

Which way now?

*With the quest for a theory of everything facing a dead end,
Amanda Geffer explores four radical new routes*

THESE days it seems like every physicist is an Indiana Jones on the hunt for the Holy Grail, a theory that can unite the fractured worlds of quantum mechanics and general relativity – Einstein’s theory of gravity – and bring order to the universe. Some call it a “theory of everything”, some call it “quantum gravity”, but for decades nearly everyone has been using the same old treasure map – the one drawn up by string theory.

String theory is the most widely known candidate in the search for a theory of everything, and with good reason. It has elegance: the messy array of particles that make up matter and forces, including gravity, can be pared down to vibrations of infinitesimal strings. It has mystique: it posits the existence of six or seven hidden dimensions of space. And it has manpower: the vast majority of researchers working on a quantum theory of gravity have wrapped themselves up in strings.

But string theory also has a fundamental problem. Though remarkably successful at describing the behaviour of particles, so far it fails to explain the nature of space and time. According to general relativity, gravity is a manifestation of the curvature of space-time, so to truly unite quantum mechanics with gravity, physicists need to deduce the quantum structure of space-time itself. A theory of everything that leaves out space and time hardly lives up to its name, so over the years physicists have proposed several alternatives to string theory. The best known is loop quantum gravity (*New Scientist*, 12 August 2006, p 28), though this too has its share of problems.

Now a growing number of physicists are starting to solve these kinds of problems by developing alternate ways of understanding space-time itself. Though their approaches are still at an early stage, four groups in particular

have made crucial progress and are beginning to challenge our most basic notions of cosmology. They represent a significant shift in the search for a theory of everything: suddenly there are a wide variety of non-string-theory approaches, any of which might be the starting point of an ultimate answer (see Table, page 30).

Causal dynamical triangulations

The first, and perhaps most advanced, of these is known as causal dynamical triangulations (CDT). Developed over the last few years by Renate Loll of Utrecht University in the Netherlands and her colleagues Jan Ambjorn and Jerzy Jurkiewicz, CDT models space-time as being made up of tiny, identical building blocks – in this case, higher-dimensional analogues of triangles, called 4-simplices. Governed by quantum mechanics, the triangles perpetually rearrange themselves into new configurations, each of which has its own curvature.

Just as you can glue six equilateral triangles together at a point to make a piece of flat space, so CDT can produce flat, positively curved or negatively curved space-time by allowing different numbers of 4-simplices to meet at a point. The triangles are not physical objects; rather, they are a mathematical and computational tool – and they lead to compelling results.

The crucial step in deriving space-time on a large scale is to “sum over” all possible configurations of these triangles. This is in keeping with the spirit of Richard Feynman’s approach to quantum mechanics, in which every possible path of a particle must be added up to calculate how it gets from A to B. Back in the late 1970s, a similar approach to space-time was taken by Stephen Hawking at

the University of Cambridge, but it failed as it ended up producing universes that had either no dimensions or an infinite number of them.

Loll’s insight was to include time in the mix, or more precisely, causality. She insisted that causal structure – the fixed ordering of cause and effect – be incorporated in the way the triangles can arrange themselves from one configuration to the next. Due to some quantum quirks, the sum of these configurations could yield a space-time with any number of dimensions. Yet when she performed the calculation, what emerged were three dimensions of space and one of time – a smooth, expanding universe like the one in which we live, governed by the laws of general relativity and consistent with standard cosmology.

