One way to understand the forces that rule our Universe is to venture outside it . . .

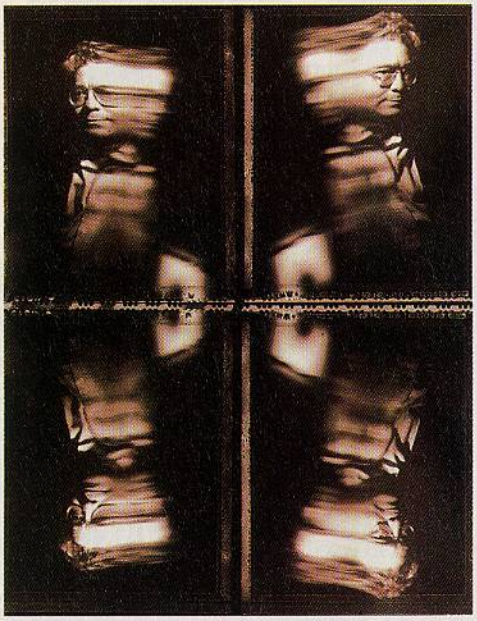
Beyond space and time

by Robert Matthews

WHEN Abhay Ashtekar sits down to work at Pennsylvania State University, he doesn't stay in his office for very long. A few lines of mathematics and he's away on an expedition to—well, it's hard to say where, exactly. It's certainly not anywhere you would recognise, and it doesn't even make much sense to talk about the precise location of this new realm. For those few lines of mathematics have taken Ashtekar outside space and time. He has left our Universe altogether.

Ashtekar, a theoretical physicist, does not leave the familiar world of three dimensions and clocks just for fun. He is one of a small coterie of theorists who believe that it is only outside this realm that they will find the solution to one of the great conundrums in modern physics: how to marry Einstein's theory of gravity to quantum theory. The discoveries now being made by Ashtekar and his colleagues in their forays outside space and time are catching the attention of some big names in theoretical physics. "Of all the approaches to quantum gravity I have seen, Ashtekar's has the most going for it," says mathematician Roger Penrose of Oxford University, a founding father of the subject. Chris Isham of Imperial College, London, who is another veteran of many unification campaigns, describes recent progress as "very impressive".

That progress includes insights into the very nature of space, time and gravity, and a growing vision of what the long-sought quantum theory of gravity will look like. Best of all, these developments come from a strategy that neatly avoids an embarrassing paradox at the heart of "superstring" theory, the approach that is still regarded as the front runner in the race to combine quantum theory and gravity (see "Into the eleventh dimension", *New Scientist*, 18 January, p 32).



Ethereal elastic

The origins of that paradox date back to 1915, when Einstein published his general theory of relativity (GR), the successor to Newton's 250-year-old theory of gravity. According to Einstein, gravity is not some kind of ethereal elastic that binds every mass to every other. Rather, it is a manifestation of the curvature of space and time. Einstein came up with a complex equation showing just how much space-time curvature is caused by a given amount of mass, and its predictions have been borne out with impressive accuracy. As a result, GR now stands as one of the pillars of modern physics. The other is quantum theory, which describes the subatomic world with similar precision.

For more than half a century, physicists have been trying to meld these two great theories into a single, unified "Theory of Everything". All their efforts have failed, though over the past decade superstring theory has emerged as the best attempt yet. It embraces the standard idea in quantum theory that all the fundamental forces—electromagnetism, the strong and weak nuclear forces and gravity—come from the exchange of "carrier" particles. In this picture, gravity is simply another force, which is transmitted from one mass to another by its own carrier particle, called the graviton. In superstring theory all these subatomic particles and forces are manifestations of the vibration of string-like entities that exist on an even smaller scale.

One of its great attractions is that the mathematical equations that are involved do not just allow the possibility that gravitons exist alongside the carriers of the other forces; the mathematics actually seems to demand their existence. Supporters of superstring theory take this as a sign that they are on the right track.

