Quantum Gravity and Symmetry

BY
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Quantum gravity and emergent spacetime

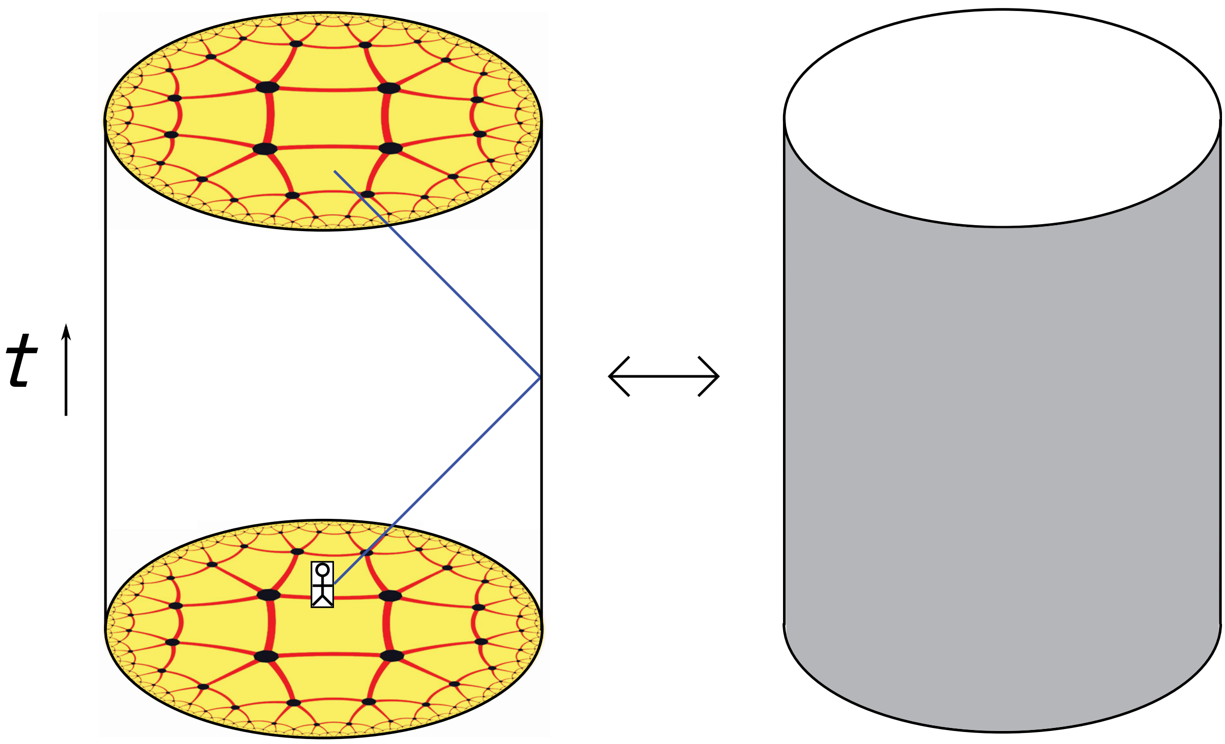
Our current best understanding of the fundamental laws of nature is a combination of using quantum mechanics to understand the behavior of elementary particles, such as electrons and quarks, and using general relativity—Einstein's theory of gravity—to understand the behavior of the universe at the largest scales. Both of these theories have been confirmed with remarkable precision by experiments such as the Large Hadron Collider (LHC) at CERN and the Laser Interferometer Gravitational-wave Observatory (LIGO) in the United States. However, combining them has proven quite difficult, and more than 100 years after quantum mechanics and general relativity were discovered we still do not have a candidate theory of quantum gravity that is consistent with everything we know about the universe.

