How to Build a Black Hole

Gravity and quantum mechanics are seemingly at odds. That, in a nutshell, is the biggest open problem in modern physics. We have two highly successful theories – gravity, as defined by Einstein's theory of relativity, and quantum mechanics, as expressed in quantum field theory – and no idea how to use both theories at once.

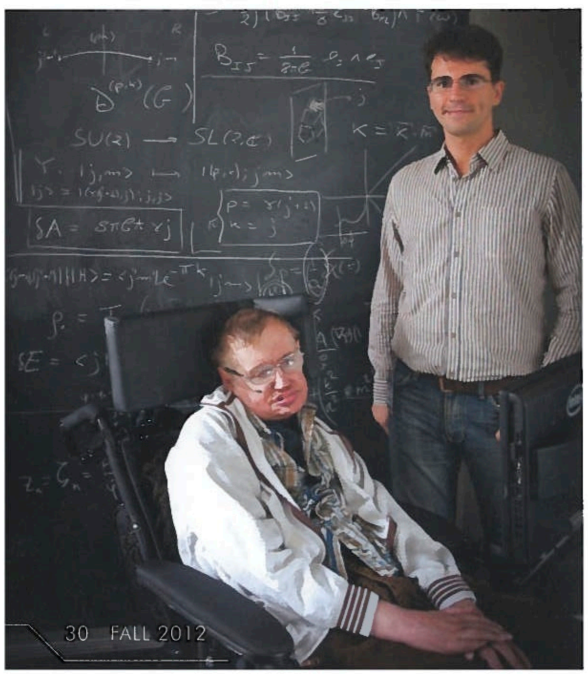
The two theories do, however, have a single, tantalizing intersection: the Bekenstein-Hawking formula for the entropy of black holes:

$$S = \frac{A}{4\hbar G}.$$

As physics formulae go, that's an attractive one. The math is simple. The equation fits on one line. And then there's that intersection: it is one of the few places in physics where G, Newton's constant (which defines the strength of gravity as we know it), meets *h*, Planck's constant (which defines the size of energy quanta in quantum mechanics). Quantum mechanics and gravity, together in one line.

Since this equation often seems the one signpost on the difficult road to quantum gravity, researchers revisit it regularly. Recently, Perimeter Postdoctoral Researcher Eugenio Bianchi made a landmark breakthrough: taking a loop quantum gravity approach, he re-derived the Bekenstein-Hawking formula from first principles.

Bianchi discussed his results with one of the originators of the Bekenstein-Hawking formula during his recent visit.



Loop quantum gravity, or LQG, is one of several competing theories which attempt to reconcile quantum mechanics and gravity. Among other things, LQG predicts that space is "discretized" at very small scales. If this is true, then quantities like area and length can only come in multiples of a fundamental unit of length, in much the same way Lego blocks only come in multiples of the same length.

There are a number of black hole entropy results in LQG, all consisting in a sophisticated counting of configurations. To understand the idea of configurations, consider a three-dimensional shape made out of Lego. If you wanted to build such a shape, you might use only the smallest kind of blocks, or you could replace two of the small blocks by a bigger block, or you could try to use as many big blocks as possible, only filling in the cracks with small blocks, and so on. There are a number of different ways to make the same shape out of different blocks. Taking the logarithm of that number will tell you the entropy of the Lego sphere. Analogously, in LQG, there are a number of different ways to make a black hole's horizon out of the discretized chunks of space, and entropy is a measure of this multiplicity.

One of the triumphs of loop quantum gravity is that calculating the entropy of a black hole by counting configurations gives an entropy that grows as the black hole grows. Indeed, it's directly proportional to the area of the hole's horizon, just as Bekenstein and Hawking predicted.

But until now, the equation showing the entropy of a black hole in loop quantum gravity contained a parameter not present in the Bekenstein-Hawking equation: the so-called Immirzi parameter γ, which defines the quantum of area – the size of a single Lego block. Specifically, that area is $A = 8\pi\gamma\hbar G j$. Since loop quantum gravity is built up from such blocks, the appearance of the Immirzi parameter in any LQG result is not a surprise – but still, it's not a perfect duplication of the famous Bekenstein-Hawking formula.

Another concern is the thermodynamic interpretation of the results. A black hole is a dynamic system with a temperature and energy, and it should be possible to interpret the entropy in terms of these quantities. Unfortunately, the usual "build and count" LQG calculations do not provide much insight into this matter.

Bianchi was determined to change that. On the chalkboard outside his office at Perimeter's Stephen Hawking Centre, he set to work studying the energy and temperature of each of the LQG Lego blocks that make up the one-way surface of a black hole – what physicists call the hole's horizon.

The hallway in the Hawking Centre proved the perfect place for such work, and not just because the building and equations share a namesake. It was also a place where Bianchi could easily share his ideas. For example, he employed a relatively new formalism in LQG called spinfoams, and was able to discuss his work with Perimeter Faculty members Lee Smolin and Laurent Freidel, two of the originators of LQG and spinfoams. Other colleagues would pass by his chalkboard and ask questions about his work, which helped him to further refine his argument. Among them was Carlo Rovelli, who first calculated black hole entropy in LQG and just happened to be visiting Perimeter at the right time to see Bianchi's work in progress.

After many such discussions and months of chalkboard work, Bianchi found that each LQG Lego block in a black hole's horizon contributes an entropy that's a simple multiple of the Immirzi parameter: $2\pi\gamma j$. Since the area of each block is also expressed in terms of the Immirzi parameter, the two γ's neatly cancel each other and the entropy of the black hole is just:

$$S = \frac{A}{4\hbar G}.$$

Bingo – a perfect match for the Bekenstein-Hawking formula. The Immirzi parameter is notably absent. Bianchi's formula even has the correct factor of ¼.

Rediscovering a formula from 30 years ago suggests that LQG might be on the right track. More importantly, it provides a stepping stone for a better understanding of LQG. As Bianchi says, "I think of the result I presented as a first exploratory step and I expect more developments in this direction in the future."

- Ross Diener

Further Exploration:

- E. Bianchi, "Entropy of Non-Extremal Black Holes From Loop Quantum Gravity," arXiv: 1204:5122.
- Watch Bianchi's talk, "Black Hole Entropy from Loop Quantum Gravity": PIRSA: 12050053.