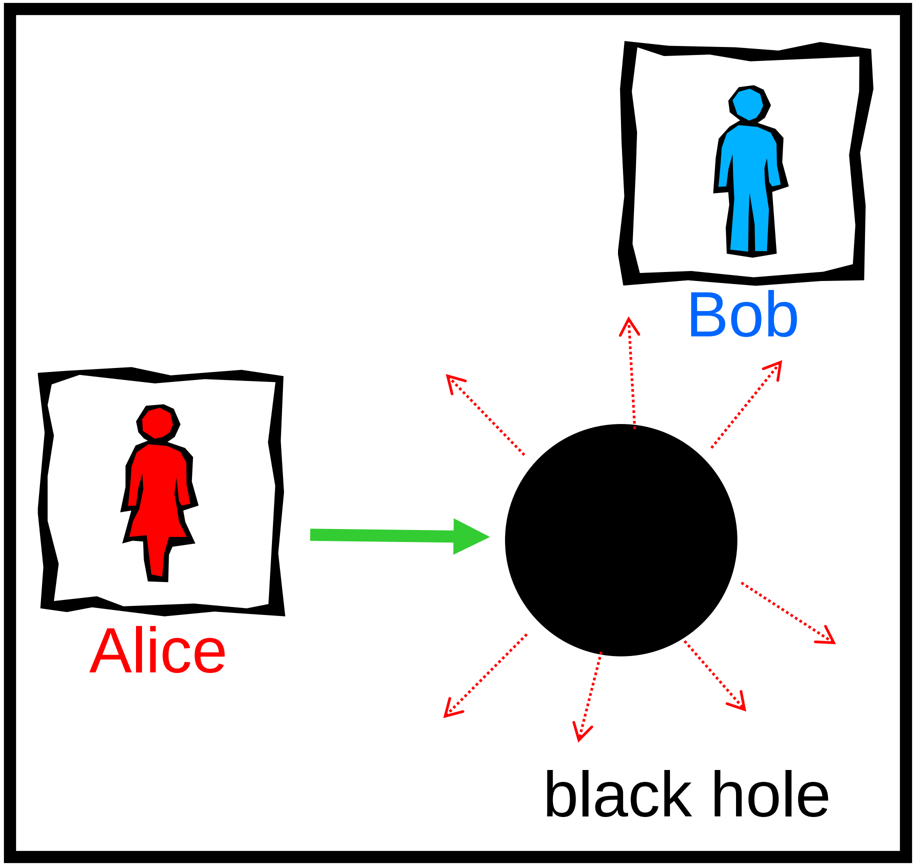
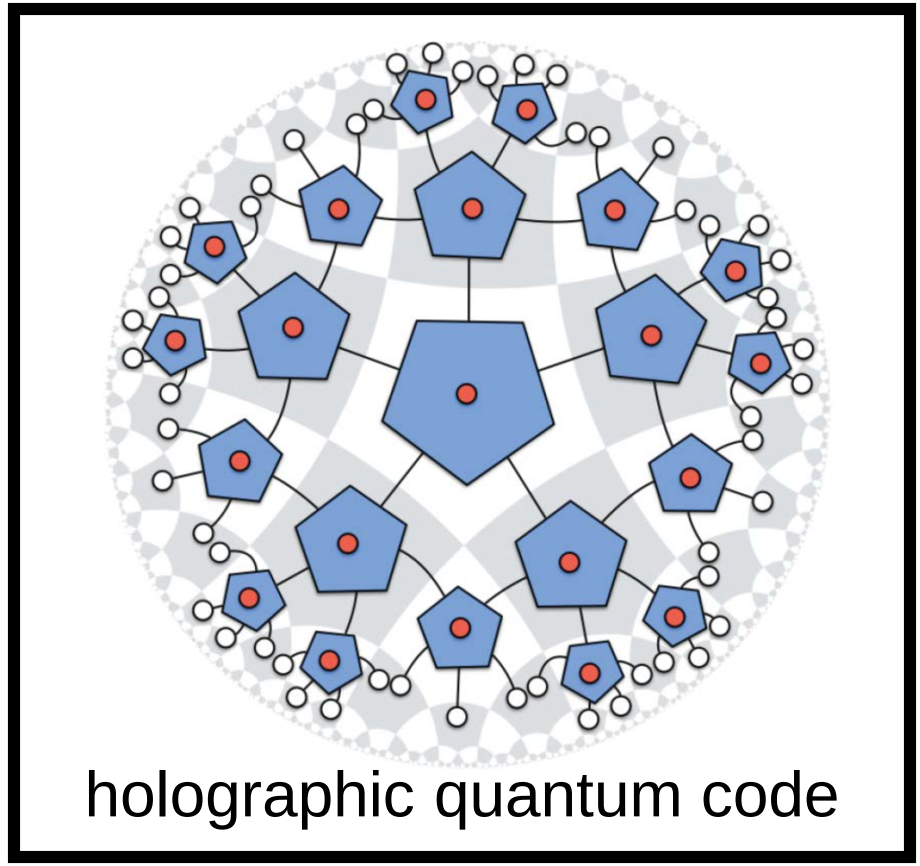
Quantum Information and Spacetime





INSTITUTE FOR QUANTUM INFORMATION AND MATTER

GORDON AND BETTY MOORE FOUNDATION

John Preskill, Caltech
QIP 2017, 15 Jan 2017

Information is stored by physical systems, and processed by physical devices.

Whatever you say about information storage or processing is a statement about physics.

The real world is quantum mechanical

What underlying theory explains the observed elementary particles and their interactions, including gravity?

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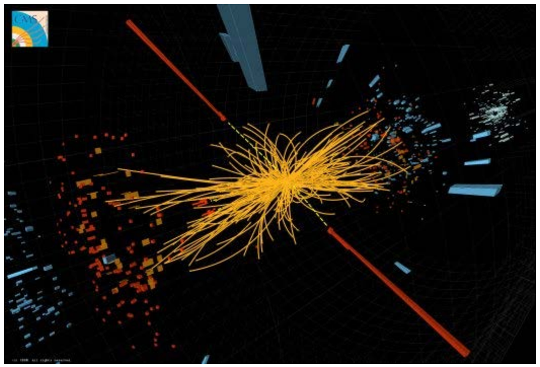
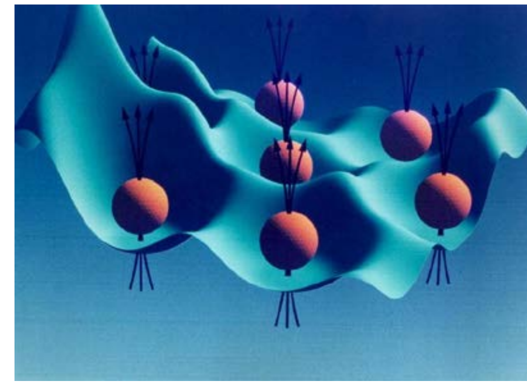
Can we control complex quantum systems and if so what are the scientific and technological implications?

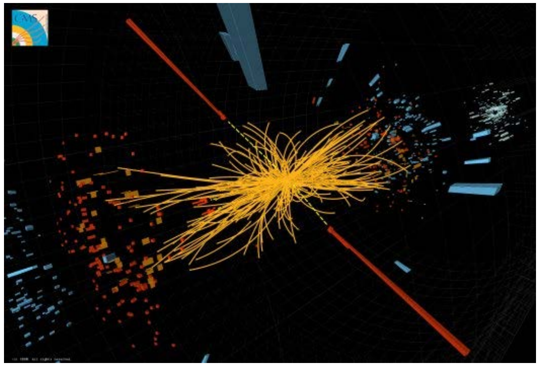
(104 characters)

Frontiers of Physics

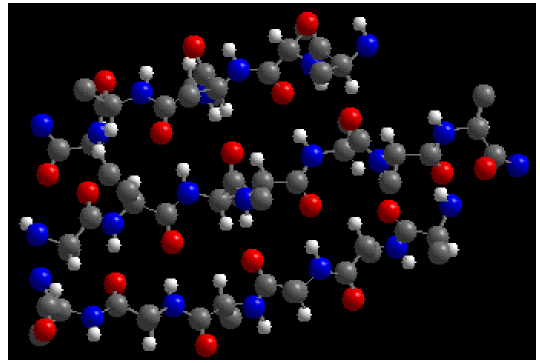
short distance	long distance	complexity
		
Higgs boson	Large scale structure	“More is different”
Neutrino masses	Cosmic microwave background	Many-body entanglement
Supersymmetry	Dark matter	Phases of quantum matter
Quantum gravity	Dark energy	Quantum computing
String theory	Gravitational waves	Quantum spacetime

"Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical."

