Hit a wall? Take a holographic view

From pre-big bang physics to the origins of mass, there may be no limit to holography's reach

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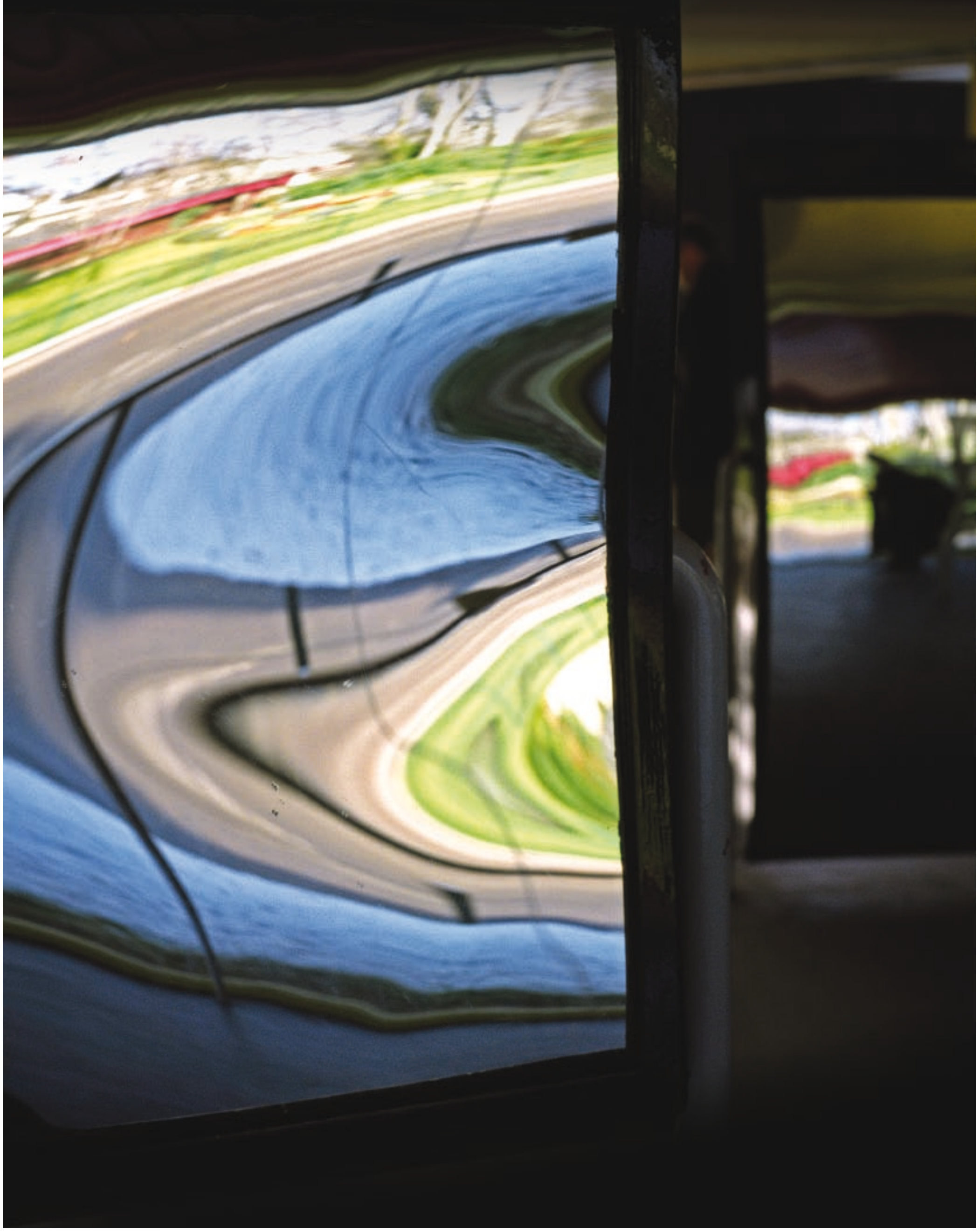

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HOW would you feel if you were told that everything you did today – drinking your morning latte, your commute, your post-work jog – was a holographic projection of another, flat version of you living on a two-dimensional "surface" at the edge of this universe?

Whether we actually live in a hologram is up for debate, but it is now becoming clear that looking at a raft of other phenomena through a holographic lens could be key to solving some of the most intractable problems in physics, including what gives particles mass, the physics that reigned before the big bang, even a theory of quantum gravity. There may be no limit to holography's reach.

To discuss some of these new uses, last month, a motley bunch of string theorists and particle physicists from 13 European countries assembled at the Ecole Normale Supérieure in Paris, France, for the first meeting of a European collaboration called the HoloGrav Network. Elsewhere, physicists are also taking a keen interest. "I have never encountered a feeling that the rules are changing as rapidly as they are now," says Jan Zaanen, a condensed matter theorist from the University of Leiden in the Netherlands, who is not part of HoloGrav.

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To understand the part holography plays in these problems, rewind to 1997 when string theorist Juan Maldacena, now at the Institute for Advanced Study in Princeton, New Jersey, made an interesting discovery. Just as the 3D holographic bird that seems to pop out of your credit card can be encoded in a 2D etching, so the physics of general relativity in a hypothetical, string-

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theory universe of five dimensions is mathematically equivalent to a quantum particle description of what is happening on a 4D "surface" (see "Duality's gift to strings"). The tool he used is known as the anti de Sitter/conformal field theory correspondence (AdS/CFT).