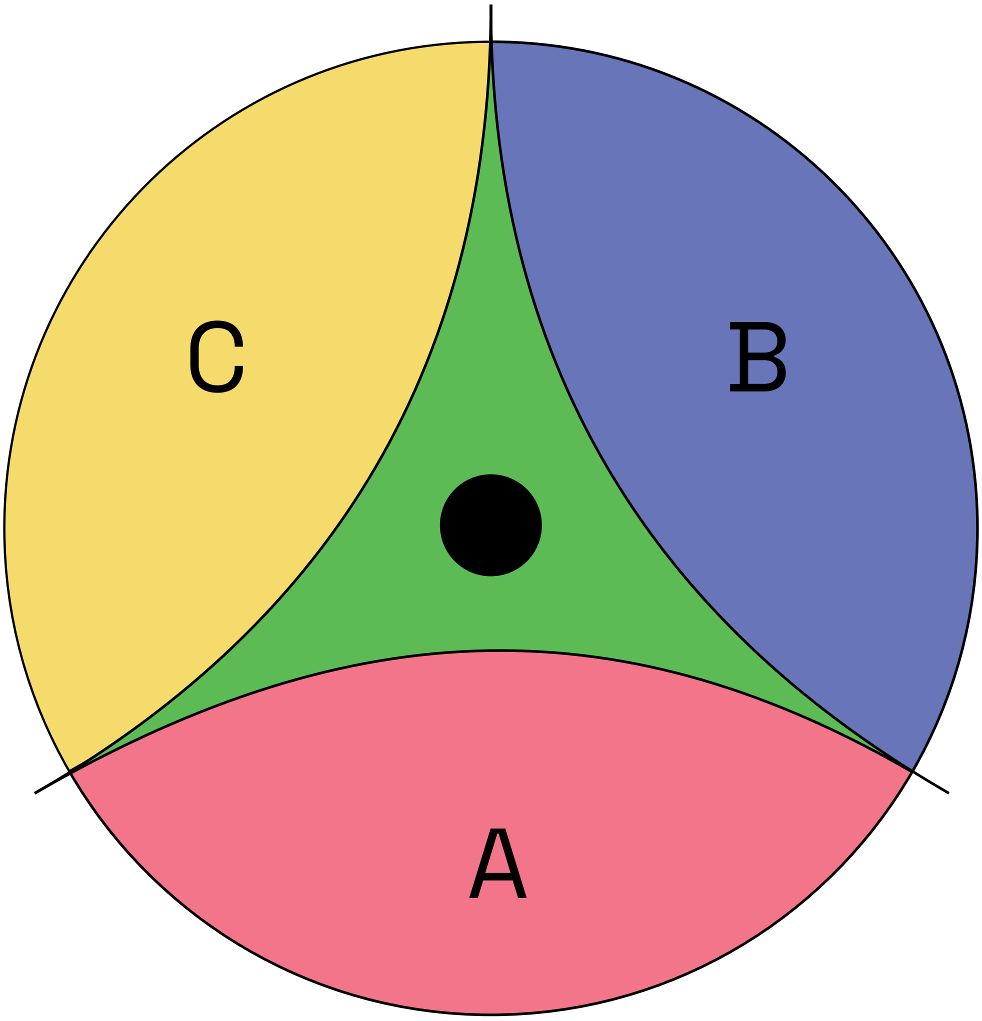
There are various opinions about why quantum gravity is hard, but the deepest reason has to do with the quantum mechanics of black holes. Back in the early 1970s Jacob Bekenstein and Stephen Hawking realized that in general relativity black holes behave as if they were thermal systems, with a vast amount of thermal entropy given by the famous Bekenstein-Hawking formula

$$S = \frac{Ac^3}{4G\hbar}$$

where A indicates the area of the black hole horizon. This formula has several remarkable features. For one thing it involves gravity (Newton's constant G), quantum mechanics (Planck's constant $\hbar$), and relativity (the speed of light c); for another, it says that the number of degrees of freedom in a black hole, while large, is actually considerably less than one might expect. This is because in most quantum systems with many degrees of freedom (such as a magnet or an oven) the number of degrees of freedom is *extensive*, meaning that it is proportional to the volume of the system. For a black hole the number of degrees of freedom is instead proportional to its surface area. In essence this means that there are not really independent degrees of freedom at each point in space inside of a black hole, or in more modern language, that spacetime itself is *emergent*.

FIGURE 1:
The AdS-CFT correspondence. On the left we see an observer in AdS space, who shoots a photon and sees it reflected back in finite time. On the right, the boundary of AdS is shaded grey: this is where the precise formulation of the theory lives.





