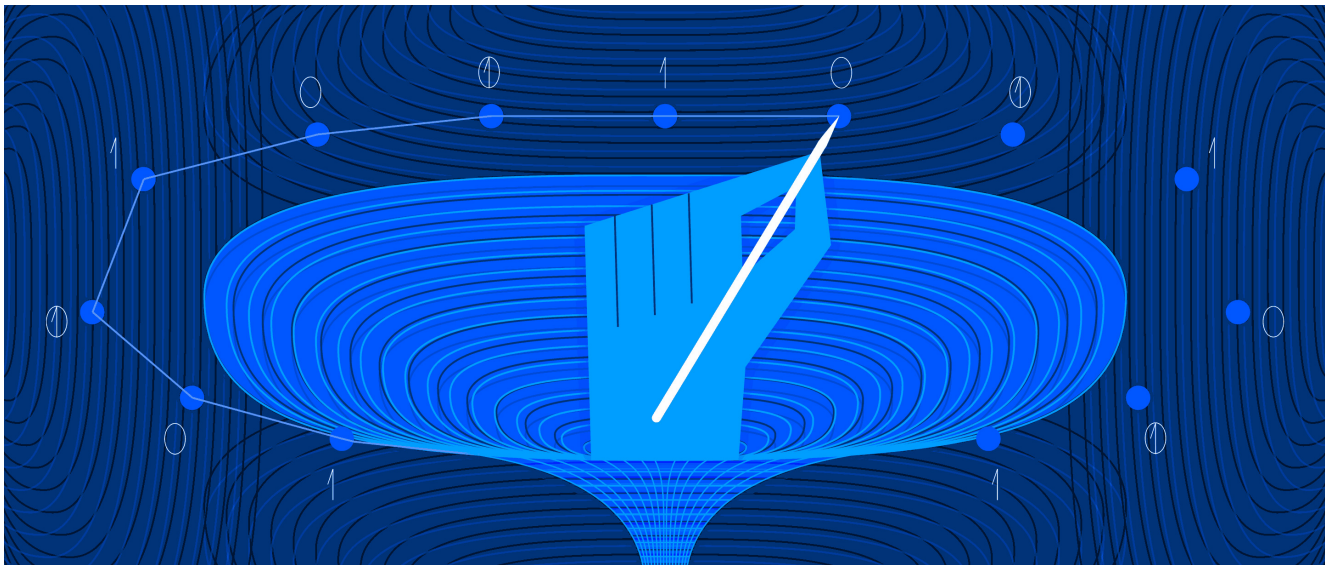


Spotting Quantum Black Holes in the Lab

By [John Preskill](#)

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Can we test speculations about how quantum physics affects black holes and the Big Bang?



[James O'Brien](#) for Quanta Magazine

In physics, we discover a new law by making a guess, and then comparing the consequences of the guess with experimental results. As the ever-quotable Richard Feynman put it: “It does not make any difference how beautiful your guess is. It does not make any difference how smart you are ... if it disagrees with experiment it is wrong.”

This is the essence of what separates physics from, say, math. Mathematicians make guesses too, and their final arbiter of the truth is rigorous proof. Physicists may use or even invent sophisticated mathematical tools, but theirs is a different objective: to explain the universe as it really is. For that purpose, experiments are indispensable.

Of course, experimental validation may lag far behind our theoretical speculations. It took 100 years for scientists to detect gravitational waves on Earth, and 50 years to discover the Higgs boson. Both required much ingenuity, technological development and monetary investment. And those experimental observations not only confirmed theoretical predictions, they also taught us something new, while opening the door to further investigation. We expected that astrophysical sources could produce detectable gravitational waves, but we couldn’t know how common those sources would be, and we had reason to believe the Higgs boson existed but were not sure about its mass.

The study of quantum gravity is an extreme case of theory getting in front of experiment. We have a quite satisfactory understanding of quantum physics at the scale of atoms and subnuclear particles, but no experimentally validated quantum theory that applies to very strong gravitational forces. Without such a theory we cannot understand what happened in the early universe right after the Big Bang, or predict the exact fate of an unfortunate astronaut compressed to unimaginably high density

within a black hole. We need experiments to guide us, yet they are depressingly elusive.