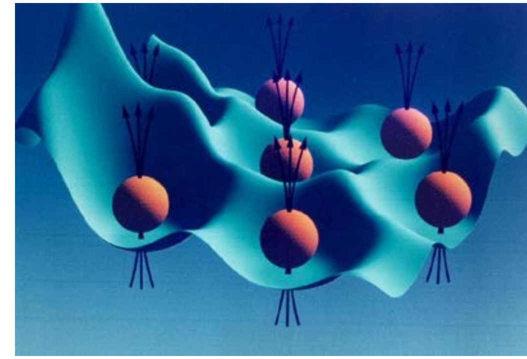
Caltech Course 1983-84:
Potentialities and Limitations of Computing Machines



particle collision



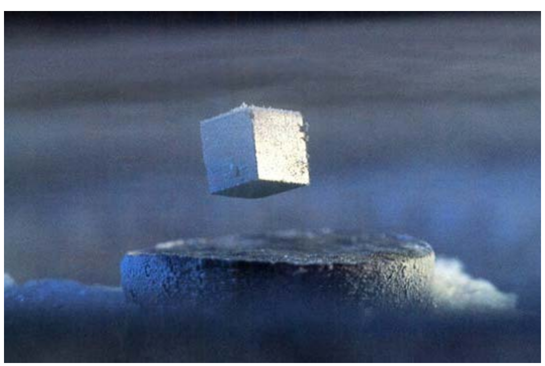
molecular chemistry



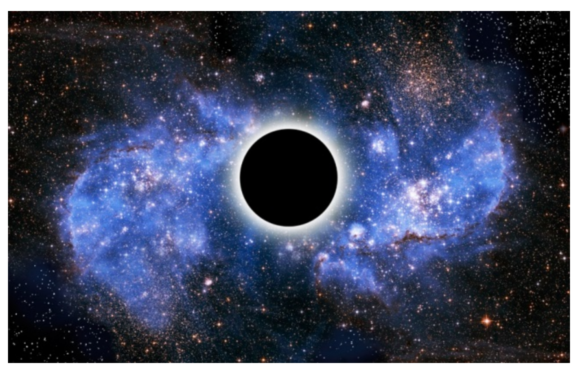
entangled electrons

A quantum computer can simulate efficiently any physical process that occurs in Nature.

(Maybe. We don’t actually know for sure.)



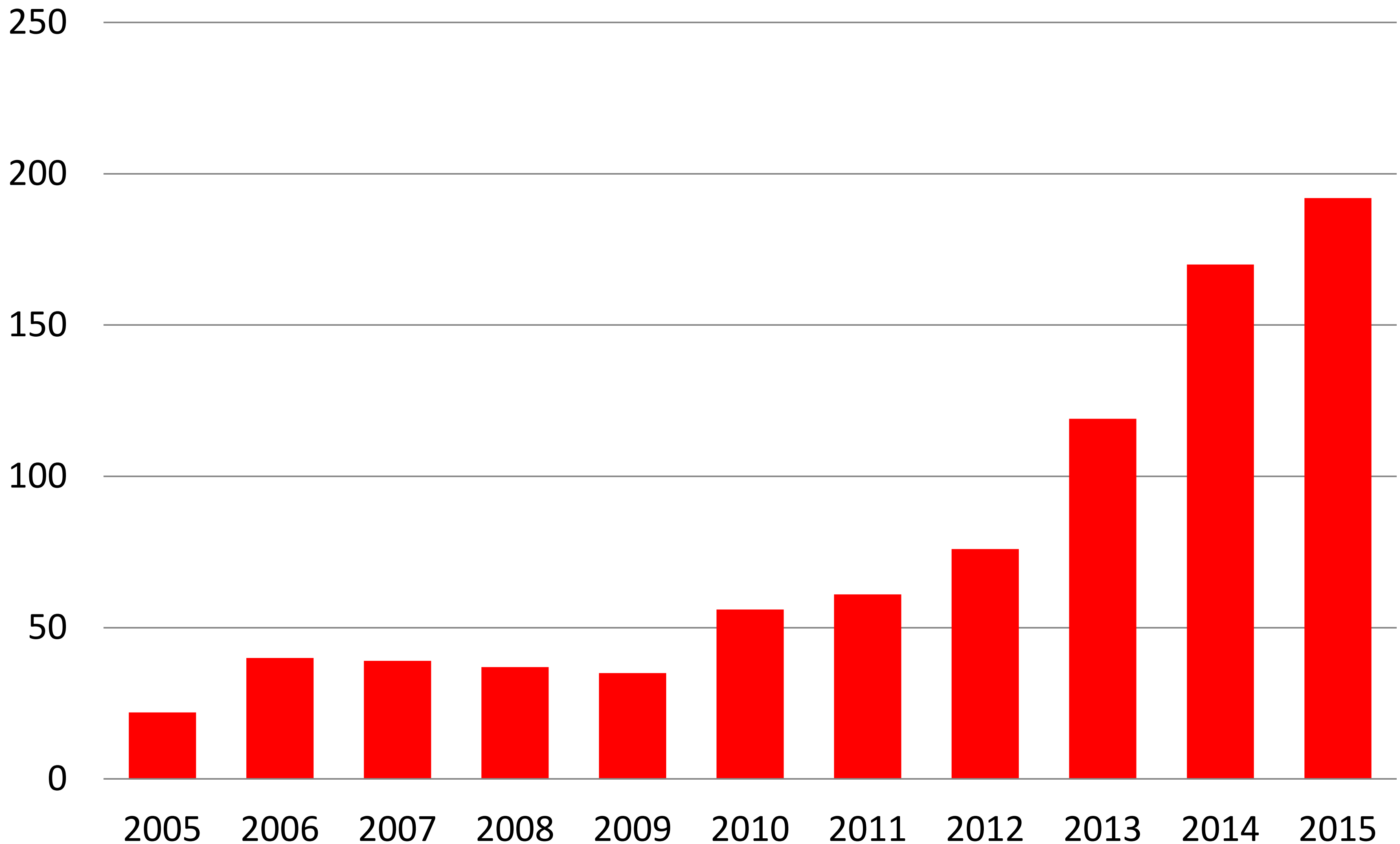
superconductor



black hole

early universe

hep-th papers with "entanglement" in the title



General Relativity

Spacetime tells matter how to move.

Matter tells spacetime how to curve.

Cosmological Constant = Vacuum Energy

Positive vacuum energy tells spacetime to have positive curvature (de Sitter space).

Negative vacuum energy tells spacetime to have negative curvature (anti-de Sitter space = AdS).

Cosmological Constant = Vacuum Energy

De Sitter space has no boundary.

Anti-de Sitter space has a boundary.

This makes quantum mechanics in anti-de Sitter space easier.

Observables are anchored to the boundary.

Reality

We live in de Sitter space.

Too bad …

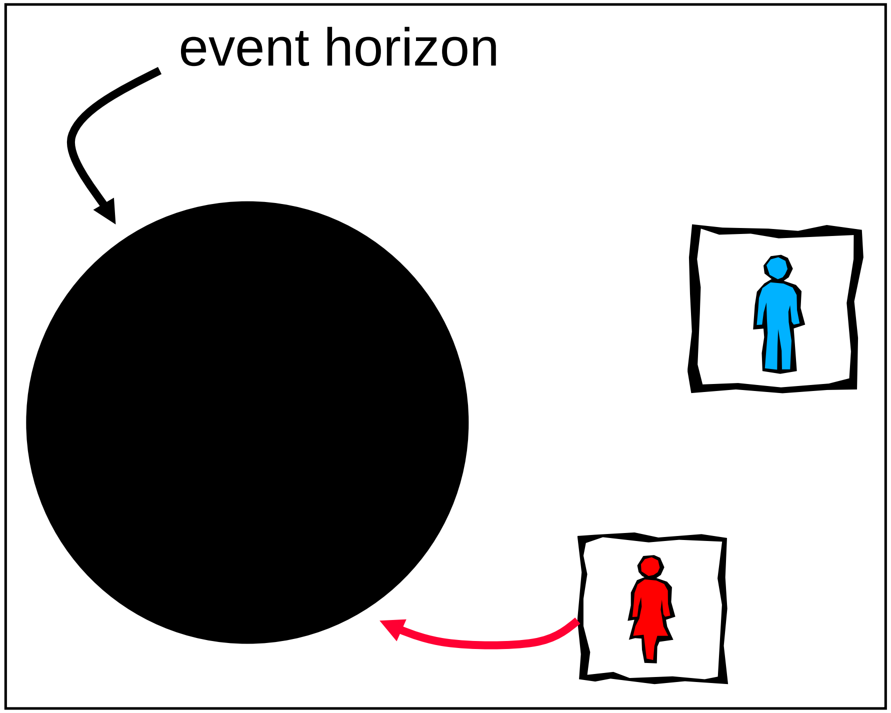
We'll need to learn how to do quantum mechanics in de Sitter space eventually.

