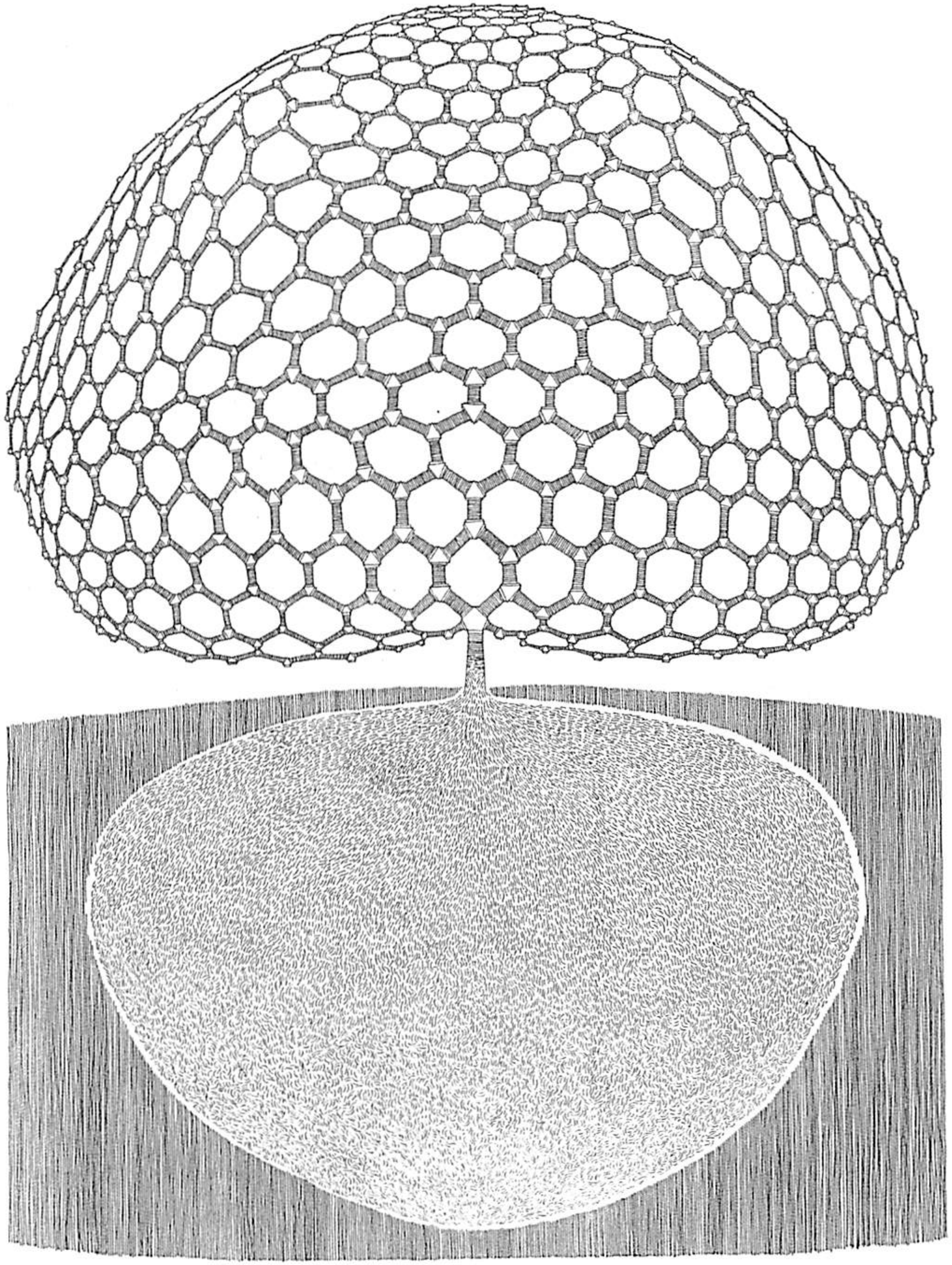

SAMUELE BASTIANELLO

What string theory's **really** good for

It was supposed to lead us to a theory of everything, but it's far more useful than that, **Jessica Griggs** discovers

STRING theory: you love it or loathe it. To some it represents our best hope for a route to a "theory of everything"; others portray it as anything from a mathematically obtuse minefield to a quasi-religion that has precious little to do with science.

There might be a middle way. String theory's mathematical tools were designed to unlock the most profound secrets of the cosmos, but they could have a far less esoteric purpose: to tease out the properties of some of the most complex yet useful types of material here on Earth.