What does it mean for spacetime to be emergent? Rather than the austere arena in which physics plays out, spacetime must instead be a limited notion that is only valid in certain situations and only to some approximation. It must have no fundamental role in the equations which describe the laws of physics at the foundational level. How then are we to formulate these equations when spacetime is so integral to our understanding of the world? In general, we do not know, but there is a special situation where we know quite a bit: the situation where the universe is filled with a constant negative energy density—a negative cosmological constant [1]. A universe with negative cosmological constant is essentially a universe in a box with reflecting walls, where if you turn on a flashlight after some time the light turns around and comes back. Such a universe is called *Anti de Sitter Space*, and a graphical representation of AdS space is shown in Figure 1. The advantage of working in AdS space is that gravitational fluctuations turn off at its spatial boundary, giving a relatively manageable closed system. Indeed, it has been understood for more than 25 years that the precise formulation of quantum gravity in AdS space is in terms of a non-gravitational theory living on this spatial boundary, called the *AdS/CFT correspondence*.

FIGURE 2:
Redundant encoding of information into the boundary description in AdS/CFT: information about what is happening in the green region in the center of the spacetime is inaccessible to someone who can only measure boundary degrees of freedom in one of the three boundary regions (A, B, and C), but it is accessible to anyone who can measure in two of them.

In the AdS/CFT correspondence the gravitational spacetime is emergent because the fundamental boundary formulation of the theory makes no reference to it. Where then does it come from? This has been a topic of considerable research in recent years, and there is now an emerging consensus that the answer is the following:

> The emergent spacetime geometry in AdS/CFT arises from pattern of nonlocal entanglement in the fundamental boundary description, which is described mathematically as a *quantum error correcting code*.

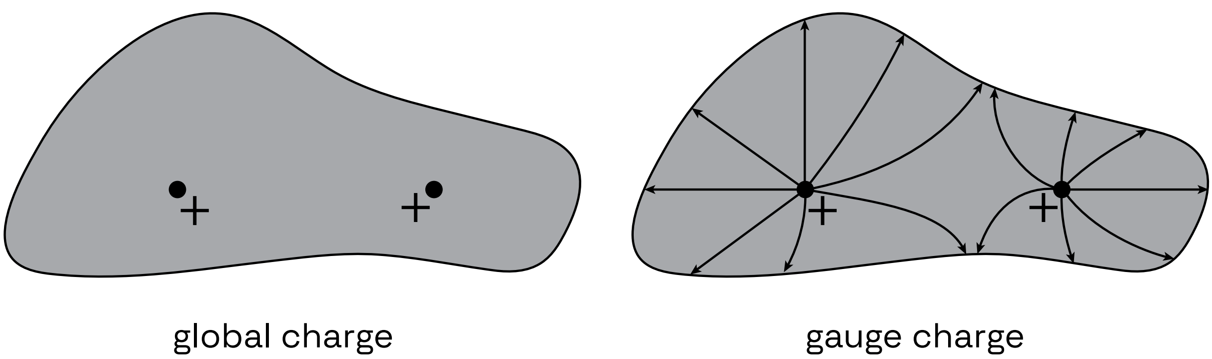
Quantum error correcting codes were invented by my MIT colleague Peter Shor as a method for protecting quantum computers from noise, but in 2014 with Ahmed Almheiri (now at NYU Abu Dhabi) and Xi Dong (now at UC-Santa Barbara) we realized that they are also the perfect mathematical vehicle for describing the emergence of spacetime in the AdS/CFT correspondence. The essential feature of quantum error correcting codes is that they store quantum information redundantly in the entanglement between the qubits in the memory of the quantum computer, and it turns out that this redundancy is just what it is needed to describe the emergence of spacetime! See Figure 2 for an illustration of the basic idea. This connection has led to many new insights into the nature of quantum gravity, and we will now discuss a particular set of such insights which are related to the idea of symmetry.