These techniques are based on an assumption. It is an assumption so basic that most physicists don't even stop to think about it. Superstring theory and all its works start from the premise that

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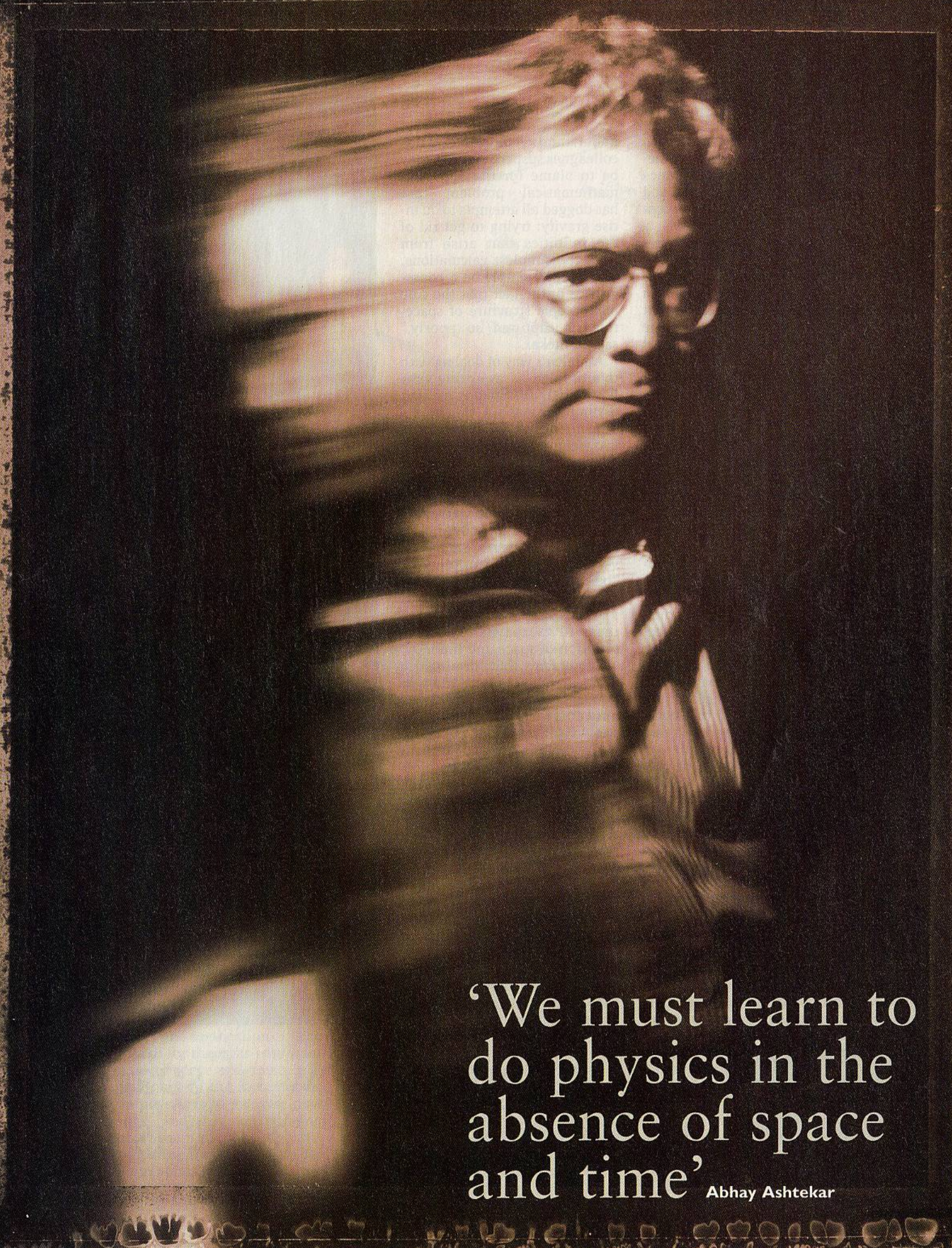


‘We must learn to do physics in the absence of space and time’ **Abhay Ashtekar** space-time is nice and regular—and flat. This is the space-time of school geometry books, where the shortest distance between two points is a straight line, and where parallel lines never meet except at infinity.