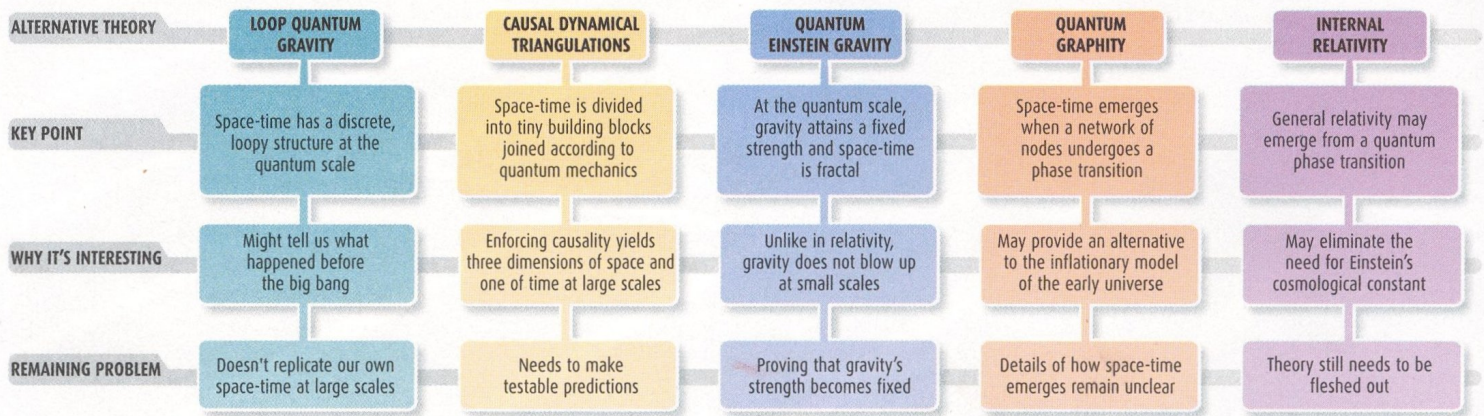
This is a notable achievement. Even loop quantum gravity, for instance, has yet to generate a familiar space-time at large scales. What’s more, the result suggests that quantum-level causality may even explain why we live in a four-dimensional universe in the first place. “Her models are the furthest anyone has gotten to show explicitly the geometry of space emerging from something more fundamental. I take that seriously,” says physicist and noted string-theory critic Lee Smolin of the Perimeter Institute for Theoretical Physics in Waterloo, Ontario.

According to CDT, though, space-time is four-dimensional only at large scales. At the tiniest scales, the model comes up with only two dimensions, and it produces a space-time with a fractal structure – rough, jagged and self-similar, with increasingly detailed structure at ever-smaller scales. This could be a clue as to how gravity behaves at extremely small distances, where general relativity is thought to break down.

CDT still has its work cut out – for instance, it needs to show how matter arises, and how the 2D fractal geometry at small scales

THEORIES OF EVERYTHING

In the quest for an ultimate theory of the universe, there is now a bevy of alternatives to string theory. These seek to develop models of space-time and gravity on a quantum scale



affects the physics of elementary particles. Loll and her colleagues need to make specific testable predictions. For now, though, the fact that they have derived something resembling our universe from quantum interactions is unique. "They are the one research programme that makes quantum gravity look reasonable," says physicist Olaf Dreyer at the Massachusetts Institute of Technology.

Quantum Einstein gravity

Martin Reuter, a physicist at the University of Mainz in Germany, has other ideas. He has been developing a different theory he calls "quantum Einstein gravity", which begins where the earliest approaches to quantum gravity left off.

After physicists successfully merged the classical theory of electromagnetism with quantum theory to create quantum electrodynamics in the 1940s, and later extended their methods to work with the strong and weak nuclear forces, they had hoped that they could likewise "quantise" gravity. The idea failed miserably, because of the way gravity behaves at small scales. As you zoom in on smaller distances, the strength of gravity increases, but gravity also acts on itself, creating a feedback loop that sends the gravitational force skyrocketing. Eventually the ability of general relativity to describe the fabric of the universe breaks down.

So most physicists went off in other directions, mainly towards string theory. Reuter, however, feels they were too quick to abandon the methods that had worked when applied to every other force in nature. He had been thinking about an idea proposed by physicist Steven Weinberg in the 1970s: that at extremely small scales, there might be a "fixed point" at which the strength of gravity no longer increases, no matter how much you zoom in. There is reason to think this might

work. Quantum chromodynamics, the theory of how the strong nuclear force acts on quarks and gluons, says that the strong force decreases at smaller scales until it reaches a fixed point, where it goes to zero. If a similar point exists for gravity, it would mean that physics would be able to describe gravity down to the quantum realm.

When Weinberg proposed the idea, physicists didn't have the mathematical tools to calculate this fixed point in the four-dimensional space-time of general relativity. Then in the late 1990s Reuter developed such a method. His calculations were approximate, but they suggested that a fixed point for gravity might indeed lurk in the equations. "Personally, I am completely convinced that it exists," he says.