Both string theorists and condensed matter physicists – those studying the properties of complex matter phases such as solids and liquids – are enthused by the development. "I am flabbergasted," says Jan Zaanen, a condensed matter theorist from the University of Leiden in the Netherlands. "The theory is calculating precisely what we are seeing in experiments."

If solid science does turn out to be the salvation of string theory, it would be the latest twist in a tangled history. String theory was formulated in the late 1960s to explain certain features of the strong nuclear force, one of four fundamental forces of nature. It holds that electrons, quarks and the like are not point-like particles but minuscule, curled-up, vibrating strings. No sooner had this idea emerged, though, than it lost ground to particle physicists' "standard model", which proved capable of describing not just the strong force but also the weak and electromagnetic forces – and did so far more intuitively through the interactions of point-like quantum particles.

Then string theory staged a dramatic comeback. Gravity had resisted incorporation into the standard model, still being described by Einstein's general theory of relativity, a resolutely non-quantum theory. In the 1980s, it became clear that certain features of strings correspond perfectly to properties predicted for the graviton, a hypothetical quantum particle that would transmit the gravitational force. Suddenly it looked as though string theory could unite all of nature's workings into one grand quantum-physical scheme.

Holographic worlds

If that's true, progress has been abysmally slow. "The string theorists were saying, 'Give us two more weeks and we will have explained all the big puzzles in the universe'," Zaanen observes. "That was 20 years ago."

The critical voices have in the meantime been getting more strident. They complain about string theory's weird, unverifiable predictions – for instance, that space-time has any number of dimensions, usually 10, rather than the three of space and one of time we see. Folding 10 dimensions down to four can be done in a mind-boggling 10^{500} ways, with no way of saying which of them corresponds to how our universe does it. As if that weren't enough, the energies needed to create the tiny strings the theory is woven from make them impossible to detect. To its detractors, string theory is long on mathematical elegance, but woefully short on real-world relevance.

A string-theory curiosity with the forbidding moniker of the anti-de-Sitter/conformal field theory correspondence (AdS/CFT for short) is at first glance a classic of the genre. Dreamed up in 1997 by Juan Maldacena, a young Argentinian physicist then working at Harvard University, it is a special case of what is known as the "holographic principle", floated by physicist Gerard 't Hooft of Utrecht University in the Netherlands and developed by Leonard Susskind at Stanford University in California in the early 1990s.

Their basic premise was this: much as a hologram you might find on your credit card encodes all the information for a 3D image in just two dimensions, a quantum theory in a certain number of dimensions that includes gravity can be encoded as an entirely different theory without gravity in one dimension fewer. The three spatial dimensions of our universe – along with gravity and us too – might, for instance, all be a holographic image generated from the interactions of particles on the cosmos's 2D boundary.

Maldacena took that idea further. He was trying to do something that had consumed some of the best minds in cosmology for decades: to reconcile the behaviour of black holes, which are a core prediction of general relativity, with quantum theory. One way to

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model black hole behaviour was to turn to multidimensional membranes known as D-branes that pop up in string theory. Like black holes in our cosmos, these curiosities are extremely heavy and capable of curving higher-dimensional space around them.

Maldacena's insight was to see that the goings-on on a D-brane could be described in two entirely equivalent, holographically related ways. The first comes from string theory: it includes gravity, and involves 10 dimensions. Of these, five are rolled up tightly while the other five are configured as an "anti-de-Sitter space" – one that warps back on itself like a saddle, rather than being broadly flat as our cosmos is assumed to be.

The second description sits on the edge of this 5D space. It is a 4D quantum field theory without gravity, not unlike the sort that underpins the theories of the strong, weak and electromagnetic forces in the standard model, but with a few extra symmetries thrown in. Such a theory is known as conformal because the particles behave in the same way regardless of the energy or length scale at which you look at them. Thus the AdS/CFT correspondence was complete.