Yet if there is one lesson that Einstein's general theory of relativity should have taught us, it is that anyone who hopes to understand gravity must grapple with the possibility that space-time is not flat at all, but curved. This is not just some pedantic gripe. It could make a dramatic difference to the search for a Theory of Everything. And the solution could be more dramatic still.

Going metric

To capture the essence of what space and time really mean, Einstein used a concept called a metric. Put simply, this is a formula that allows you to calculate the distance between any two points if you know their coordinates. Everyone is familiar with one kind of metric: Pythagoras's theorem. If you know the coordinates of any two points on a flat sheet of paper, the theorem tells you how far apart they are (see Diagram). By adding a couple of extra terms, Pythagoras's theorem can be extended to cover the four dimensions we inhabit—three of space plus one of time. Known to mathematicians as the Minkowski metric, the resulting formula allows you to plug in any two space-time coordinates and find the distance between them.

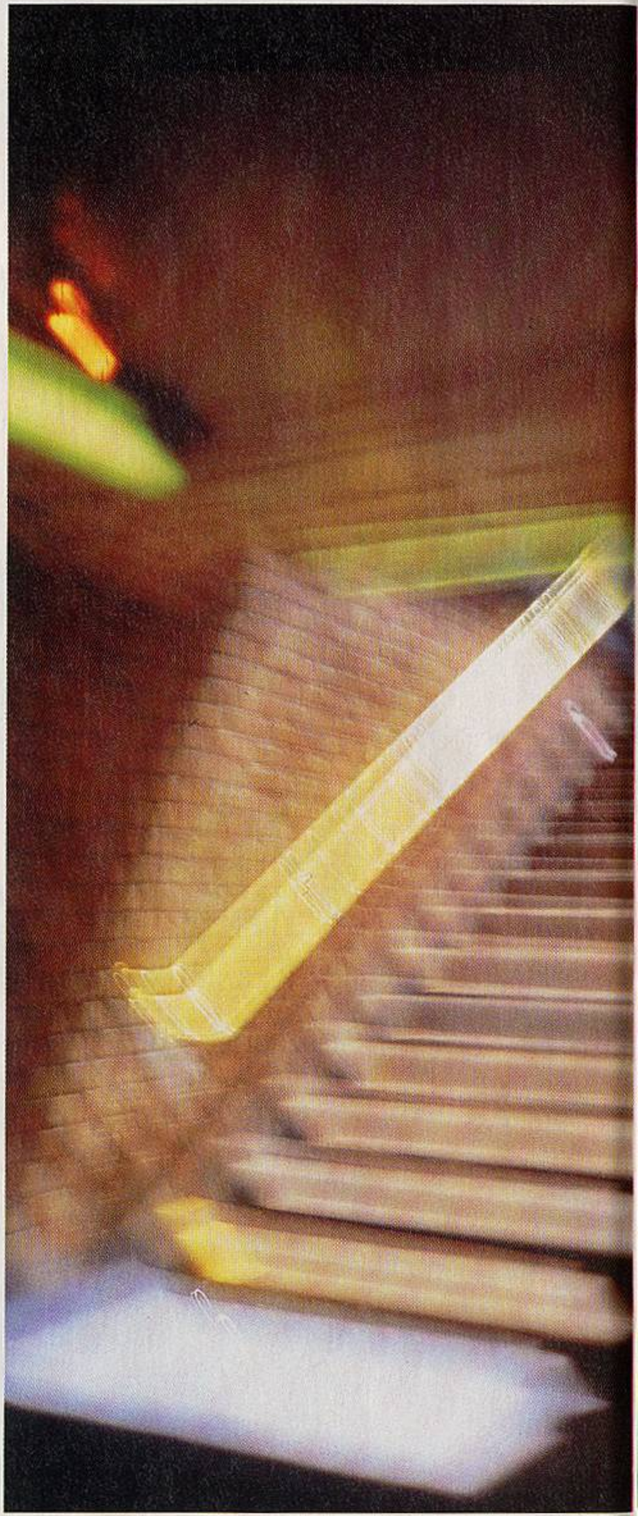
What worries Ashtekar and his colleagues is that all "unifying" theories like superstrings blithely assume that they can use the Minkowski metric of flat space-time as the arena for their calculations. But Einstein's most brilliant contribution to physics was to show that space-time is not always flat. He showed that mass can curve it, and GR provides the equations for calculating how a space-time metric is affected by mass. The result is what we call gravity.