Symmetry

Symmetry is perhaps the most important organizing principle in physics. When a physicist encounters a new system for the first time, most likely the first question they will ask is: What are its symmetries? Knowing the symmetries helps us organize our thinking about the system, and also helps us obtain results that otherwise would be much too difficult. For example, *time translation symmetry* says the laws of physics are the same today as they were yesterday, while *space translation symmetry* says that they are the same in Boston and New York. In conventional quantum systems there are two fundamental kinds of symmetries: *global symmetries* and *gauge symmetries*. The difference between the two is shown in Figure 3: a global symmetry is a symmetry with the property such that to find out how much symmetry charge there is in a region, you need to walk around the region and add up all the charge, while a gauge symmetry is one where you can measure the total charge in a region by doing a measurement at the boundary of the region. A simple example of a global symmetry is the symmetry that flips all the spins in a magnet, while a simple example of a gauge symmetry is the symmetry generated by electric charge. That you can measure the electric charge in a region by looking at its boundary is the statement of *Gauss's law*, familiar to anyone who has taken MIT Physics classes 8.02 or 8.022: the total charge in a region is equal to the electric flux through its boundary.

The combination of quantum mechanics and gravity has important consequences for the possible symmetries of nature. This was already noticed by Hawking in the 1970s, who pointed out that global charge which falls into a black hole seems to disappear from the universe,

FIGURE 3:
To detect global charge in a region you need to look throughout the region, but to detect gauge charge you can measure the flux at the boundary.



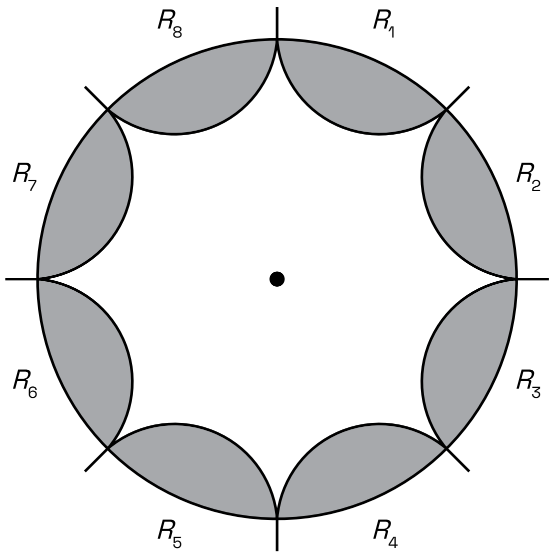


FIGURE 4:
A global charge in the center of AdS cannot be detected in the fundamental boundary description, as adding up the charges in a bunch of boundary regions only gives us something which can measure what is going on in the parts of AdS near those regions.

while gauge charge which falls in leaves behind a record at the boundary of spacetime. This observation was gradually refined into two conjectures about the nature of symmetry in quantum gravity:

1. In quantum gravity there are no global symmetries.
2. Gauge symmetries are allowed in quantum gravity, but only if there are objects in the theory with all possible values of the gauge charge.

Neither of these conjectures is true for non-gravitational physics, so if they hold in quantum gravity this teaches us something fundamentally new about the world. In 2015 I realized that our quantum-error-correcting machinery for understanding the emergence of spacetime had something to say about these conjectures, and with Hirosi Ooguri from Caltech we set out to understand what. After several years of work, we wrote a pair of papers using error-correction methods to give arguments that both conjectures must be true within the context of the AdS/CFT correspondence.

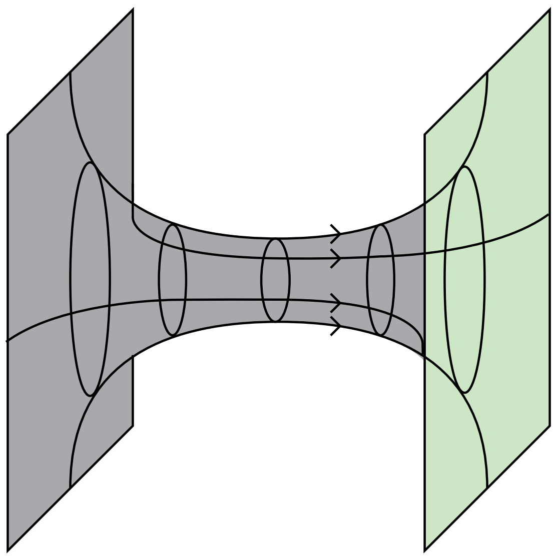
The basic idea of our argument for conjecture #1 is shown in Figure 4: if we had a global symmetry in AdS space then the total global charge should be found by adding up the global charges at each point in space. On the other hand, by the AdS/CFT correspondence the global charge should also be found by adding up the global charges *on the boundary*. This gives a contradiction: we can split the boundary into small enough regions that none of them can know about the charge in the center of the spacetime, so we cannot give a consistent rule for determining the global charge. This contradiction is avoided for gauge symmetries, since the charges for these can indeed be detected solely by measurements near the boundary.