It's hard …

Black Hole

Classically, a black hole is a remarkably simple object (it has "no hair") composed of *pure spacetime geometry.*

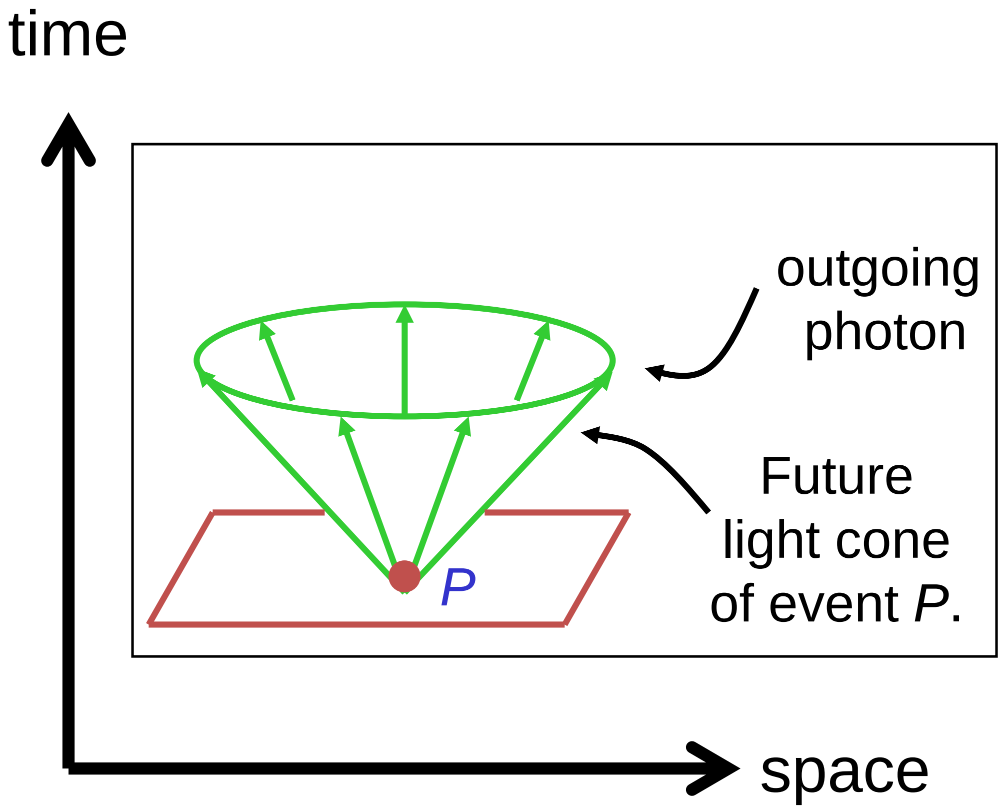
If Alice crosses the event horizon of a black hole, she will never be able to return to or communicate with Bob, who remains outside.



Light Cone

Imagine a light source that emits a flash (the spacetime event *P*). The flash travels outward as a spherical shell expanding at light speed. Plotted as a function of time, the expanding shell defines a cone, the future light cone of *P*.

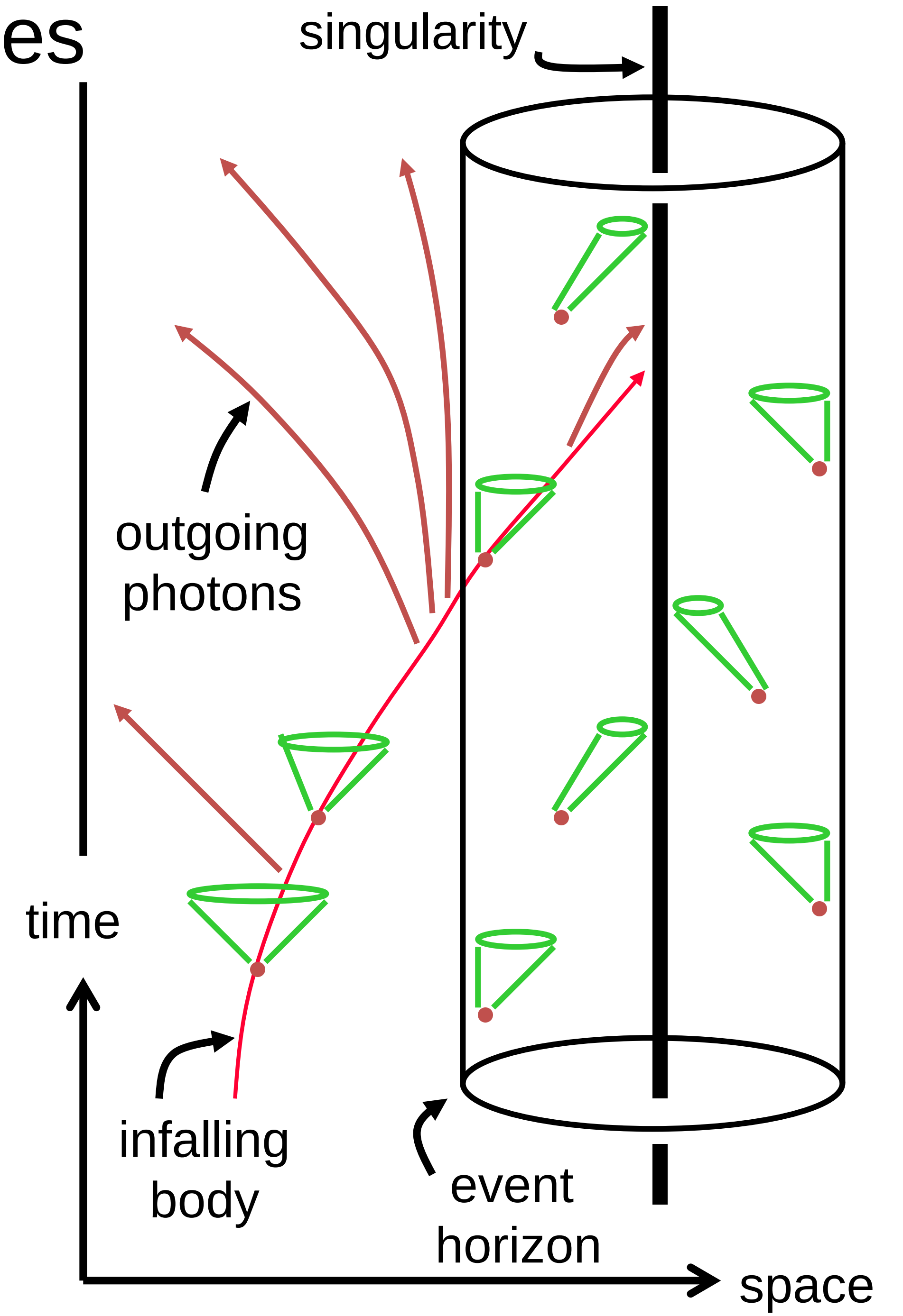
All events that can be influenced by event *P* lie inside its future lightcone.