In other words, using the Minkowski metric in your attempts to understand gravity smacks of assuming the properties of the very thing you are trying to understand. Ashtekar and his colleagues suspect that this may be to blame for the appalling mathematical problem that has dogged all attempts to quantise gravity: trying to get rid of the infinities that arise from even the simplest calculations. "These may simply be a consequence of the fact that the true microscopic structure of space-time is captured so poorly," says Ashtekar.

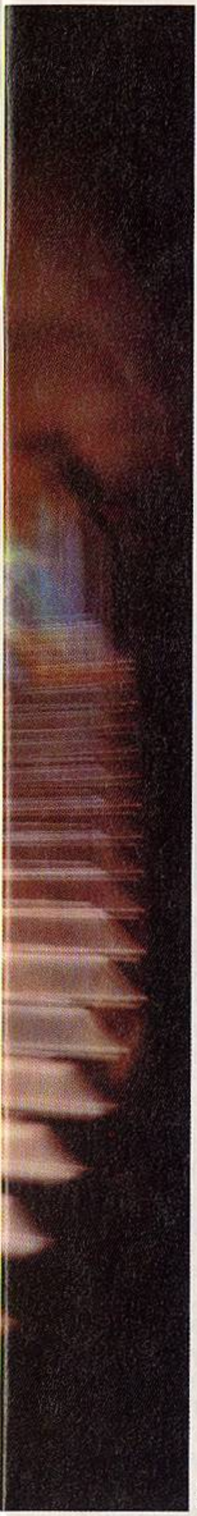
Ashtekar's way of dealing with this problem is as daring as it is radical. To avoid making assumptions about the space-time metric, he simply abandons it. "We must learn to do physics in the absence of space and time," he proclaims. So over the past seven years, Ashtekar, Carlo Rovelli of the University of Pittsburgh and Lee Smolin, also at Pennsylvania State University, have been digging "below" the concept of the metric to develop an arsenal of mathematical tools that allows them to escape its rigid prescription of space and time.

Remember that the metric defines distances between two points: but points on what? The answer is a mathematical entity known as a differentiable manifold, which is a sort of smooth "surface" on which those points can exist. On its own, the manifold is simply a blank background; the whole point of metrics is to put the familiar features of space and time into it. But there is another way of turning the manifold into a suitable place for doing physics. It involves the use of "connections".

While the metric is all about distances between points, a connection captures the notion of parallelism along curves. At first sight, this hardly seems a decent swap for the metric. Yet



'The standard view of space as a kind of smooth fabric is just an approximation that breaks down'