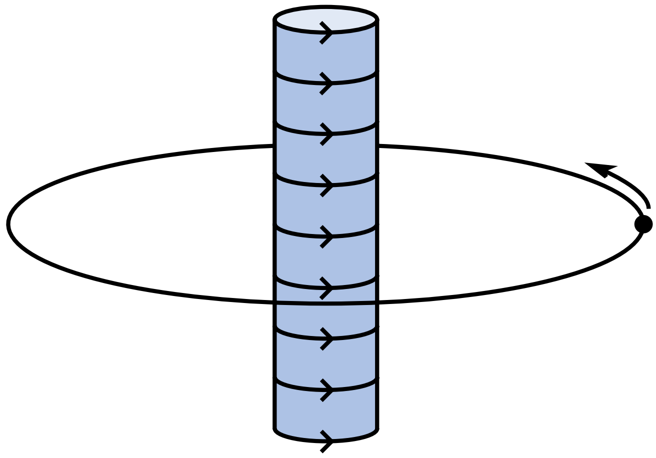
Our argument for conjecture #2 uses one other recent idea from spacetime emergence, which is that if you have two black holes that are entangled with each other in the right way, then their interiors are actually *connected* by a wormhole, as shown in Figure 5. The point is that once the interiors are connected, it is possible for electric (or magnetic) field lines to go through the wormhole from one end to the other. Any number of field lines can go through, corresponding to any possible charge. On the other hand, since the wormhole is built from an entangled pair of black holes, these black holes must be the sources of the field lines. It therefore must be possible for a black hole to carry any possible gauge charge [2].

Gauging time-reversal symmetry

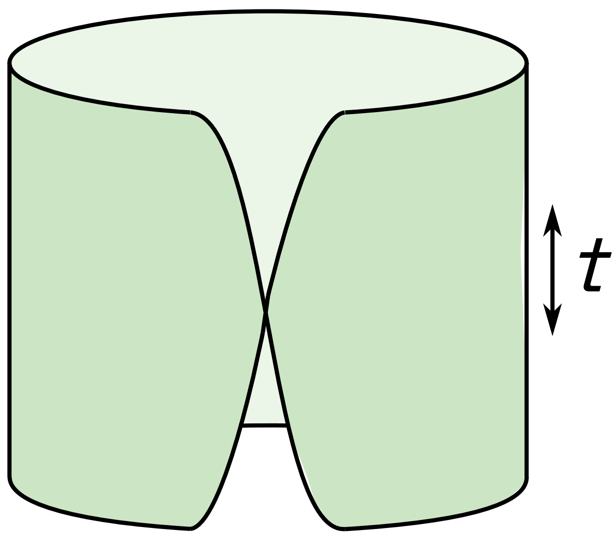
The conclusion that all symmetries in quantum gravity must be gauge symmetries leads to some rather surprising conclusions when we consider symmetries that reverse the direction of time. The simplest such symmetry is called *time-reversal symmetry*, which says

FIGURE 5:
A wormhole connecting two entangled black holes that is threaded by electric flux.





Aharonov-Bohm effect



Time-reversing loop

that the laws of physics look the same going forward and backwards in time. For example, if you are making a movie of a bunch of billiard balls banging into each other, and at some point you instantaneously reverse the directions of all the billiard balls, then their future behavior will be the same as if you played the movie you just made backwards. Time-reversal symmetry isn't actually a true symmetry of nature, as it is broken by the weak nuclear force, but there is a slightly more complicated symmetry, called *CPT symmetry*, which is indeed a true symmetry. The idea of CPT is that in addition to reversing the direction of time, you should also reflect space and exchange particles and antiparticles. It is a theorem that any quantum system which respects special relativity and locality should have CPT as a symmetry, and as far as we can tell CPT should also be a symmetry of quantum gravity. By conjecture #1 above it must be a gauge symmetry. In theories of quantum gravity that do have pure time-reversal symmetry, this must also be gauged.