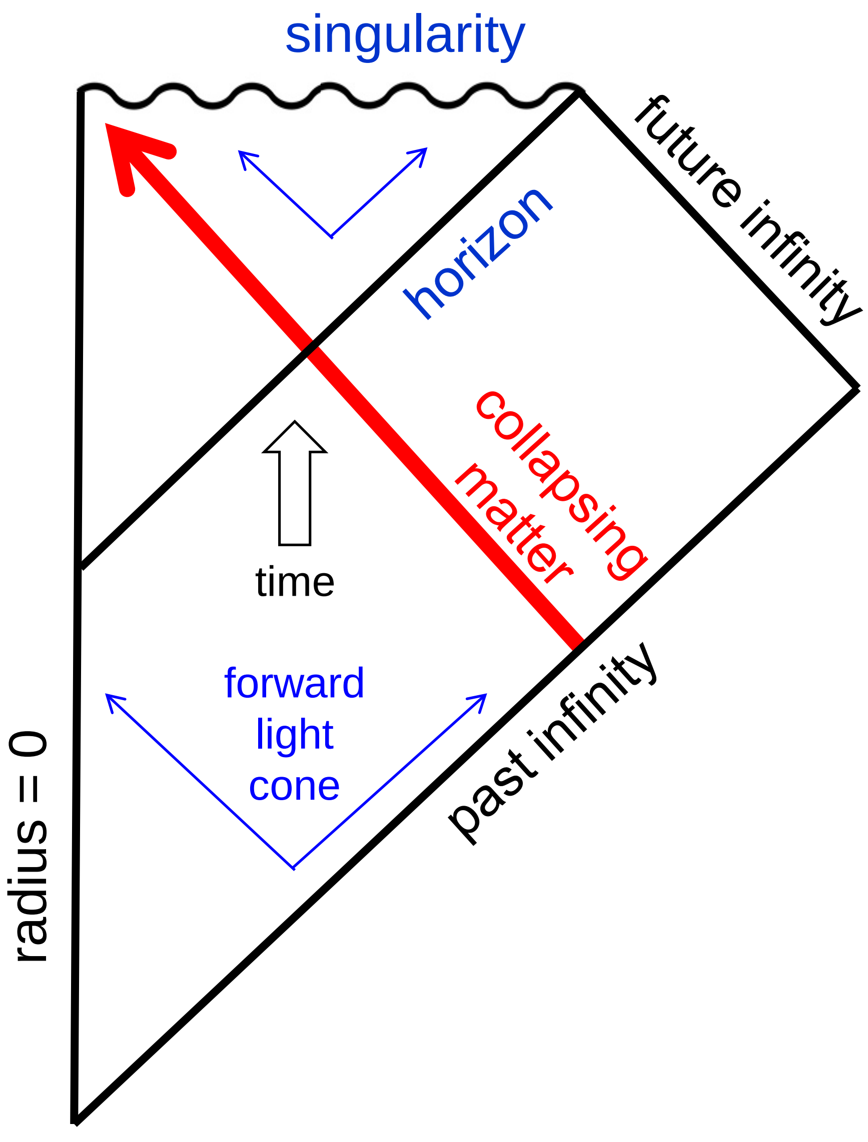
Tipping of the light cones

We find by solving the Einstein field equations that the lightcones tip inward as one approaches the black hole. The future light cone of a point inside the horizon lies entirely inside the horizon. Any signal emitted from a point inside the horizon necessarily travels more deeply into the black hole.

The unfortunate astronaut who enters the black hole is unavoidably drawn toward the singularity, where enormous gravitational forces tear him apart.



Penrose diagram



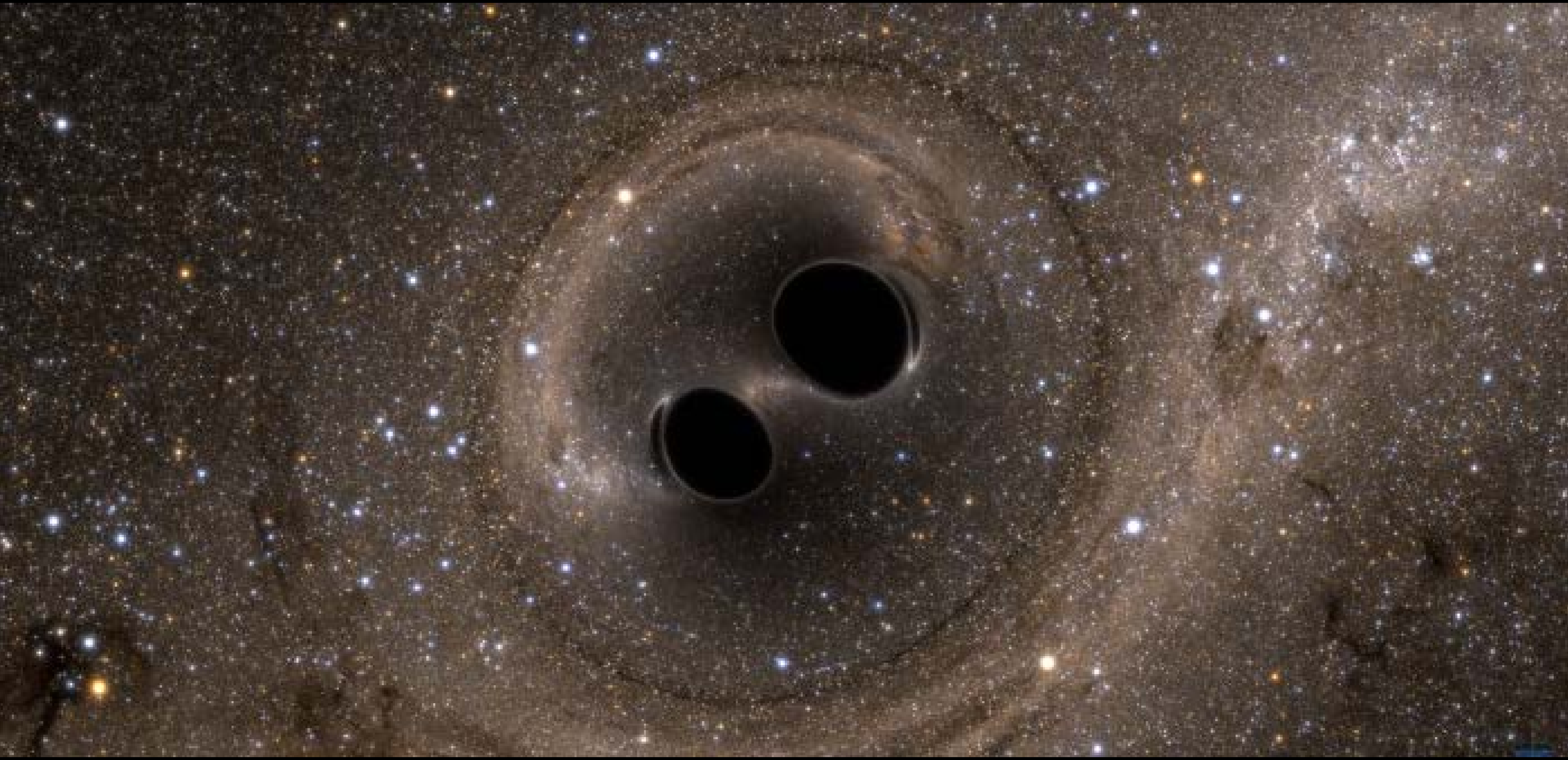
Another way to represent the spacetime geometry of the black hole is often convenient and illuminating.

Each point represents a two-sphere, infalling and outgoing light rays (null geodesics) are lines tilted at 45 degrees.

The forward light cone of a point behind the horizon meets the singularity.

A conformal mapping makes past and future null infinity appear to be a finite affine distance away.

LIGO!



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Quantum field theory

An infinite number of degrees of freedom in an arbitrarily small volume.

If we took that literally, we could store an unbounded amount of information in a tiny region.

We shouldn't take it literally. There is a "short distance cutoff."

Quantum field theory

Think of it this way. We have a system defined on a spatial lattice with spacing a. There is a geometrically local Hamiltonian coupling neighboring lattice sites.

Now ask what physics looks like at distances arbitrarily large compared to a (the “continuum limit”)

This limit might not exist. Or rather … it might be that the theory becomes a boring noninteracting (“free”) field theory in this limit.

We say that the theory defined on the lattice, with a finite number of lattice sites per unit of physical volume, is a “regulated” version of the continuum theory.

Universality

You might think that the long-distance theory depends in a very complicated way on the short-distance theory. But something wonderful happens.

All of the short-distance details can be absorbed into a small number of "renormalized parameters" needed to describe long-distance phenomena.

This is called "universality" because many different short-distance theories are all equivalent for describing long-distance physics.

Universality makes quantum field theory (QFT) useful for condensed matter physics (in which there really is a short distance cutoff, such as the atomic scale). It is also used in fundamental particle physics.

In the latter case the QFT is "relativistic;" this means there is no preferred frame of reference. The same laws of physics govern all observers who move at constant velocity relative to one another. This property, called Lorentz invariance, holds in the continuum limit. For the regulated theory on a lattice, there is preferred frame in which the lattice is at rest.

Universality

Universality makes physics possible.

We'd be in trouble if we needed to know all the details of physics at 10^{-33} cm to understand the hydrogen atom (10^{-8} cm). Fortunately that is not necessary.

Even if there were literally an infinite number of degrees of freedom per unit volume, at low energy we could only excite long wavelength modes of the fields.

On the other hand … since low-energy phenomena do not depend much on short-distance physics, it is hard to learn about short-distance in feasible experiments. That frustrates the high-energy physicists.

Effective field theory

We use quantum field theory very successfully to describe all known physics, excluding gravitation. (We also have a very successful classical theory for gravitation.) The Standard Model of particle physics has not been challenged by data for 40 years.

We say this is an “effective” field theory. That just means it works at the energy (distance) scales we have explored experimentally, but we anticipate it breaks down at sufficiently short distances.

It might be that we need to introduce new degrees of freedom to complete the theory (as when the W, Z , and Higgs bosons were needed to compete the standard model).

One way of saying this is that, unless we choose the right theory at the scale of the lattice spacing, we won’t be able to obtain the effective theory we are looking for as a continuum limit of the lattice theory.

If a short distance completion of the effective theory exists, because of universality it need not be unique. To find out how physics behaves at shorter distance, we need to do experiments at higher energies.

Renormalization group

Physicists use the word “infrared” to mean “long distance” (low energy) and “ultraviolet” to mean “short distance” (high energy).

We use different effective theories to give an accurate description of physics at different length scales. The theory has a scale, which is called the renormalization scale. As the scale changes, the effective theory changes. We call this scale-dependence of the theory “renormalization group flow.”