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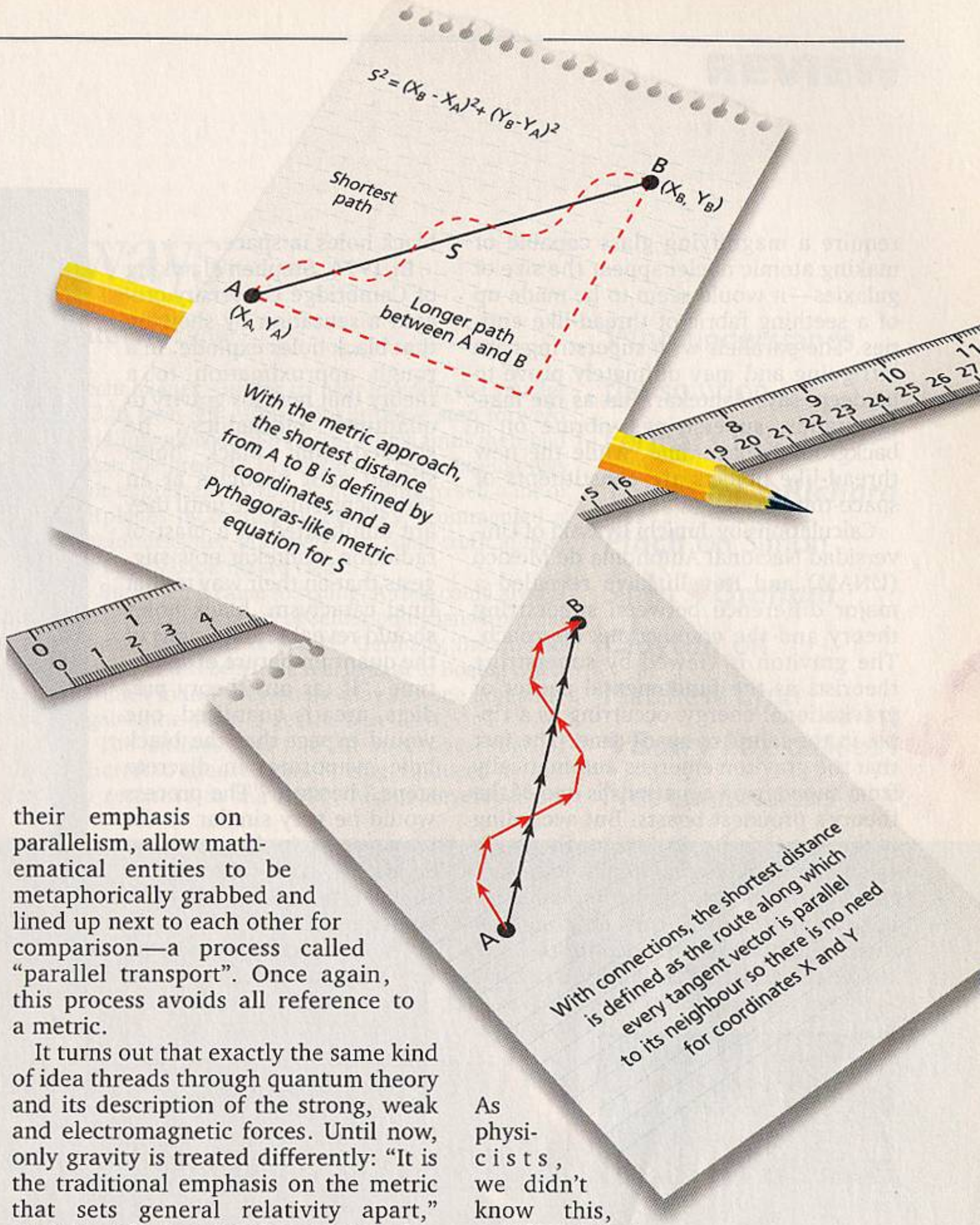


connections are deceptively powerful, and allow physicists to do detailed calculations, but without having to make any assumptions about the nature of the space-time they are dealing with.