Intriguingly, in quantum Einstein gravity, space-time at the smallest scales is fractal and the number of dimensions shrinks from the familiar four to two. This is reminiscent of CDT, which leads some to wonder if they are two descriptions of the same theory. "Ultimately the two approaches could turn out to be equivalent," Reuter says.

Quantum graphity

While CDT and quantum Einstein gravity start with space-time and apply quantum mechanics to it, other physicists are taking a more radical approach: doing away with space-time altogether. Their idea is to show that space-time, and gravity, emerge from what they call a "pre-geometric" state.

Fotini Markopoulou of the Perimeter Institute and her colleagues are developing one such model, which they have whimsically named "quantum graphity". It starts with the idea that at extremely small scales and extremely high energies – conditions that would have applied at the birth of the universe – there is no such thing as space.

All that exists is an abstract network, a graph made of nodes connected by edges governed by quantum mechanics. In this state, every node is connected to every other node. It's a highly counter-intuitive picture, as if every atom in the universe were next to every other atom. "When everything is on top of everything else, there's no notion of space," she says.

The idea of a pre-geometric phase of the universe originated in the 1950s with the late John Wheeler, the physicist who pioneered the field of quantum gravity. "My intention was to be a bit more radical about what it means," says Markopoulou. "People talk about pre-geometry and quantum geometry, but they seem to mean something more like really bumpy geometry. It turns out it's actually much stranger than people thought."

According to quantum graphity, this pre-geometric phase didn't last long. When the early universe cooled, it went through a phase transition akin to ice crystals forming when water freezes. During this phase transition, many of the nodes became unlinked; everything was no longer connected. Some nodes became far away from others, so distance, and hence space, emerged and the collection of nodes "crystallised" into a regular lattice-like structure. This structure represents space on the quantum scale and gives rise to smooth space at large scales.

Markopoulou thinks this transition might explain a long-standing puzzle in cosmology: the fact that there are distant regions of the universe that are at precisely the same temperature. This would require these regions to have been near enough to each other in the past to be able to exchange radiation and even out their temperatures. But if we extrapolate their earlier positions based on the speeds at which they have been moving apart, we find they would never have been sufficiently close. To get round this difficulty, the well-known

inflationary model of cosmology proposes that the early universe went through a brief period of faster-than-light expansion.

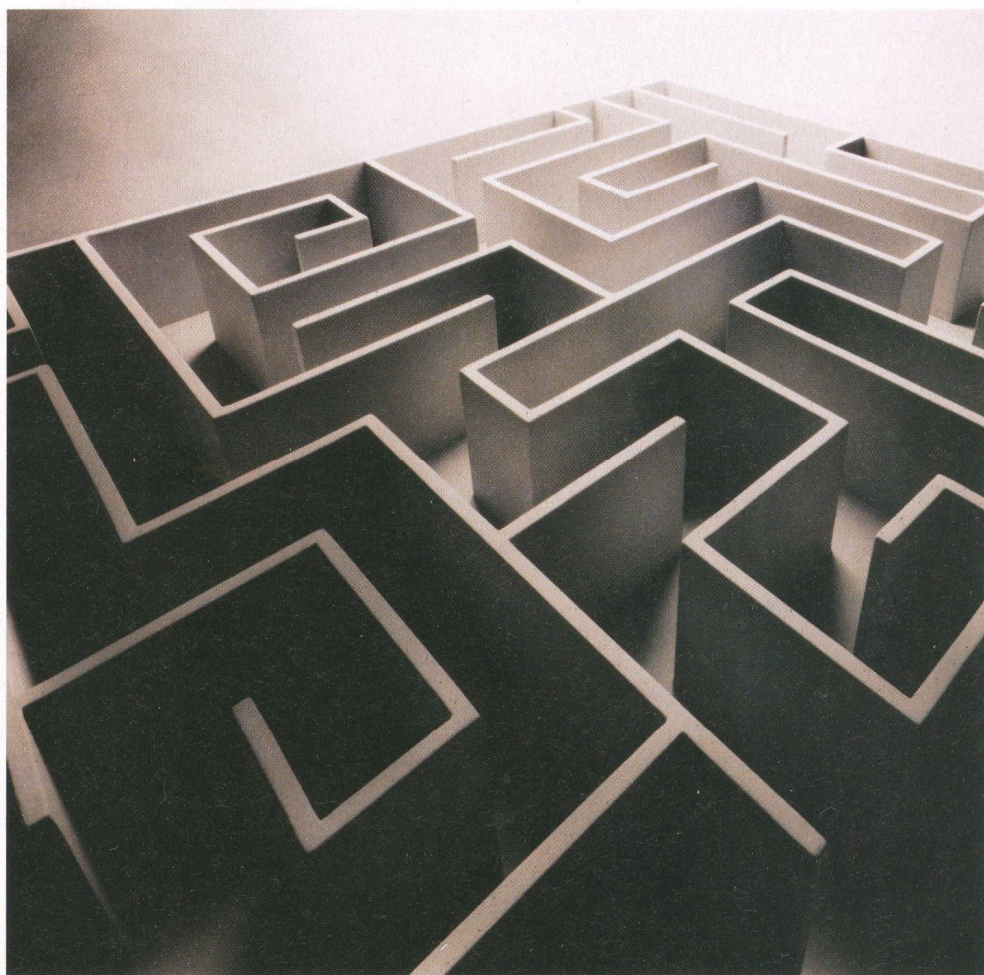
Quantum graphity, however, can potentially solve this thermal equilibrium puzzle without the need for inflation. If everything was in contact with everything else during the pre-geometric phase, then we should expect to see striking similarities between distant regions of the universe. Markopoulou says that she has a lot more work to do before her model can compete with inflation, but she is excited about the prospect of finding evidence for it in the vastness of space. "I like the fact that it should have large-scale signatures, because in quantum gravity you're often stuck in really small-scale physics," she says. "Here, cosmology would be the place to look."