"STRING THEORY IS NOT A ONE-WAY STREET"

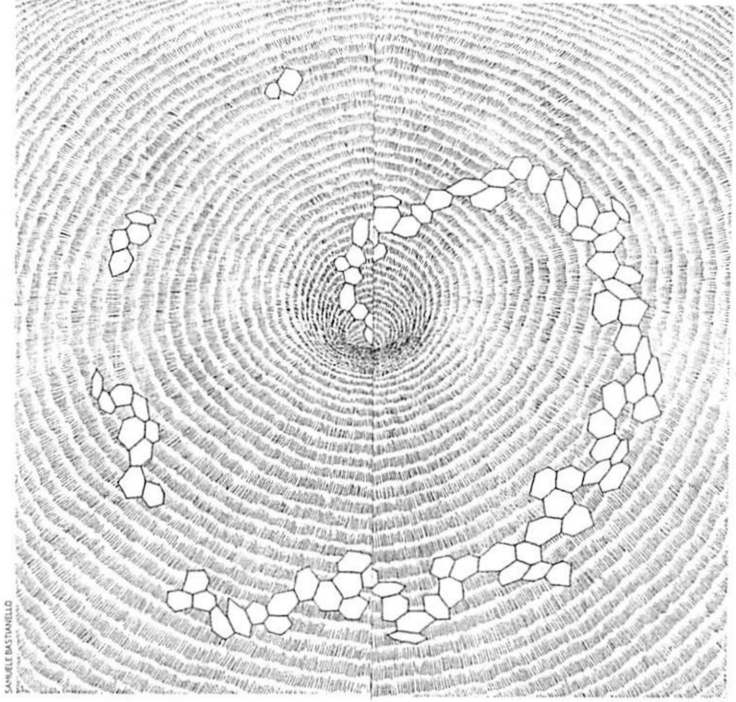
Sean Hartnoll - a string theorist looking for answers

I think it's crucial to see the lofty "theory of everything" and the "real world" aspects of string theory as complementary. That's partly why I drifted into the application of string theory to condensed matter physics. It's not a one-way street: I'm completely sure that string theory will also learn a lot from condensed matter physics. It would be arrogant to assume otherwise.

Critics of string theory often just focus on one aspect - the attempt to reproduce the standard model by compactifying down string theory's 10 dimensions to four. I've never been especially attracted to that question, as it is hard to make robust predictions.

What is great about string theory in the last few years is that it has become a melting pot of concepts from different areas of physics, such as quantum gravity, particle physics, cosmology and condensed matter. It is broad, ties together a lot of concepts and hopefully something will come out of it. I don't really care whether that turns out to be the ultimate theory of nature or not. Stuff like AdS/CFT could usher in a new period of unity in physics that would have been completely unanticipated 10 years ago.

To theoretical physicists, Maldacena had stumbled on something profound. For the first time, he had connected a condensed-down string theory with a normal field theory of particle interactions. Instead of having to grapple with the notoriously intractable mathematics of quantum field theory, physicists could now make use of the somewhat more manageable algebraic apparatus of general relativity courtesy of the higher-dimensional member of the duo. Calculations of complex particle interactions could be made easier at the stroke of a pen.



SAMUELE BASTIANELLO

Right theory, wrong universe

A shame, then, that the correspondence applied to the wrong shape of universe. That didn't put off Maldacena's peers. When he presented his work at a conference in Santa Barbara, California, in 1998, several hundred string theorists joined in with a specially composed song, *The Maldacena*, to the tune of the then-popular dance hit *The Macarena*.

But why should anyone care? What possible relevance could this little-known theoretical conjuring trick have to the real world?

Quite a lot, it seems, and in particular to the behaviour of certain types of condensed matter. Understanding these materials at the deepest level involves calculating how huge numbers of particles interact – something that we simply don't have the tools to cope with. "It's very dissatisfying that in the centuries since Galileo kick-started modern physics, we still can't deal with that," says Sean Hartnoll, a string theorist at Harvard University.

That's where the tricks of the AdS/CFT correspondence come in handy. Though formulated for a different type of space, its mathematics provides a convenient bypass for a variety of problems that involve strongly interacting particle systems.

Take the exotic form of matter known as the quark-gluon plasma. In normal matter, quarks and gluons are bundled together into more familiar entities like protons and neutrons. At temperatures comparable with those seen in the immensely hot first microseconds of the universe, those bonds should break down, releasing a dense fireball of quarks and gluons acting in a similar way to the atoms of a gas, with few or no interactions between them.

That, at least, is what the field theory of the strong nuclear force predicts. But in 2005, when researchers at Brookhaven National Laboratory in Upton, New York, created a quark-gluon plasma by smashing together fast moving gold ions, they saw something very different. The plasma acted not as a gas, but as a superfluid – an almost perfectly flowing liquid with virtually no viscosity. Clearly, the interactions between the quarks and gluons of this exotic state were more complex than the standard theory could easily compute.