The history of particle physics provides an instructive parallel. By the 1950s, we had a theory of the weak nuclear force that agreed with experiment. But for purely theoretical reasons, we knew that it was flawed and incomplete; we could even estimate that the theory's predictions would fail at very short distance scales, around 10^{-18} meters or less. Eventually, accelerators powerful enough to explore matter at these tiny scales led to the discovery of new phenomena, such as the W and Z bosons and the Higgs particle, pointing toward a more complete theory.

With gravitation, we again have good reason to believe that the current theory is incomplete, and here too we can estimate the distance scale at which new phenomena must appear: about 10^{-35} meters. Unfortunately, building a particle accelerator that could probe that scale using existing technology would require a machine about as big as the Milky Way galaxy. Clearly, that will be far out of reach even in the distant future.

Since investigating quantum gravity by “brute force” isn't going to work, we'll have to find a more ingenious and less direct way to make progress. And we do in fact have various proposals for probing quantum gravity in the lab, all requiring heroic — but not necessarily futile — efforts by experimentalists. I'd like to discuss one particular approach that I find exciting.

To understand it, let's focus on the formation and eventual evaporation of a black hole due to quantum effects, the quintessential phenomenon studied in quantum gravity. At first it may seem impossible, not to mention dangerous, to perform related experiments in the lab. But there may be a way.

Theoretical investigations of quantum gravity have established an astonishing equivalence between two different formulations of the same physical phenomena. Thanks to that equivalence, a black hole's life cycle can be described in a completely different language that does not involve gravity at all. Instead, the “dual” quantum system consists of many particles strongly interacting with one another. One goal of current research is to flesh out the dictionary that translates one of these languages into the other.



Quantized Columns

A regular column in which top researchers explore the process of discovery. This month's columnist, John Preskill, is a professor of theoretical physics at the California Institute of Technology, and his main research area is quantum information science. You can follow him on Twitter [@preskill](#).

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This equivalence of two different descriptions of the same underlying physics may seem like a “merely” mathematical observation, but its implications for experiments are profound. It turns out that the experimental tools needed to study the nongravitational description of a black hole are exactly the ones physicists have already been developing for completely different reasons — to operate quantum devices that solve very hard computational problems. That’s because in both a simulation of quantum gravity and a quantum computation, we need to store a complex system of many particles and accurately control how they interact.

I have been deeply interested in both quantum computing and black holes for many years, so for me this connection between the two is fascinating and satisfying. To be sure, [quantum computing technology](#) is still immature, so we won’t be able to simulate a realistic black hole in the lab anytime soon. That’s OK — we’ll settle for studying simplified models that capture some of the interesting features of quantum gravity. Even these can be instructive, and as quantum technology advances we’ll be able to do increasingly sophisticated experiments.

Furthermore, duality is a two-way street. Not only will quantum computers teach us about quantum gravity; by relating the behavior of many strongly interacting particles to gravitational phenomena, we can better understand that behavior. Typically, if we imprint some information at a particular location in a strongly interacting system, this information spreads rapidly and soon becomes exceedingly hard to read. But we know of a few intriguing situations where, for reasons that are far from obvious, the

information eventually refocuses and becomes easily readable at a different location far away.

When translated into the dual gravitational language, [this mysterious process is much easier to grasp](#). In this framework, a wormhole connects two distant points in space. The imprinted information disappears as it enters one end of the wormhole, and then reappears as it emerges from the other. Physicists long for such intuitive explanations of complex phenomena, and the joint efforts of experimentalists and theorists are bound to yield further insights of the same sort.

We sometimes worry that as science progresses, it continually splinters into narrower and narrower specialties that interact less and less with one another. But based on my own experience, I see a more powerful countervailing trend: As knowledge advances, scientists working in different fields find that they have more and more to learn from one another. The opportunity to probe quantum gravity in the lab is fueled by the speculations of high-energy theorists, but it also draws heavily from the expertise of condensed matter physicists, atomic physicists and computer scientists. These exciting and deepening connections make me optimistic about the future.