To compare how metrics and connections work, take the notion of the "geodesic", one of the most important concepts in physics. The geodesic is the path followed by a ray of light as it travels from one point to another in space-time. The metric captures this very simply: a geodesic is the shortest distance between two points. If you know the coordinates of the points in space and time, and you know the metric, it's easy to work out the geodesic. In the Minkowski metric, for instance, you would use the four-dimensional version of Pythagoras's theorem. But change the metric, and the answer changes, so it's crucial to state which metric is being used: flat or curved.

Toolkit for theorists

The great thing about connections is that they let you define geodesics without having to specify a metric. In terms of connections, a geodesic is simply a trajectory for which all tangents are parallel to one another at every point. In flat space, only a straight line has this property (see Diagram). In curved space geodesics can be curved, but the connection-based definition still holds true. Many other much more abstract mathematical concepts can also be freed from their reliance on specific assumptions of space and time by switching from metrics to connections. The result is a toolkit for theorists who want to work "outside" space and time.

For example, one of the most important tasks in physics is to measure how things change, and that means being able to compare them at different points. Thus, by comparing the velocity of a car at two different points, you can work out its acceleration, which tells you the force being applied to it. Connections, with their emphasis on parallelism, allow mathematical entities to be metaphorically grabbed and lined up next to each other for comparison—a process called "parallel transport". Once again, this process avoids all reference to a metric.

It turns out that exactly the same kind of idea threads through quantum theory and its description of the strong, weak and electromagnetic forces. Until now, only gravity is treated differently: "It is the traditional emphasis on the metric that sets general relativity apart," explains Ashtekar. "In the quantum theory of the other forces, the basic dynamical variable is a connection that enables us to parallel-transport objects along curves. In electrodynamics, the object is a charged particle such as an electron and the connection is a photon; in the theory of the strong force, the objects are particles like quarks, which carry strong charge and the connections are gluons."

So using the connection approach could put general relativity onto a similar footing. Until very recently, the prospects of success hardly seemed bright. Superstring theory, based on the simple idea of flat space-time, has always been able to exploit the tools of standard quantum theory. In contrast, the connection approach has had to start from scratch. Ashtekar turned to mathematicians to see what help they could give—only to find that they viewed his task as hopeless. "Some mathematicians thought that there was some deep technical reason why it wasn't possible. As physicists, we didn't know this, and found that it was possible after all. Which shows that sometimes you can know too much."

Ashtekar, together with John Baez of the University of California at Riverside, Isham at Imperial, and Jerzy Lewandowski, then at Warsaw University in Poland, set about developing the mathematics they needed to study quantum gravity without a metric. By 1995, Ashtekar and Lewandowski were ready to probe the nature of space and time. They hoped that being the first to wield techniques independent of any metric would give them a unique perspective on the nature of space. They were not disappointed.

Their equations confirmed what physicists have long suspected: that the standard view of space as a kind of smooth "fabric" is merely an approximation, which breaks down at really small scales. Ashtekar and Lewandowski found that if one could look at the nature of space on a scale of 10^{-35} metres—which would require a magnifying glass capable of making atomic nuclei appear the size of galaxies—it would seem to be made up of a seething fabric of thread-like entities. The parallels with superstrings are intriguing and may ultimately prove to be deep, says Ashtekar. But as the matter stands, superstrings vibrate on a background space-time, while the new thread-like objects are constituents of space-time itself.

Calculations by Junichi Iwasaki of Universidad Nacional Autónoma de Mexico (UNAM) and Rovelli have revealed a major difference between superstring theory and the connections approach. The graviton is viewed by superstring theorists as the fundamental packet of gravitational energy, occurring as a ripple in the fabric of space-time. The fact that the graviton emerges automatically from superstring equations is one of the theory's proudest boasts. But according to the metric-free calculations, the graviton is not fundamental at all, but something that emerges from the collective behaviour of those truly fundamental threads that make up space-time.