We might speak of the “ultraviolet theory,” meaning the effective theory which applies at short distances, and the “infrared theory,” meaning the effective theory which applies at long distances.

Given an effective theory, a theory which makes sense at shorter distances and flows to that effective theory at longer distances is called the “ultraviolet completion” of the effective theory.

Quantum gravity

The standard model, plus gravitation, is an effective theory. What is its ultraviolet completion?

We don't know. This effective theory cannot be extended to arbitrarily short distances; new degrees of freedom must come into play at high energy. There is a candidate UV completion, sometimes called string theory or M theory. It seems to be mathematically consistent, but much about it is not understood.

Even if it is mathematically consistent, we don't know whether string theory describes nature.

Many physicists think string theory is on the right track, but there are missing ingredients which must be discovered to arrive at a more complete understanding.

There is a rigorous version of relativistic quantum field theory, in which we can formulate axioms and prove theorems. We can't yet do that for string theory.

There are many possible RQFTs, but it may be that the theory of quantum gravity is in some sense unique. However, that does not mean it makes unambiguous predictions about what we see in our (part of the) universe, because the equations of the theory have many different solutions.

Quantum gravity

We want a quantum theory of gravity …

1) To erect a complete theory of all the fundamental interactions in nature.

2) To resolve deep puzzles about the quantum physics of black holes.

3) To understand the very early history of the universe.

Experiments provided essential guidance for building the standard model of particle physics, excluding gravity. But it is hard to do experiments which explore quantum gravity.

We are trying simultaneously to determine both what the theory predicts and what the theory is.

Are we smart enough to figure it out?

I don't know … But why not?

Planck scale

$$L_{\text{Planck}} = \left(\hbar G / c^3\right)^{1/2} = 10^{-33}\,\text{cm}$$

We explore shorter and shorter distances by banging together elementary particles at higher and higher energy. For example, we can "see" quarks inside a proton by scattering electrons off the proton.

But gravitation imposes a limitation. If we collide (say) electrons at high enough energy, a black hole is created. Increasing the energy makes the black hole larger, not smaller.

The shortest distance we can explore is the Planck length, the size of the smallest possible black hole. This is the quantity with the units of length which can be constructed from the fundamental constants G (Newton's gravitational constant), hbar (Planck's constant), and c (speed of light). The Planck length is about 10^{-33} cm, much smaller than we can explore in today's high energy physics experiments (about 10^{-17} cm).

It's not clear whether it makes sense to speak of "space" or "time" for distances shorter than the Planck length, of for durations less than the Planck time (about 10^{-43}s).

Perhaps spacetime is itself "emergent," meaning that is arises only in an effective theory describing the IR behavior of a theory whose UV completion is really something quite different.

Conformal field theory

A conformal field theory (CFT) is a field theory with no intrinsic length scale. For example there are no massive particles, since the particle mass would define a scale. We are interested in theories which are both scale invariant and Lorentz invariant.

For the CFT, the laws of physics look the same on all length scales; hence the renormalization group flow is trivial. We say the CFT is a renormalization group fixed point.

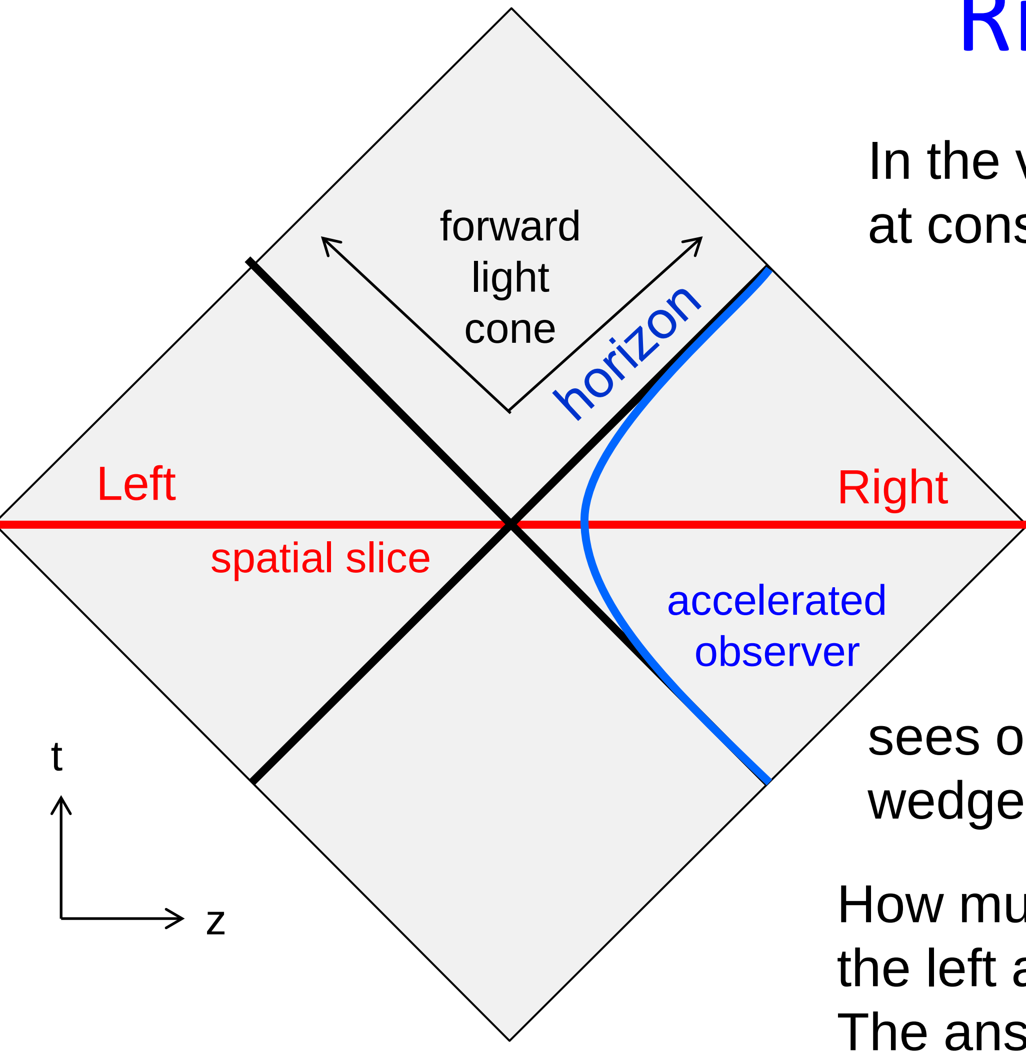
The CFT is UV complete (there is a continuum limit), since there is no problem following the flow (or lack thereof) as far as we please into the UV or IR.

There is a parameter called the central charge of the CFT, denoted c, which counts degrees of freedom. For example, $c = N$ for a theory of N uncoupled free massless scalar fields. For interacting theories, large c means that each of many fields has (geometrically nonlocal) interactions with many other fields at the same site.

We may perturb a CFT by changing its Hamiltonian a little bit. Generically this perturbation breaks the scale invariance, so that the RG flow becomes nontrivial. The theory may become massive, or it might flow to another RG fixed point.

For D=2 spacetime dim, The IR CFT has c no larger than the UV CFT (the “c-theorem”).

Rindler spacetime



In the vacuum, a particle detector moving at constant velocity detects no particles.

