are simple mathematical points that are connected by links, with each link pointing from past to future. Such a link is a bare-bones representation of causality, meaning that an earlier point can affect a later one, but not vice versa. The resulting network is like a growing tree that gradually builds up into space-time. "You can think of space emerging from points in a similar way to temperature emerging from atoms," says Sorkin. "It doesn't make sense to ask, 'What's the temperature of a single atom?' You need a collection for the concept to have meaning."

In the late 1980s, Sorkin used this framework to estimate[9] the number of points that the observable Universe should contain, and reasoned that they should give rise to a small intrinsic energy that causes the Universe to accelerate its expansion. A few years later, the discovery of dark energy confirmed his guess. "People often think that quantum gravity cannot make testable predictions, but here's a case where it did," says Joe Henson, a quantum-gravity researcher at Imperial College London. "If the value of dark energy had been larger, or zero, causal set theory would have been ruled out."

CAUSAL DYNAMICAL TRIANGULATIONS

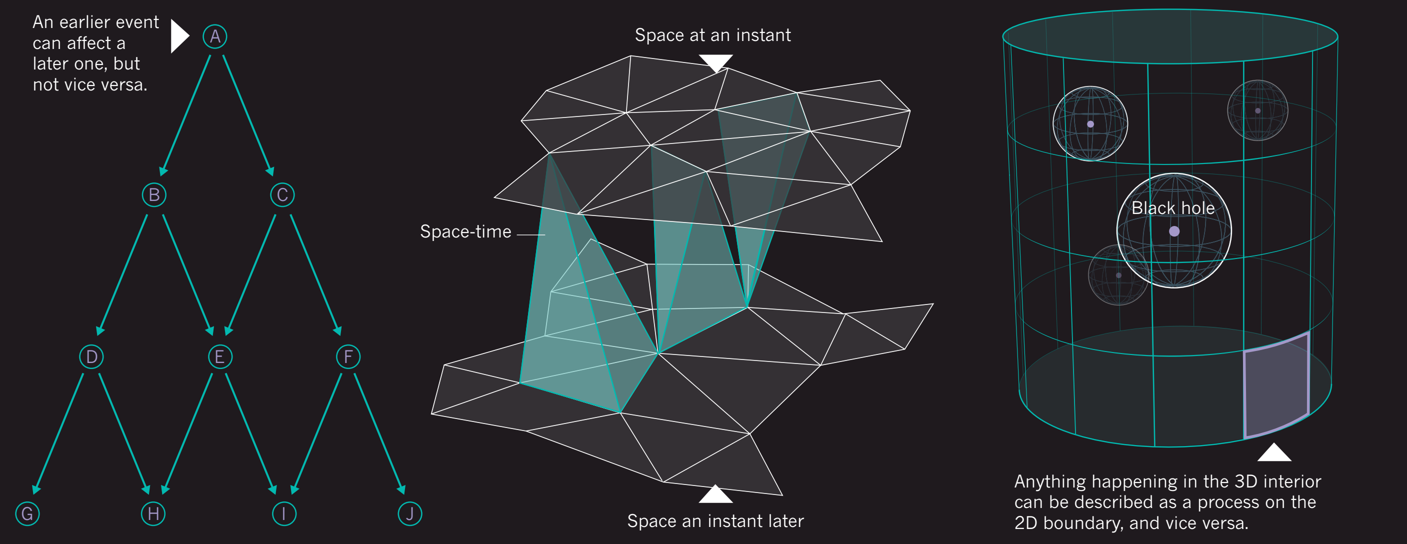
That hardly constituted proof, however, and causal set theory has offered few other predictions that could be tested. Some physicists have found it much more fruitful to use computer simulations. The idea, which dates back to the early 1990s, is to approximate the unknown fundamental constituents with tiny chunks of ordinary space-time caught up in a roiling sea of quantum fluctuations, and to follow how these chunks spontaneously glue themselves together into larger structures.

The earliest efforts were disappointing, says Renate Loll, a physicist now at Radboud University in Nijmegen, the Netherlands. The space-time building blocks were simple hyper-pyramids — four-dimensional counterparts to three-dimensional tetrahedrons — and the simulation's gluing rules allowed them to combine freely. The result was a series of bizarre 'universes' that had far too many dimensions

3. Causal sets
The building blocks of space-time are point-like 'events' that form an ever-expanding network linked by causality.

4. Causal dynamical triangulations
Computer simulations approximate the fundamental quantum reality as tiny polygonal shapes, which obey quantum rules as they spontaneously self-assemble into larger patches of space-time.

5. Holograpy
A three-dimensional (3D) universe contains black holes and strings governed solely by gravity, whereas its 2D boundary contains ordinary particles governed solely by standard quantum-field theory.



(or too few), and that folded back on themselves or broke into pieces. "It was a free-for-all that gave back nothing that resembles what we see around us," says Loll.

But, like Sorkin, Loll and her colleagues found that adding causality changed everything. After all, says Loll, the dimension of time is not quite like the three dimensions of space. "We cannot travel back and forth in time," she says. So the team changed its simulations to ensure that effects could not come before their cause — and found that the space-time chunks started consistently assembling themselves into smooth four-dimensional universes with properties similar to our own[10].

Intriguingly, the simulations also hint that soon after the Big Bang, the Universe went through an infant phase with only two dimensions — one of space and one of time. This prediction has also been made independently by others attempting to derive equations of quantum gravity, and even some who suggest that the appearance of dark energy is a sign that our Universe is now growing a fourth spatial dimension. Others have shown that a two-dimensional phase in the early Universe would create patterns similar to those already seen in the cosmic microwave background.

HOLOGRAPHY

Meanwhile, Van Raamsdonk has proposed a very different idea about the emergence of space-time, based on the holographic principle. Inspired by the hologram-like way that black holes store all their entropy at the surface, this principle was first given an explicit mathematical form by Juan Maldacena, a string theorist at the Institute of Advanced Study in Princeton, New Jersey, who published[11] his influential model of a holographic universe in 1998. In that model, the three-dimensional interior of the universe contains strings and black holes governed only by gravity, whereas its two-dimensional boundary contains elementary particles and fields that obey ordinary quantum laws without gravity.

Hypothetical residents of the three-dimensional space would never see this boundary, because it would be infinitely far away. But that does not affect the mathematics: anything happening in the three-dimensional universe can be described equally well by equations in the two-dimensional boundary, and vice versa.

In 2010, Van Raamsdonk studied what that means when quantum particles on the boundary are 'entangled' — meaning that measurements made on one inevitably affect the other[12]. He discovered that if every particle entanglement between two separate regions of the boundary is steadily reduced to zero, so that the quantum links between the two disappear, the three-dimensional space responds by gradually dividing itself like a splitting cell, until the last, thin connection between the two halves snaps. Repeating that process will subdivide the three-dimensional space again and again, while the two-dimensional boundary stays connected. So, in effect, Van Raamsdonk concluded, the three-dimensional universe is being held together by quantum entanglement on the boundary — which means that in some sense, quantum entanglement and space-time are the same thing.

Or, as Maldacena puts it: "This suggests that quantum is the most fundamental, and space-time emerges from it." ■

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