Betting on the Future of Quantum Gravity

By Natalie Wolchover

Einstein described gravity as equivalent to curves in space and time, but physicists have long searched for a theory of gravitons, its putative quantum-scale source.

Zvi Bern is riding a winning streak more befitting a poker shark in Vegas than a theoretical particle physicist at the University of California, Los Angeles. He is famous in his field for betting colleagues that he can calculate with increasing precision the behavior of gravitons, hypothetical particles that are believed to impart the force of gravity. At stake in each wager is a fine bottle of wine. Against all odds, Bern's wine collection is growing.

"Unfortunately, I've been on the losing side of these bets," said Kelly Stelle, a professor of particle physics at Imperial College London and Bern's frequent opponent. Each loss has its consolation prize, however. As Bern and his team pull off increasingly sophisticated calculations, the odds improve that they possess the framework of a working theory of quantum gravity, which would describe the quantum-scale source of the force that moors planets to stars and keeps feet on the ground.

"I keep on telling him, he can't lose," Bern said.

Physicists have searched for a theory of quantum gravity for 80 years. Though gravitons are individually too weak to detect, most physicists believe the particles roam the quantum realm in droves, and that their behavior somehow collectively gives rise to the macroscopic force of gravity, just as light is a macroscopic effect of particles called photons. But every proposed theory of how gravity particles might behave faces the same problem: upon close inspection, it doesn't make mathematical sense. Calculations of graviton interactions might seem to work at first, but when physicists attempt to make them more exact, they yield gibberish — an answer of "infinity." "This is the disease of quantized gravity," Stelle said.


UCLA particle physicist Zvi Bern in 2009 with a bottle of wine he won in a bet against Paul Howe, then of King's College London.

But now, Bern is betting big on a once sidelined theory called supergravity, which posits the existence of new gravity-related particles that mirror gravitons' effects. Supergravity, developed in the 1970s, has long been assumed to suffer from the infinity problem, which would indicate that the theory is mathematically flawed. But the calculations were so difficult that no one could find out for sure — "until Bern and his friends came along," Stelle said. Using newfound tools and shortcuts, Bern and his team are now calculating these gravitational interactions with ever-increasing precision. Instead of blowing up, the theory keeps making sense.

Supergravity itself cannot exactly describe nature, because it was designed for a more symmetric theoretical world. But if the theory holds up in Bern's current wager with Stelle, then it could provide physicists with the scaffold they need to build a more realistic theory. "It means that supergravity has a very special structure," Bern said. "I believe it would be the key to unlocking a theory of gravity."

Bern's calculations are part of a larger drive to understand the full nature of gravity. He is dealing in handfuls of colliding gravitons, but the ultimate theory of quantum gravity must also make sense of the mighty swarms that constitute black holes. Profound conceptual puzzles posed by black holes suggest that the true theory will demand a radical new perspective on the universe — one in which space and time are mere illusions. One alternative approach makes use of the amplituhedron, an object that simplifies calculations of certain particle interactions and could help physicists resolve some of the puzzles.

"We're sort of on the right track," said Steve Giddings, a professor of theoretical physics at the University of California, Santa Barbara, who is a leading expert on black hole paradoxes. "We can see the outlines of a black hole in the calculations."

Going Quantum

Albert Einstein theorized that gravity is a consequence of curves in space and time. As the space-time fabric stretches under the weight of heavy objects, smaller objects fall toward them. Einstein's theory works perfectly for describing gravity on the macroscopic scale, where apples fall to the ground and Earth orbits the sun. But when his equations for calculating the outcomes of gravitational interactions are applied to the smallest possible ripples in the space-time fabric — the bundles of energy known as gravitons — the calculations go haywire. "Einstein gravity is polluted with infinities," Stelle said.

The problem is that gravitons can theoretically interact in infinitely many ways. Physicists calculate "scattering amplitudes," numbers that represent the probabilities of different outcomes of particle interactions, by drawing pictures of the various ways the particles can morph or shuffle during an interaction, and then summing the likelihoods of the different drawings. (The pictures are called "Feynman diagrams" after their inventor, Richard Feynman.) Unlikely, convoluted diagrams far outnumber likely, straightforward ones. This means that computing a scattering amplitude for each new level of precision requires drawing exponentially more Feynman diagrams and solving a vastly more complicated mathematical formula. In some cases, these formulas simplify neatly. For graviton interactions as defined by Einstein's equations, they do not.

Supergravity tries to help by adding new "supersymmetries" to Einstein's theory. Like mirrors, these dictate that if one type of particle exists, then so must its opposite. In a variant of the theory called $N = 8$ supergravity, which has eight such doublings, the new mirror-image particles allow physicists to cancel out some of the more troublesome parts of the formulas. This approach works for the first four levels of precision. But experts have long suspected that infinity would rear its head again if they tried to make the calculations more exact. "You reach a point where the diagrams are so complicated that supersymmetry can't cancel it anymore," explained Kristan Jensen, a physicist at Stony Brook University.