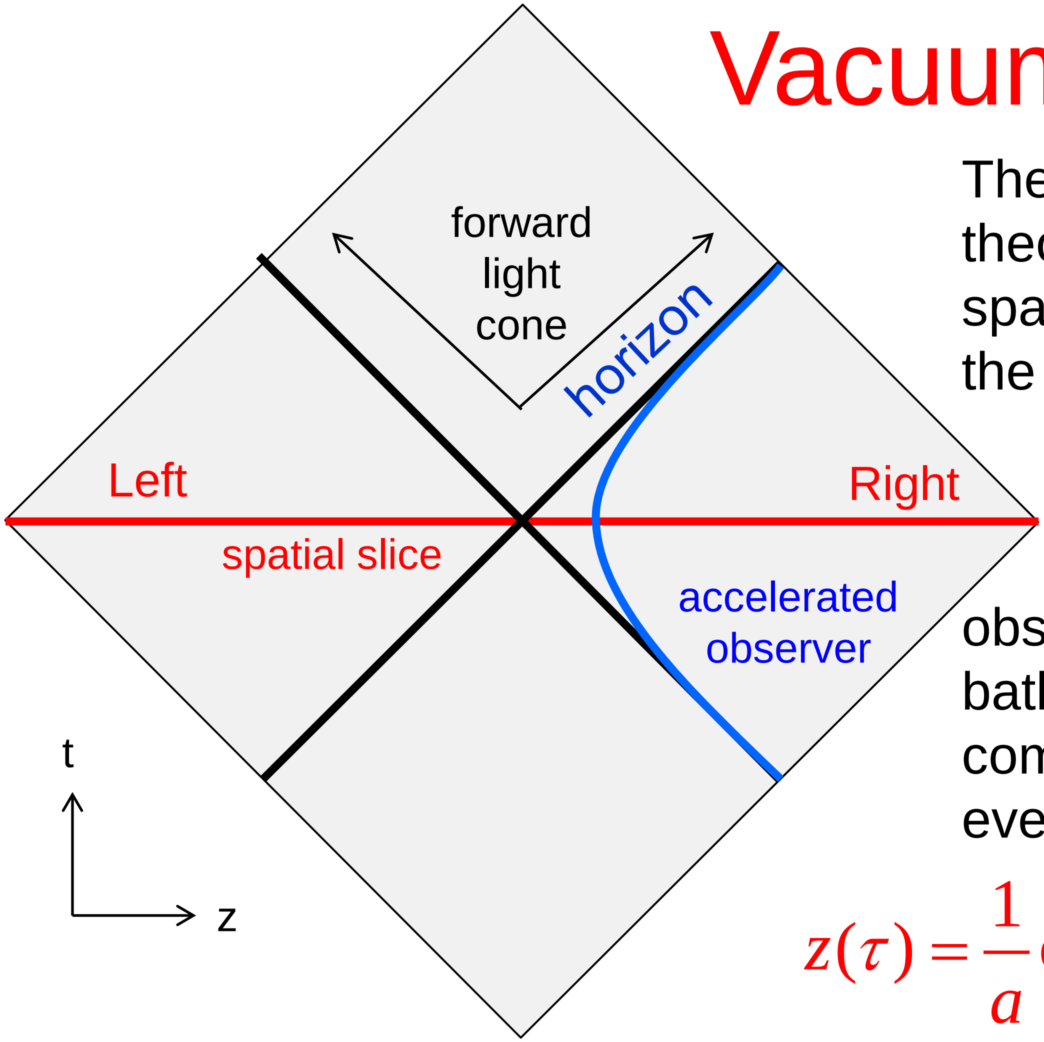
But a uniformly accelerated detector does detect particles. How can that be?

Though the vacuum is a pure state, the uniformly accelerated observer sees only a subsystem (the "right Rindler wedge"), which is in a mixed state.

How much entanglement is there between the left and right wedges?
The answer is: an infinite amount.

That's not really a surprise, because field modes of arbitrarily short wavelength contribute to the entanglement. To get a finite answer, we need to introduce a short distance cutoff, e.g., a lattice spacing a.

Vacuum entanglement



The vacuum state of a quantum field theory is highly entangled. If we divide space in half, field fluctuations on the the left side are correlated with fluctuations on the right side.

A uniformly accelerated observer in flat space sees a thermal bath of quanta, with typical wavelength comparable to proper distance to the event horizon.

$$z(\tau) = \frac{1}{a}\cosh(a\tau), \quad t(\tau) = \frac{1}{a}\sinh(a\tau).$$

Field fluctuations are periodic in imaginary time, with period equal to inverse temperature (Unruh temperature):

$$e^{-i\tau H} \sim e^{-\beta H}$$

$$k_B T = \frac{\hbar}{2\pi c} a \approx (10^{-20}\,\mathrm{K}\ \text{for}\ a = 1g).$$

Vacuum entanglement

Consider a CFT in 1 spatial dimension, in its vacuum state, and consider an interval of length R. How entangled is the inside with the outside?

Modes of various wavelength contribute to the entanglement entropy. Because of scale invariance, each decade of wavelength makes the same contribution. Integrating over the wavelength…

$$S = O(1) \times \int_{r_{UV}}^{r_{IR}} \frac{dr}{r} = O(1) \times \log\left(\frac{r_{IR}}{r_{UV}}\right)$$

This O(1) constant is actually c/3, where c is the central charge. We can take this to be a definition of c. The coefficient of the log is a universal property.

$$S = \frac{c}{3}\log\left(\frac{R}{a}\right)$$

c counts degrees of freedom;
another "definition," from thermal entropy:

$S = (\pi c/3)TR$ where T is temperature.

This quantity is infinite (dependent on the UV cutoff a), but we can obtain finite quantities in various ways, for example by differentiating S with respect to R, or computing mutual information of disjoint regions, or comparing S for different states, so that the divergent piece cancels out.

Strong subadditivity and the c-theorem

We can prove the c-theorem using Lorentz invariance and strong subadditivity of the entropy (Casini and Huerta 2004).

$$S(\rho) = -\mathrm{tr}(\rho \log \rho), \quad I(A;B) = S(A) + S(B) - S(AB) \geq 0$$

$$I(A;BC) \geq I(A;B) \Rightarrow S(AB) + S(BC) \geq S(B) + S(ABC)$$

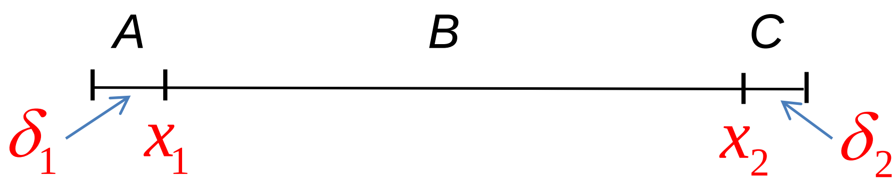
where *A, B, C* are disjoint subsystems. Suppose *B* is an interval $[x_1, x_2]$, and *A, C* are infinitesimal increments at each end. Strong subadditivity says:

$$S[x_1 - \delta_1, x_2] + S[x_1, x_2 + \delta_2] - S[x_1 - \delta_1, x_2 + \delta_2] - S[x_1, x_2] \geq 0$$

$$\Rightarrow \delta_1 \delta_2 \partial_1 \partial_2 S[x_1, x_2] \leq 0 \quad (\delta_1, \delta_2 > 0)$$

Now use Lorentz invariance (of vacuum). The entropy depends only on the *invariant length* of the interval. This length, from (0,0) to (x,t), is

$$R = \sqrt{x^2 - t^2} = \sqrt{-uv}, \quad u = x + t, \quad v = -x + t$$



Strong subadditivity and the c-theorem

Strong subadditivity (extending left and right endpoints in any spacelike direction):

$$S[x_1-\delta_1,x_2]+S[x_1,x_2+\delta_2]-S[x_1-\delta_1,x_2+\delta_2]-S[x_1,x_2]\geq 0$$

$$\Rightarrow \delta_1\delta_2\partial_1\partial_2 S[x_1,x_2]\leq 0 \quad (\delta_1,\delta_2>0)$$

Lorentz invariance:

$$S=S(R),\quad R=\sqrt{x^2-t^2}=\sqrt{-uv},\quad u=x+t,\quad v=-x+t$$

We find (if we extend the endpoints in the null direction):

$$\partial_{u_1}\partial_{u_2}S(\sqrt{-(u_1-u_2)(v_1-v_2)})\leq 0\Rightarrow c'(R)\leq 0, \text{where } \; c(R)=3RS'(R)$$

At a RG fixed point (CFT): $\boxed{S=(c/3)\log(R/a)\Rightarrow c(R)=3RS'(R)=c}$

If the RG flow is from a UV CFT to an IR CFT, then the UV theory applies for small R and the IR theory applies for large R. Therefore we have shown that c cannot increase under RG flow. This is the c-theorem.

This method, based on strong subadditivity, is completely different from the method of Zamolodchikov 1986. (Entropy inequalities are useful in QFT!)

Relative entropy and the c-theorem

Relative entropy measures the distinguishability of two quantum states. It is non-negative and monotonic

$$S(\rho \| \sigma) = \mathrm{tr}\left(\rho \log \rho - \rho \log \sigma\right) \geq 0$$

$$S(\rho \| \sigma) \geq S(N(\rho) \| N(\sigma))$$

where *N* is a quantum channel. For example, tracing out a subsystem cannot improve distinguishability.

We can compare the vacuum entanglement in two different theories (Casini et al. 2016). The relative entropy will be UV-finite if the two theories are sufficiently similar at short distances. Suppose σ is the ground state of a UV fixed point, and ρ is the ground state of a theory that flows from that UV fixed point to an IR fixed point. For an interval of length R:

$$S(\rho \| \sigma) = \frac{1}{3}\left(c_{UV} - c_{IR}\right) \log \mu R$$

where 1/μ is the renormalization length scale. As μ decreases we are tracing out degrees of freedom, so relative entropy decreases. Distinguishability is lost along the flow … which means c cannot increase.