So how can we work out what's going on? A less than obvious answer is to approach the problem through the physics of a black hole. Black holes have thermodynamic properties, such as entropy and temperature, just as liquids do, and in higher dimensions they can also have viscosity. In 2005, three theorists used these connections to calculate the viscosity of a quark-gluon plasma through the holographically equivalent problem of how a black hole in an anti-de-Sitter space absorbs gravitational waves. The result was a close match to the experimental value – a triumph for a decidedly left-field approach.

This was no fluke. Last year, theorists made the same leap of faith with another, very different exotic phase of matter that had been made at Duke University in North Carolina. Here lithium atoms are suspended in an intricate web of laser beams and cooled to a temperature 10 billion billion times lower than that of the sizzling quark-gluon plasma. Again, they behave as a superfluid. The correct behaviour can be calculated with conventional theory at the expense of some complex mathematics – but AdS/CFT could provide the right answer much more easily.

Zaanen pinpoints the moment at which his area got into bed with string theory as a paper published in 2007 by Hartnoll, fellow Harvard physicist Subir Sachdev and a couple of colleagues (*Physical Review B*, vol 76, p 144502). It applied the AdS/CFT correspondence to high-temperature superconductors – the mysterious materials to which Zaanen had devoted so many years of theoretical effort. In these materials, electrons can flow without resistance, losing no energy as heat, at temperatures as mild as 150 kelvin.

> "When Maldacena presented his theory, his colleagues joined in with a specially composed version of *The Macarena*"

High-temperature superconductors behave as they do because of the way electrons organise themselves in the material, but 20 years and hundreds of thousands of research papers on from their discovery, we are no closer to knowing exactly how that is. "If someone genuinely knew the microscopic description of a high-temperature superconductor, they would already have a Nobel prize," says Joe Bhaseen, a condensed matter physicist at the University of Cambridge.

The paper by Hartnoll and his colleagues concerned the Nernst effect, which occurs when a magnetic field and a temperature gradient applied to a material produce a voltage at right angles to both. The effect is particularly pronounced in high-temperature superconductors. Conventional theory can predict the magnitude of the Nernst effect, but requires pages of laborious algebra. Hartnoll's team showed that AdS/CFT correspondence produces the same answer in just a few lines. It was the first time that AdS/CFT and normal approaches had been tested against a real experimental result in condensed matter physics – and the language of black holes came up with by far the more fluent answer.

"I THOUGHT STRING THEORY WAS HOCUS-POCUS"

Jan Zaanen - matter theorist and backdoor string enthusiast

String theory isn't easy to learn. I got interested in it because I was frustrated that I could understand everyone speaking at physics lectures except the string theorists. I thought I ought to know what these guys were talking about - it sounded like hocus-pocus, but they were pretty obsessed. I wanted to find out why.

So in 2005 I employed a couple of string theorists, and one of them organised a course. It took two years and two 1000-page books of dense mathematics, but I learned string theory and got kind of enchanted by it.

Then the AdS/CFT thing began to encroach on my horizon when it started to make predictions about high-temperature superconductors, my traditional mainstay. I was one of the few condensed matter physicists with the preparation to take it up.

As far as the bigger picture goes, gravitational physics seems to be infinitely far away from how atoms and particles behave, but with string theory, it is all part of one package. It tells you that there are deep relationships between the nature of space and time and quantum physics.

Hartnoll and others have since developed the idea of the "holographic superconductor" further. They are still far away from a theory of how high-temperature superconductors work, Hartnoll stresses, and he doesn't expect string theory to deliver that on its own. Yet by enabling us to compute with ease certain properties of the superconductors – how their resistance changes with temperature, or how the temperature at which superconductivity kicks in is related to how electrons behave – it provides an unexplored route towards it.

High-temperature superconductors are not the only useful materials that might benefit from the AdS/CFT approach. Sachdev has used the correspondence to compute properties of the plasma of electrons found in graphene – sheets of graphite a single atom thick that have been touted as a successor to silicon as the base materials of microelectronics.

Where does all this leave string theory and the search for a theory of everything? Clifford Johnson, a string theorist at the University of Southern California in Los Angeles, thinks that the subject could mature simply by broadening its horizons. Honing its mathematical tools on condensed matter, where results from the lab provide stringent tests of any predictions it might come up with, will furnish string theory with a more powerful arsenal for attacking areas where verification comes less easily.

Others suggest the lesson is that string theory should lower its sights, and concentrate less on lofty claims that it harbours a theory of everything and more on where it can actually produce results. Whatever the answer, for Zaanen his new direction has been an eye-opener. "The correspondence is fascinating stuff because it allows you to relate very different chapters in the book of physics," he says. "It's been superb entertainment." ■

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