Internal relativity

At MIT, Dreyer is developing a similar model called "internal relativity", in which space-time emerges from a pre-geometric state – and he is betting the laws of general relativity will too. This is perhaps the most ambitious model of all. Dreyer's starting point is a simple quantum system of spins, each of which can be either up or down, in a random distribution. At a critical temperature, the system undergoes a phase transition in which the spins align to form an ordered pattern.

The trick, he says, is to consider what observers inside the system see after the phase transition. They will never see the underlying spins that act as a backdrop; all they see are the excitations of the system which, it turns out, they perceive as space-time and matter. Taking this "internal" perspective seriously, Dreyer says, he has shown that the effects of special relativity, such as time dilation and length contraction, arise naturally. What's more, he has been able to derive Newtonian gravity by showing that two nearby particles in his model will mutually attract, as this lowers the overall energy of the system.

It is more difficult to show that general relativity also arises in Dreyer's model, but he is confident he can do it. According to general relativity, space-time and matter influence one another but remain distinct. Dreyer's confidence is inspired by the fact that in his model space-time and matter are no longer



considered separate, but emerge together from the same pre-geometric state. Markopoulou is supportive of his approach to deriving the equations of general relativity. "It's the only thing I've heard in years that gives us a chance to actually explain the Einstein equations," she says.

For now, Dreyer's claim that general relativity will emerge remains conjecture. If it does, though, he thinks his model can help solve another vexing problem, that of Einstein's cosmological constant. Representing the energy of space-time itself, the constant is predicted from quantum theory to be enormous, but experiments reveal it is extremely small. "This problem is a result of making a split between space-time and matter. That gets you into a lot of trouble," Dreyer says. In internal relativity, on the other hand, there is no space-time without matter, so the energy of space-time would have to be calculated differently. He

predicts it would be tiny, as is observed.

Dreyer has come up with a way to test his model. If the early universe went through a period of inflation, we should be able to detect relic gravitational waves rippling through the cosmic microwave background. If, however, the universe emerged from a pre-geometric state, no such waves should be found. The Planck satellite, expected to be launched by the European Space Agency later this year, should be sensitive enough to detect these gravity waves if they exist, and either corroborate or rule out Dreyer's model.

It's anyone's guess which quantum gravity treasure map, if any, will lead physicists to a theory of everything. For now they've got plenty of clues and no shortage of paths to follow. They might converge on the answer, or they might be heading down blind alleys.

"For most of my time in quantum gravity, it was hard enough just to have one theory," Dreyer says. "Now we have so many different approaches and a lot of them are making progress. We have to ask nature which one is the right one. This gets me really excited. It's the way physics is supposed to work." ●

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