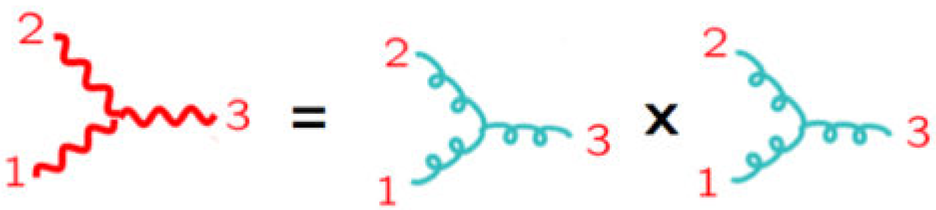
According to Bern, that long-held assumption "may not be true."

In the 1990s, Bern, Lance Dixon of the SLAC National Accelerator Laboratory in Menlo Park, California, and David Kosower of CEA Saclay in France developed powerful new techniques for computing scattering amplitudes, for which they will receive the 2014 J. J. Sakurai Prize for Theoretical Particle Physics in April. Their shortcuts have streamlined calculations about the known particles of nature, enabling theorists to predict with stunning precision the outcomes of collisions at the Large Hadron Collider in Switzerland, and then look for "new physics" in the form of deviations from these predictions. In the mid-2000s, Bern, Dixon, Kosower and other collaborators also began applying the techniques to the much more theoretical — and formidable — supergravity calculations that were abandoned decades ago. When the calculations started yielding finite results, "that was just an incredible shock," said John Joseph Carrasco, a physicist at Stanford University who works with Bern.

Henrik Johannson of CERN, Zvi Bern of UCLA and John Joseph Carrasco of Stanford (left to right) discovered in 2008 that gravitons behave very much like two gluons laid on top of each other.

The most powerful shortcut for completing the supergravity calculations emerged from the discovery by Bern, Carrasco, and Henrik Johansson of CERN Laboratory that [gravitons behave like two copies of gluons], the carriers of the strong nuclear force, which "glues" quarks together inside atomic nuclei. This "double copy" relationship between gravitons and gluons has shown up in every variant of supergravity the researchers have studied, and they expect it to hold in the correct theory of quantum gravity, too, regardless of [whether supersymmetry exists in nature]. In practice, the discovery means that once a gluon's scattering amplitude has been computed in a particular form to a given level of precision, "extracting the gravity amplitude is child's play," Dixon said.

The double-copy property is more than a calculation tool. "It's also a philosophical shift in how we should be viewing gravity theories," Bern said. "This is very concrete and makes absolutely clear that [gravitons and gluons] really do belong together. They really should be part of a unified theory."



To calculate the properties of graviton collisions (red), physicists can use two copies of the equivalent interaction in gluons (blue), which are much easier to work with.

In Giddings' words, "it's extremely suggestive." Because physicists have an operable quantum theory that describes gluons, called quantum chromodynamics, the double-copy property suggests that supergravity (or a related theory) might work, too.

For the latest wager with Stelle, Bern and his collaborators will subject $N = 8$ supergravity to an unprecedented test. If they can calculate what happens when gravitons collide to a level of precision known as "five loops" in a fictional world with 4.8 space-time dimensions, then Bern wins. In that case, Stelle must give him a bottle of Flint Dry from the Chapel Down Winery in England. "It's the wine that was served at William and Kate's wedding," Stelle explained.

If, on the other hand, the calculation yields infinity in 4.8 dimensions, then Stelle wins. In that case, Bern must settle up with a bottle from Stags' Leap in Napa Valley.

Of course, fractional dimensions don't really exist. But Stelle and his colleagues have shown that the five-loop calculation for 4.8 dimensions roughly corresponds to a much more difficult seven-loop calculation in the dimensions of the real world. (The full seven-loop calculation is the subject of another bet between Bern and Nobel Prize winner David Gross of the University of California, Santa Barbara.) If the theory remains finite to such a degree, "that would be a real miracle," Stelle said. The harmonious interplay between the particles in $N = 8$ supergravity would go beyond what physicists understand.

It's too early to tell how the wager between Bern and Stelle will turn out. However, in work that appeared in Physical Review Letters in December, Bern's team found "much better than expected behavior" of another variant of the theory called $N = 4$ supergravity, and that result has changed the odds. "It's fair to say things are looking in my favor now," Bern said.

Black Hole Woes

Any theory of quantum gravity must get to grips with black holes, which are described by Einstein's theory as inescapably steep curves in space-time, but which, at a more fundamental level, are intricate quantum systems that transcend description even in terms of gravitons. Explaining these systems may require a radical new perspective on how nature works.

Black holes form when particles collide with a total energy of more than 10 billion billion protons (called the "Planck energy"). At such high energies, an infinite number of Feynman diagrams are needed to make even a rough approximation of the scattering amplitude. This cripples physicists' efforts to directly calculate the detailed quantum properties of black holes, even those in the highly symmetric world governed by $N = 8$ supergravity. Extrapolating Bern and his colleagues' calculations for low-energy gravitons to high energies crudely reproduces the familiar picture of a black hole — that of a steep curve in space-time. But this extrapolation isn't detailed enough to address physicists' deepest question about black holes: what happens to information about the particles that fall in (the so-called information paradox).

