# The Black Hole and the Babel Fish

Subir Sachdev needs a universal translator to unite condensed matter physics and string theory. Has he found it?

**by KATE BECKER**

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In *The Hitchhiker's Guide to the Galaxy*, writer Douglas Adams proposed a novel solution to the classic science fiction problem of the interspecies language barrier: a babel fish. Stick this wriggly yellow fish in your ear and you can understand any language in the universe, instantly.

Sadly, there is no such thing as a babel fish (and even if there were, we don't have any interplanetary aliens to try it out on). But Harvard physicist Subir Sachdev and his colleagues have tapped into a different kind of translator: An object that effortlessly translates from the language of very small things, like photons and quarks, to the language of big things like, well, people. It's not little, yellow and wriggly, and you definitely shouldn't stick one in your ear. It is a black hole.

Sachdev never set out to study black holes. "The last time I studied gravity was in grad school," he laughs. "I have to relearn all these things!"

Instead, Sachdev's work for the past two decades has focused on quantum phase transitions. We're all familiar with classical phase transitions, like ice melting to form water or water boiling to create steam. In these examples, heat prods the atoms into motion and brings about a change of phase. Sachdev investigates the quantum cousins of these transitions.

## Quantum Magic Wand

According to quantum mechanics, atoms are never completely still. Heisenberg's uncertainty principle tells us that we can never know a particle's position and momentum at the same time. If the position of an atom is pinned down to a small region of space, quantum uncertainty means that it must have some momentum, keeping the atom buzzing. It's the subtle action of quantum uncertainty that nudges atoms between phases, just as heat can change water to steam, says Sachdev.

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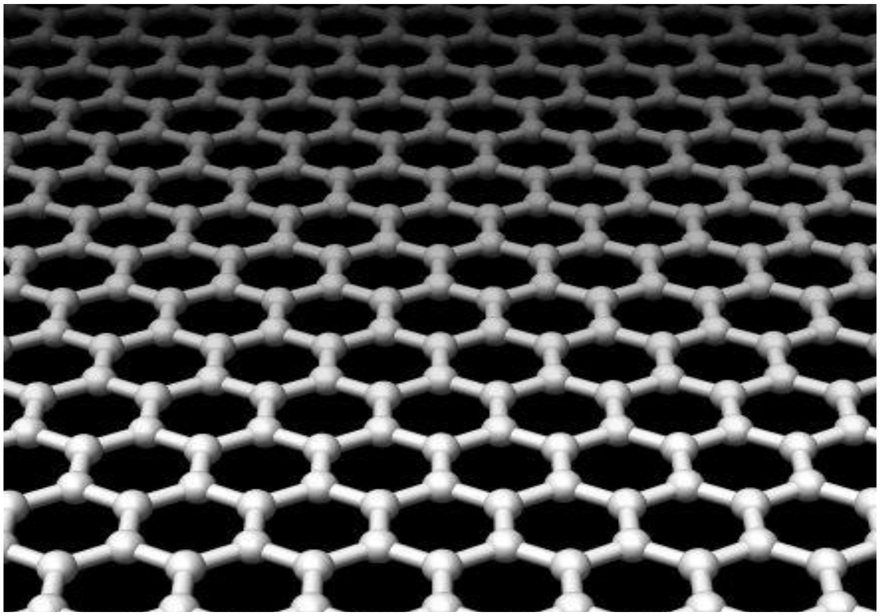
> \- *Subir Sachdev*

Quantum phase transitions are at the heart of many of the most bizarre—and potentially useful—materials being tested in labs today. The Fairy Godmothers of materials science, these transitions can turn ordinary materials into virtual Cinderellas. There are ceramic compounds of copper and oxygen, which snap from an insulating state to a superconducting one with a flick of the magic wand (or, more precisely, with a cool dip in liquid nitrogen); there's graphene, an ultrathin, crystalline version of the stuff in pencil lead, which has opened up to experiment a whole new class of one-atom-thick materials and could one day replace silicon in a new generation of ultrafast computers. The exotic menu of materials goes on.

Sachdev, however, has always been most interested in these materials' more esoteric properties. He's fascinated by the point at which the material is "delicately balanced in between" phases. If an insulator is black and a superconductor is white, Sachdev studies the fleeting gray in between.

In most systems, Sachdev explains,



**GRAPHENE GATEWAY**

**The one-atom-thick material could open a doorway to understanding the quantum-classical divide.**

(Credit: *Thomas Szkopek*)

quantum effects disappear on all but the tiniest scales, and the behavior of the system can be described using classical physics alone. But things are not so clear cut when quantum phase transitions come into play. Near the *quantum critical point* at which these transitions occur, the classical description fails. It is at this tipping point that Sachdev believes physicists can access the peculiar boundary that separates the microscopic world of quantum physics from the macroscopic world with which we are all familiar.

Okay, but where do the black holes come in? “So far no connection to the cosmos,” Sachdev quips.

But, in fact, it turns out that the only known mathematical description that works for both the quantum and classical scales comes out of a gravity theory used to describe black holes.