“c-theorems” in higher dimensions

For CFT in d spatial dimensions

$$S = O(1) \times \int_{r_{UV}}^{r_{IR}} \left(\frac{R}{r}\right)^{d-1} \frac{dr}{r} = O(1) \times \left(\frac{R}{a}\right)^{d-1} + \quad \cdots$$

This leading term is UV divergent and non-universal, but there are universal subleading terms.

d=2: $S = O(1) \times \left(\frac{R}{a}\right) - F$ d=3: $S = O(1) \times \left(\frac{R}{a}\right)^2 - 4A\log\left(\frac{R}{a}\right)$

There are *F*- and *A*-theorems for RQFT. (e.g., Casini et al. 2015). There is an entropic proof of the *F*-theorem, but not the *A*-theorem.

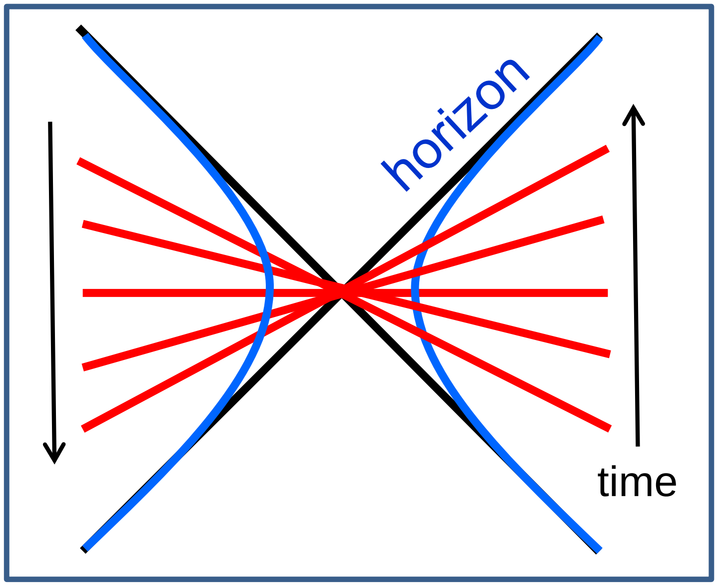
In condensed matter physics, *F* (also called γ) is the *topological entanglement entropy*. Nonzero γ in a theory with a mass gap indicates long-range entanglement in the ground state, a symptom of *topological order* (Kitaev and Preskill 2006, Levin and Wen 2006).

The first law of entanglement entropy

For any density operator, we can take its logarithm to obtain the corresponding *modular Hamiltonian*:

We can think of ρ as the thermal Gibbs state of *H*, with temperature = 1 by convention.

$$\rho = \frac{e^{-H}}{\mathrm{tr}(e^{-H})}$$



In general, *H* has no particular physical interpretation. But for Rindler spacetime it does. It is the Hamiltonian that generates the time as measured by the uniformly accelerated Rindler observer. From the perspective of an intertial observer, it generates Lorentz boosts.

It is useful to express relative entropy in terms of the modular Hamiltonian.

$$S(\rho \| \rho_0) \geq 0 \Rightarrow S(\rho) - S(\rho_0) \leq \mathrm{tr}(\rho H_0) - \mathrm{tr}(\rho_0 H_0)$$

To first order in the difference of density operators, we get equality:

$$S(\rho_0 + \delta\rho) - S(\rho_0)$$
$$= \mathrm{tr}(\delta\rho H_0) + O(\delta\rho^2)$$

This is called the first law of entanglement entropy because it resembles the first law of thermodynamics: *dE* = *TdS*.

Relative entropy and the Bekenstein bound

There is a limit to the amount of information we can squeeze into a given spatial volume with a given amount of energy *E*. This upper limit applies in quantum field theory, without gravity, though Bekenstein used gravitational ideas to motivate it. He claimed: $S=O(ER)$ for a ball of radius *R*.

Since entanglement entropy *S* is UV-divergent, we need to make a subtraction to make sense of this upper bound; we can consider the UV-finite difference between the entropy in the ball for state ρ and for the vacuum state ρ_0. Then positivity of relative entropy implies a Bekenstein-type bound:

$$S(\rho)-S(\rho_0)\leq \mathrm{tr}\left(\rho H_0\right)-\mathrm{tr}\left(\rho_0 H_0\right)$$

In what sense is the right-hand side $O(ER)$? In Rindler spacetime we know H_0 explicitly; it is the generator of boosts in the x direction, hence

$$H_0=\int dx\ xh$$

Where *h* is the Hamiltonian *density* that generates evolution in time as measured by the inertial observers.

Using conformal invariance, one can write down an explicit formula for H_0 in a CFT vacuum, for a ball shaped region in any dimension. From entanglement 1^{st} law, we can then find *S* for nearby states.

Bekenstein bound: the species problem

One might raise an objection to the bound *S=O(ER)*. Can't we consider a theory where particles come in many (*N*) species which carry different "flavors" but are otherwise identical? And if so, what can prevent us from storing as much information as we please, using specified energy and volume, just by choosing *N* large enough?

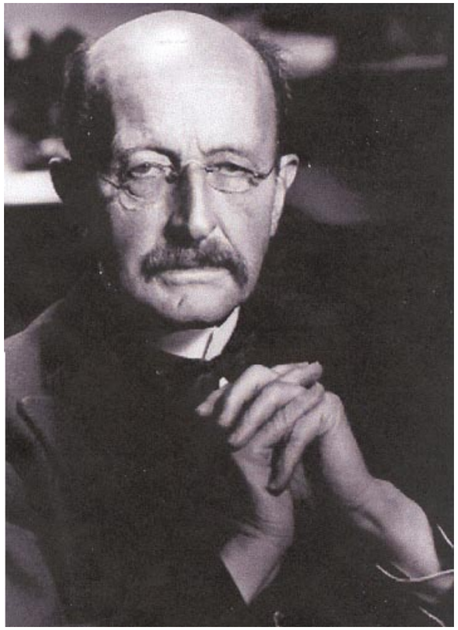
Casini's 2008 version of the Bekenstein bound pleasingly circumvents this problem.

$$S(\rho) - S(\rho_0) \le \mathrm{tr}\left(\rho H_0\right) - \mathrm{tr}\left(\rho_0 H_0\right)$$

With more species we can increase the entropy of a state with specified modular energy, but we increase the vacuum entropy, too.

In fact mixing many species makes the excited state and vacuum state harder to distinguish, so the relative entropy gets smaller for larger *N* and the Bekenstein bound is more nearly saturated, but never violated (because the relative entropy never becomes negative).

Field theorists should know about relative entropy!



PARADOX!

When the theories we use to describe Nature lead to unacceptable or self-contradictory conclusions, we are faced with a great challenges and great opportunities….

Planck
1900

Hawking
1975

“*The ultraviolet catastrophe*”

In thermal equilibrium at nonzero temperature, the electromagnetic field carries an infinite energy per unit volume …

The end of
classical physics!

“*The information loss puzzle*”

The radiation emitted by an evaporating black hole is featureless, revealing nothing about how the black hole formed …

The end of quantum physics?
(Or of relativistic causality?)

Black hole radiance

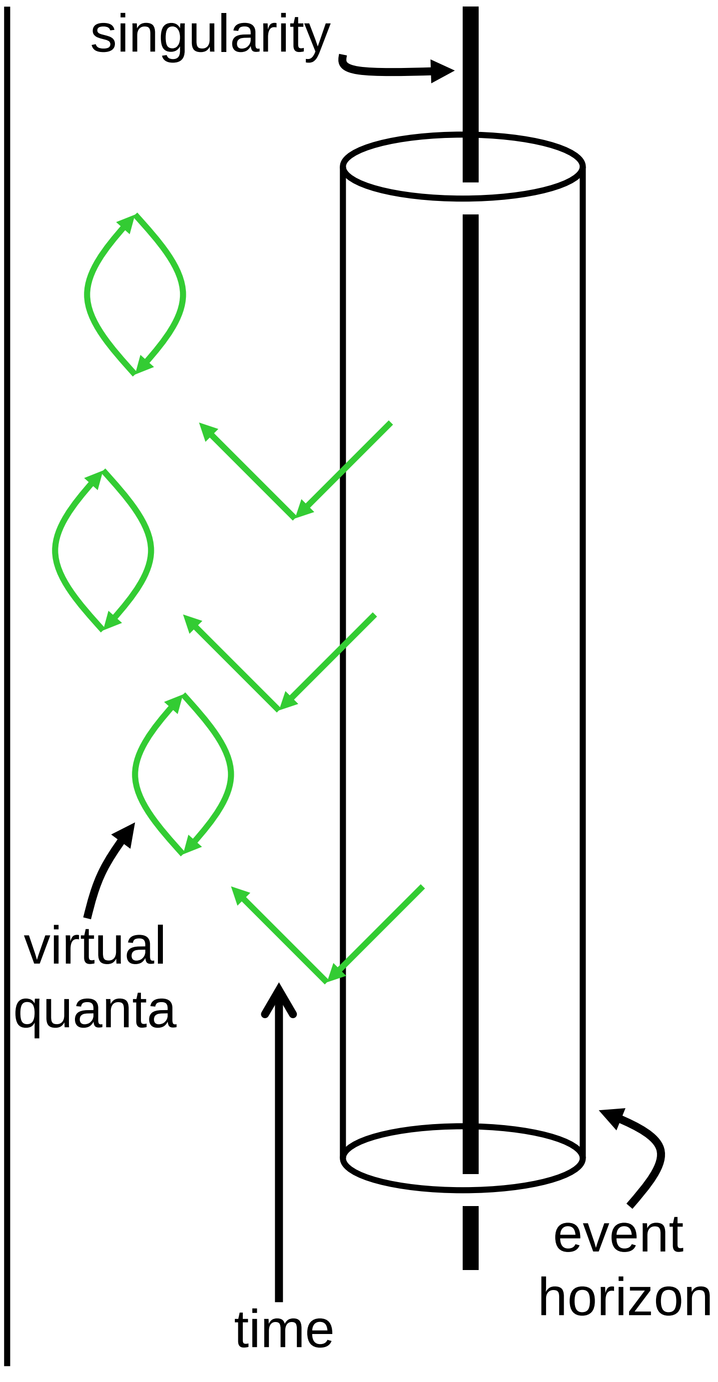
Classically, nothing can escape from a black hole, but quantumly, black holes *radiate*.