Although we live in a flat universe, whereas the 5D AdS one is saddle-shaped, this duality offered a way to solve problems in one sphere using the mathematics from the other. It also linked general relativity and quantum mechanics – two pillars of modern physics that, aggravatingly, tend to resist unification. Eager physicists began testing out the correspondence and seeking dualities between other quantum particle and gravity theories that are a better fit for our universe.

This was especially welcome in quantum chromodynamics, which explains the interactions between the quarks and gluons that make up the nuclei of atoms. QCD sums are fiendishly difficult when the particles are interacting strongly with each other, as they do in the nucleus, but substitute QCD into the CFT half of the duality and out pops an equivalent problem in the higher dimensional AdS form. Now the problem is reformulated so that the more manageable, classical equations of general relativity apply. The sums go from something that would take a supercomputer weeks to solve to "almost a pen-and-paper problem", says HoloGrav member Nick Evans of the University of Southampton in the UK.

The idea has been used to simplify a bevvy of problems in which strong interactions were causing headaches, such as in mysterious high-temperature superconductors, materials with weird properties known as "strange metals", and what happens when exotic forms of matter change state. But it is only in the last couple of years that physicists realised the potential of dualities like AdS/CFT to tackle some of the most fundamental mysteries of our universe.

One of the biggest and most well-known enigmas is what endows particles with mass. Our best guess is the Higgs mechanism – in which a sticky, pervasive "Higgs field" bestows mass on matter through the effect of Higgs particles – but it is not the only idea. "You could replace the Higgs mechanism with something related to the strong force," says Evans, "but because strongly interacting theories are so incalculable, it has been impossible to know how to go forwards with the idea."

A theory based on the strong force, which holds gluons and quarks together in particles such as protons, is a candidate for generating mass because, somewhat counter-intuitively, the attractive force between the particles increases as they get further apart. Because there's an energy associated with this interaction, mass is generated as the particles are separated. In other words, when quarks are on top of each other, they are effectively massless but as soon as they start to move apart, say to the distance they are at in a proton, they gain mass. If this applied to all other particles too, there would be no need for a Higgs mechanism – we would be able to describe where mass comes from just by using a variation of the strong force. The trouble is that the calculations are of the fiendishly difficult QCD type.

Enter AdS/CFT. Evans and his colleagues are trying to use the duality to transform quantum descriptions of how variations of the strong force change as particles move apart into theories of higher dimensions, which can then more easily be used to replicate the masses we see (*Physical Review D*, DOI: 10.1103/PhysRevD.81.025013).

"Once the theory is properly fleshed out, we will be able to apply it to almost any problem"

Meanwhile, Kostas Skenderis at the University of Amsterdam in the Netherlands and colleagues want to know what laws of physics held sway before the big bang – and how these played out in the immediate, explosive moments afterwards.

The big bang is notoriously difficult to model because it involves a singularity – a point where extreme gravitational forces mean the density of matter and energy is infinite.

A property of AdS/CFT is that when particles are interacting strongly in one half of the duality, their counterparts interact weakly in the other half – and vice versa. Skenderis reasoned that AdS/CFT can be used to turn the problem of what happened in the big bang singularity into a weakly interacting (and therefore less challenging) particle theory.

The result was a particle model that predicts what should have happened in the moments after the big bang, given certain prior scenarios (*Physical Review D*, DOI: 10.1103/PhysRevD.81.021301). The next step is to see which scenarios match with the cosmic microwave background, the radiation left over from the big bang. He will be able to do this when CMB data becomes available from the Planck satellite next year.

Some are even hoping the correspondence, which forms a rare bridge between classical and quantum theories, could shed light on a long-sought theory of quantum gravity. At present, we only have vague ideas about how that would work. "I feel that is down to a lack of imagination on our part," says Evans. Skenderis's work on the big bang singularity may offer a route to a duality that exactly describes our universe.

One thing for certain is that the correspondence will remain a useful tool. Leonard Susskind of Stanford University in California, one of the original architects of the holographic principle, describes the duality as the "new orthodoxy". Skenderis is convinced that we are only just beginning to see its potential. "If we look forward to 50 years from now, we will see this period as a precursor to a time when physics is totally reformulated in the language of holography," he says. "Once the theory is properly fleshed out, we will be able to apply it to almost any problem." ■

DUALITY'S GIFT TO STRINGS

Holography's ability to link very different types of physics has its roots in string theory.

String theory is defined in 10 dimensions but our world consists of only four: three spatial plus one of time. This discrepancy can be reconciled by imagining that we live on a "brane", where three-plus-one dimensions exist in a broader "bulk" containing the others. And there are two ways to interpret this brane.

In one interpretation, it is a surface on which the strings are tethered. In the other, the brane acts like a massive object that warps the fabric of space-time around it in a saddle shape. Looped strings live in this curved space and correspond to gravitons - hypothetical particles that transmit the gravitational force. These strings "see" one more dimension than the strings in the former interpretation. Juan Maldacena (see main story) realised that the two are holographically related, just like a flat surface encoding a hologram and its 3D projection.

This holographic duality was a boon for string theory. "It used to be a clutter of bits and bobs," says Nick Evans of the University of Southampton, UK. "With the duality you have a definitive definition... making us feel that now we are in the right century."

holography’s reach