## Black Holes and Holograms

To understand the whole picture, we have go back to 1997, when black holes weren’t even a glimmer in Sachdev’s eye. In that year, theoretical physicist Juan Maldacena, now at Princeton University, published a startling—if obscure—theoretical insight. He showed that if you take our universe, slap on an extra spatial dimension, and fashion it with a negative curvature, it’s identical (mathematically speaking) to a universe with three spatial dimensions and no gravity, suffused with quantum fields.

> It might sound like a theoretical physicist’s bad joke.
>
> *- Jan Zaanen*

That sounds a little arcane, but for physicists, the implication was something we can all understand: It made their work easier. Problems that were difficult in one domain were (relatively) simple in the other, and vice versa. For Sachdev, who can routinely ignore the comparatively puny force of gravity in his work, Maldacena’s insight opened a mathematical back door to seemingly impossible problems.

“This correspondence relates two theories that seem completely distinct—one is a theory that involves gravity whereas the other does not,” explains Sean Hartnoll, a postdoc and string theorist at Harvard, and Sachdev’s collaborator.

Maldacena’s “duality” echoed another strange mathematical confluence, this one due to Stephen Hawking at Cambridge University and Hebrew University physicist Jacob Bekenstein, who developed mathematical descriptions of black holes that run parallel to the laws of classical thermodynamics. In particular, they showed that a black hole’s entropy—classically, the number of possible configurations of particles in a system—is proportional to its surface area.

Hawking and Bekenstein’s result was “quite shocking,” Sachdev says, because every other object in the universe has an entropy that is proportional to its volume. Black holes, then, somehow encode three-dimensional information in a two-dimensional equation. Physicists call this property “holographic,” because it is reminiscent of the shiny two-dimensional images that seem to project 3D objects, like the bird on a VISA card. In this context, Maldecena

**SUBIR SACHDEV**
**Harvard University**

had shown that a theory without gravity could be a hologram of another theory with gravity, says Sachdev.

The whole thing "might sound like a theoretical physicist's bad joke," physicist Jan Zaanen, of Leiden University in the Netherlands, quipped in *Nature*. But it immediately became a touchstone for physicists trying to bridge the gap between gravity and quantum mechanics. "Difficult quantum gravity problems could now be attacked using well-developed quantum field theory methods," explains Hartnoll, and "difficult problems in quantum field theory, of the sort that arise in both particle physics and condensed matter physics, could now be attacked using general relativity."

Sachdev describes the technique as linking "three foci of modern physics"—quantum phase transitions, hydrodynamics (the collective properties of groups of atoms), and black holes. Using the black hole as a mathematical translator, quantum phase transitions could be made to speak the same language as hydrodynamics.

Sachdev first considered applying Maldacena's discovery to his own work when he encountered Hartnoll. The pair originally met at the Kavli Institute for Astrophysics in Santa Barbara, where Hartnoll was a postdoctoral researcher and Sachdev was a visitor. Hartnoll had been studying string theory and general relativity, and had just coauthored a paper that used Maldacena's approach to describe the *Hall effect*—an effect seen in electrical conductors involving the voltage generated by a current flowing perpendicular to a magnetic field.

Since his formulas worked for conductors, Sachdev suggested that the same formulas might be applied to superconductors as well. Sachdev, Hartnoll, and their collaborators tried it out on the *Nernst effect*, a phenomenon that relates the temperature and electric current of a conductor in a magnetic field, and the formulas worked. The result: a novel, elegant mathematical look at how materials behave as they teeter between superfluid and insulating states. But that was just a "rather modest" piece of a much bigger picture, says Hartnoll.

"The reason I was specifically interested in applications to condensed matter physics was that it seemed the best bet for using string theory to make progress on 'real world' physics," recalls Hartnoll.

## Culture Clash

Zaanen agrees, citing string theory's reputation as all math and no experiment: "At a moment that the string theorists were under maximal pressure to deliver something relevant to empirical reality, the big surprise popped up that their mathematical highlight," the duality described by Maldacena, was relevant "to the most empirical of all fields in physics—the condensed matter branch."

"In a way it works too well," Zaanen says of the duality. "This seems to hint at yet deeper meanings to the gravity-quantum field theory connections which are at the heart of the trade, and it might well be that it will trigger a major shift in the understanding of the foundations."

Sachdev and his collaborators hope that their work may be cracking open a doorway to a much deeper truth about the universe we live in.

But before that can happen, Sachdev and his colleagues must track down a new set of materials to which they can apply their technique. "The key question is to identify problems where these techniques can be fruitfully used and then solve them," says Hartnoll. "Finding the right problems is therefore the first key step that requires input from both fields."

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>
> *-Sean Hartnoll*

For that to happen, string theorists and condensed matter physicists will have to start talking to each other. "There is an enormous culture gap, but it is actually big fun to be in the middle, trying to communicate to both sides," says Zaanen.

Sachdev was recently awarded an FQXi grant of over $80,000 and plans to use it to bridge this "culture gap" and stimulate cross-disciplinary collaboration in both theory and experiment. Hopefully, he'll succeed—even without the babel fish.

**A BABEL FISH IS ALL YOU NEED...**
(Credit: *Jevgenij Kazanov*)