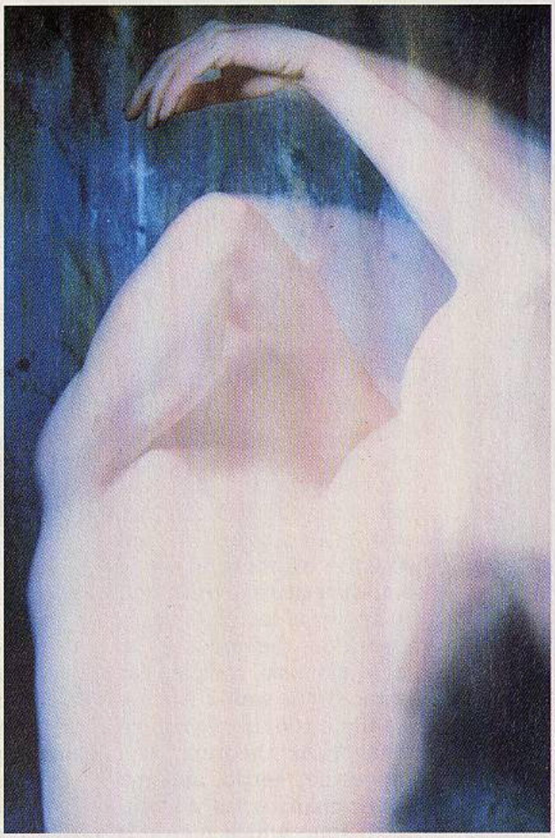
> ‘It turns out that basic geometrical concepts such as area and volume are quantised’

Illustration: Helen Garnett

The metric-free theory of gravity has thrown up many other insights too. It turns out that basic geometrical concepts such as area and volume are also quantised, though again only on very small scales. Even on the tiny scale of subatomic particles, area and volume have taken on their familiar smooth appearance, which explains why no weird quantum space-time effects have ever been seen in particle physics experiments.

Yet this raises a question. When all the predictions of connection theory are centred on scales at which we cannot make any observations, how can we even compare it with superstring theory, let alone tell if either is correct? Amazingly, Ashtekar believes that it may be possible to test the new theory by studying black holes in space.

In 1974, Stephen Hawking of Cambridge University created a sensation by showing that black holes explode. In a rough approximation to a theory that marries gravity to quantum mechanics, he showed that black holes should emit particles at an ever increasing rate until they are annihilated in a blast of radiation. Ashtekar now suggests that on their way to that final cataclysm, black holes should reveal telltale signs of the quantum nature of space-time. “If, as our theory predicts, area is quantised, one would expect that the black hole evaporates in discrete steps,” he says. “The process would be very similar to the way an excited atom descends to its ground state through a series of discrete transitions.”



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The connection-based theory leads to precise predictions about the size of these steps. “These predictions are consistent with Hawking's calculations, and also explain some key features of black hole thermodynamics,” says Ashtekar.

Mathematical elegance

So far, however, astronomers have yet to find unequivocal signs of any black hole explosions. Until they do, theorists will have to judge the merits of the new approach to quantum gravity using more tenuous criteria, such as its self-consistency and mathematical elegance.

Ashtekar insists that he and his colleagues are not seeking to supplant superstring theory. Rather, they believe it must be placed on a firmer footing. “String theory uses a background metric,” Ashtekar says. “At a fundamental level one must get rid of that. Our work shows how.”

Isham, one of the very few superstring theorists to be equally at home with the connections-based approach, agrees: “I regard the Ashtekar programme and the superstring programme as being the two most highly developed, full-blooded quantum gravity schemes. They can also serve as useful foils to each other, as they take such a very different approach to the problem.”

Ashtekar freely accepts that major questions still remain. He cannot yet link gravity to the other forces directly. “Unlike superstring theory, we do not have a natural prescription for unifying our description of gravity with that of sub-atomic particles,” he says. “But we do have a handle on quantum geometry which doesn't assume a metric, and we do have exact results that are mathematically rigorous and free of infinities.” And as any theorist trying to succeed where even Einstein failed will tell you, in this game every little helps. □

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