FIGURE 6:
[*Left*] The Aharonov-Bohm effect for electromagnetic gauge symmetry. [*Right*] Time-reversal symmetry. In the latter, spacetime is analogous to a Mobius strip, with no consistent orientation of time.

To understand the consequences of CPT or time-reversal symmetry being a gauge symmetry, we first need to understand one further aspect of gauge symmetry. Whenever there is a gauge symmetry, you can have a situation where when you move a charged particle around a circle in space it comes back to itself only up to a gauge symmetry transformation. The classical example of this is the *Aharonov-Bohm effect*, where moving a charged particle in a loop around a solenoid picks up a phase in its wave function. (Figure 6, *left*.) What is the analogous situation for time-reversal or CPT? It is a situation where if you walk around a circle in space and come back, you will find the direction of time reversed! (Figure 6, *right*.) This undoubtedly sounds crazy, but in a recent paper with Tokiro Numasawa (now at the University of Tokyo), we argued that not only is this not crazy, it is in fact necessary. I'll refer to such a configuration as a *time-reversing loop*.

The first reason we argued that time-reversing loops are possible is the one I just gave: CPT symmetry is always a symmetry and in quantum gravity only gauge symmetries are allowed. We therefore must allow them. A second reason is that in the context of AdS/CFT we were able to engineer a certain calculation in the exact boundary description that can only be matched from the gravitational side of the correspondence if one includes a spacetime geometry with time-reversing loops. On the other hand, time-reversing loops seem quite dangerous: how can physics possibly make sense in a situation where you can meet an older version of yourself going backwards in time? What we argued is that such meetings are only possible behind the horizon of a black hole, so they cannot be experienced by anyone who doesn't have the misfortune to fall into a black hole. In this way the basic causal structure of spacetime, where cause always precedes effect, is preserved except for those who are anyways doomed in the near future.

Towards the future

What next? The ideas I've described give a fairly complete picture of how quantum gravity can be made consistent in universes with negative cosmological constant. There are of course more details to fill in, but we must also try to generalize these ideas to universes which look more like our own. Some progress has been made, and in particular with Edgar Shaghoulian (now at UC-Santa Cruz), we were able to argue that global symmetries shouldn't be allowed in any theory of quantum gravity where black hole evaporation works in a way recently proposed by my MIT colleague Netta Engelhardt and collaborators (see Fall 2023 *physics@mit*). However, we are still quite far from an understanding of quantum gravity in the real world. Yet, there is a palpable sense that black holes are not so mysterious as they once appeared, and there are many natural directions to try. Hopefully there will be more to report soon.

DANIEL HARLOW is the Jerrold R. Zacharias Career Development Associate Professor of Physics in MIT's Center for Theoretical Physics. He works on combining quantum mechanics and gravity, focusing on the quantum-mechanical aspects of black holes and cosmology. Recently, he has been using methods from quantum information theory to approach these problems, in particular relating the AdS/CFT correspondence—our best theory of quantum gravity so far—to the theory of quantum error correcting codes. Harlow also works on the general structure of quantum field theory, which despite its venerable age has resisted a fully satisfactory formulation, as well as aspects of classical gravity.

Daniel Harlow was born in Cincinnati, Ohio, and grew up in Boston, MA, and Chicago, IL. He obtained a BA in physics and mathematics from Columbia University in 2006, a PhD in physics from Stanford University in 2012, and held postdoctoral fellowships at Princeton and Harvard Universities before joining MIT in July 2017. He is an avid hiker and pianist.

ENDNOTES

[1] Unfortunately, this is not the situation of our actual universe, which appears to have a positive cosmological constant, but we can hope to learn lessons that carry over to more realistic theories.

[2] One particularly interesting consequence of this argument is that objects carrying magnetic charge must exist. In other words there must be magnetic monopoles! Unfortunately they may be rather heavy, in which case we wouldn't be able to produce them.