According to the principles of quantum mechanics, information about the states of particles can never be destroyed. Thus, when particles plunge into black holes, the information must go in with them. But quantum mechanics also says that black holes evaporate and eventually disappear completely. Where does the information go?

Physicists are still actively debating the information paradox, but there is a growing consensus that its resolution will ultimately force them to relinquish a long-standing assumption called locality, the notion that particles only interact from adjacent positions in space and time. If particles inside and outside black holes can somehow exchange information, then information from evaporating black holes can be rescued. "Locality is a cornerstone of our fundamental description of physics today," Giddings said, "but in my mind, the least crazy thing to do is modify it in some way."

Removing locality from particle physics could require a complete reformulation of the way Bern and other physicists calculate scattering amplitudes, because Feynman diagrams are drawn on the assumption that particles interact from adjacent points in space-time. Motivated by this problem, a group led by Nima Arkani-Hamed, a professor of physics at the Institute for Advanced Study in Princeton, N.J., recently discovered a much simpler approach to calculating scattering amplitudes — at least for a highly supersymmetric version of quantum physics. In the new approach, gluon scattering amplitudes can be computed by measuring the volume of an amplituhedron, a geometric object whose shape is determined by the number and properties of the gluons involved in an interaction. Locality does not enter into the calculation at all; the impression that collisions occur in space and time is merely a feature of the outcomes of calculations.

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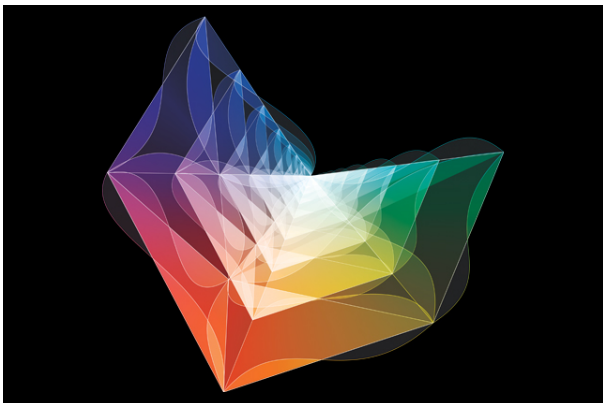

“The amplituhedron has the right feel,” Giddings said. “These guys unearthing this very pretty structure for describing amplitudes may be unearthing some profound new way to look at gravity that will carry over to the black hole regime.”

Bern and his colleagues do not use the amplituhedron in their supergravity calculations, but “we’re definitely thinking about how to import the ideas they have, and vice versa,” he said. The amplituhedron corresponds to interactions between gluons, and so the fact that gravitons behave like two copies of gluons could point the way to a geometry that incorporates both elementary particles.

“If there was an amplituhedron-like object for gravity,” Arkani-Hamed said, “the idea would be, there’s this object sitting there outside space-time that gives you the answer to any scattering event.” Sometimes, the answer would be local, conveying the impression that space and time exist. For interactions with the unknown quantum system that constitutes black holes, answers would not depend on space and time.

“The real issue is understanding how that works,” Giddings said. “How can we have physics which behaves very locally in many circumstances but there’s an apparent departure from locality in the presence of black holes? How do we think about where locality comes from and why it isn’t exact?”

The physicists are actively discussing how the different threads of quantum gravity research might come together. A vague picture may be emerging — one of gravitons, gluons and other particles acting in concert, perhaps as the components of some grand, nonlocal geometry — but they caution that it will take a huge amount of effort to make their loose ideas mathematically concrete, and to adapt them to the real world. As Jensen put it, “There’s the stories and then there’s the calculations.”

Bern reports that he and his collaborators are “pushing along quite hard” on their latest supergravity calculation. If, in the next few months, they get a finite answer for graviton scattering in 4.8 dimensions, then $N = 8$ supergravity will look like a viable, calculable theory of quantum gravity more than ever before, motivating particle physicists to try to fine-tune the theory to describe the less symmetric world we live in. “We would have to take a step back and try to find ways of twisting this theory around and maintaining its finiteness property,” Dixon said.

If, on the other hand, $N = 8$ supergravity cracks under pressure, then important factors must be missing from the theory, just as they are missing from Einstein's gravity. Many particle physicists think these missing factors would be part of string theory, an even more elaborate theory of nature that encompasses supergravity and says gravitons and all other particles are actually one-dimensional lines, or "strings." Incorporating the effects of vibrations of the strings repairs the calculations. But string theory does not predict a unique set of scattering amplitudes (having instead a vast landscape of possible solutions), and so the search for a calculable and predictive theory of graviton scattering would hit a barrier.

Given his past successes and growing wine collection, Bern is optimistic that supergravity will hold up. In that case, he'll get the royal wedding wine, but, he said, "both Kelly and I will be celebrating."

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