Quantum fluctuations in the vacuum continually create pairs of virtual particles, which then reannihilate. But if one member of the pair ducks behind the event horizon, the other escapes.

To an observer far away, the black hole seems to be a source of featureless thermal radiation with wavelength comparable to the black hole radius:

$$k_B T_{\text{black hole}} = \hbar c / 4\pi R_{\text{black hole}}$$

Since the radiation really arises from quantum fluctuations just outside the horizon, its properties don't depend on how the black hole was formed.



Black hole "thermal atmosphere"

A static observer at a fixed proper distance from the black hole horizon is uniformly accelerated (with larger acceleration closer to the horizon), and hence sees a thermal radiation bath (which is hotter closer to the horizon).

This acceleration, when red shifted to infinite distance from the black hole, is the black hole's "surface gravity":

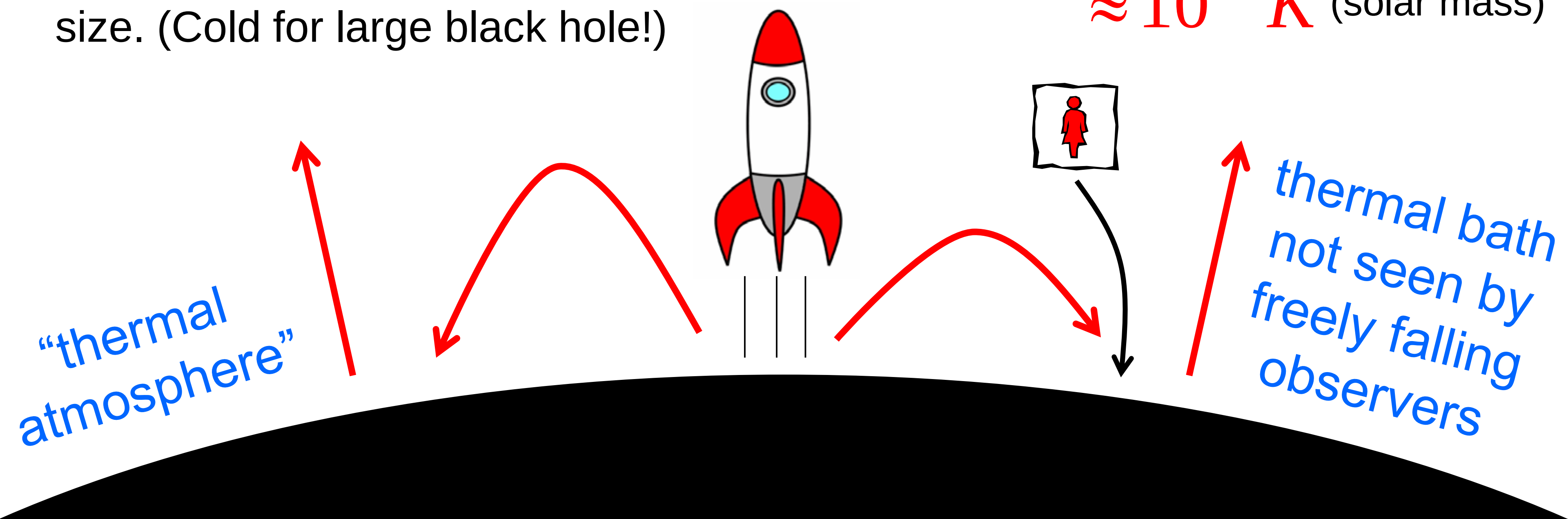
$$\kappa = \frac{c^2}{2R_{BH}}$$

Correspondingly, the thermal radiation detected by an observer at infinity has temperature:

$$k_B T_{BH} = \hbar c / 4\pi R_{BH}$$

Thermal wavelength comparable to black hole 's size. (Cold for large black hole!)

$$\approx 10^{-7}\,K$$ (solar mass)



Black hole entropy

Integrating $TdS = dE$, we find from

$$k_B T_{\text{black hole}} = \hbar c / 4\pi R_{\text{black hole}}$$

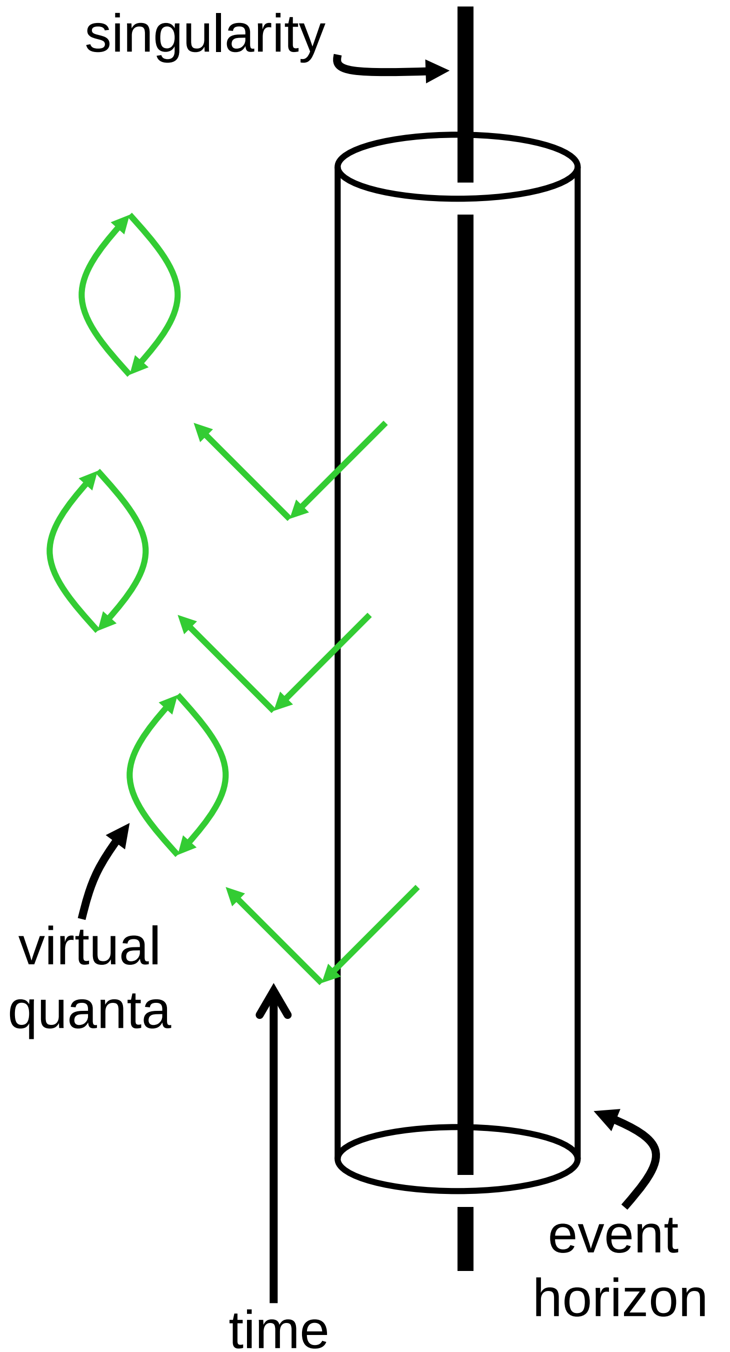
and $$E = Mc^2 = \left(c^4 / 2G\right) R_{\text{black hole}}$$

that $$S_{\text{black hole}} = \frac{1}{4} \frac{Area}{L_{\text{Planck}}^2}$$

where
$$L_{\text{Planck}} = \left(\hbar G / c^3\right)^{1/2} = 10^{-33}\,\text{cm}$$

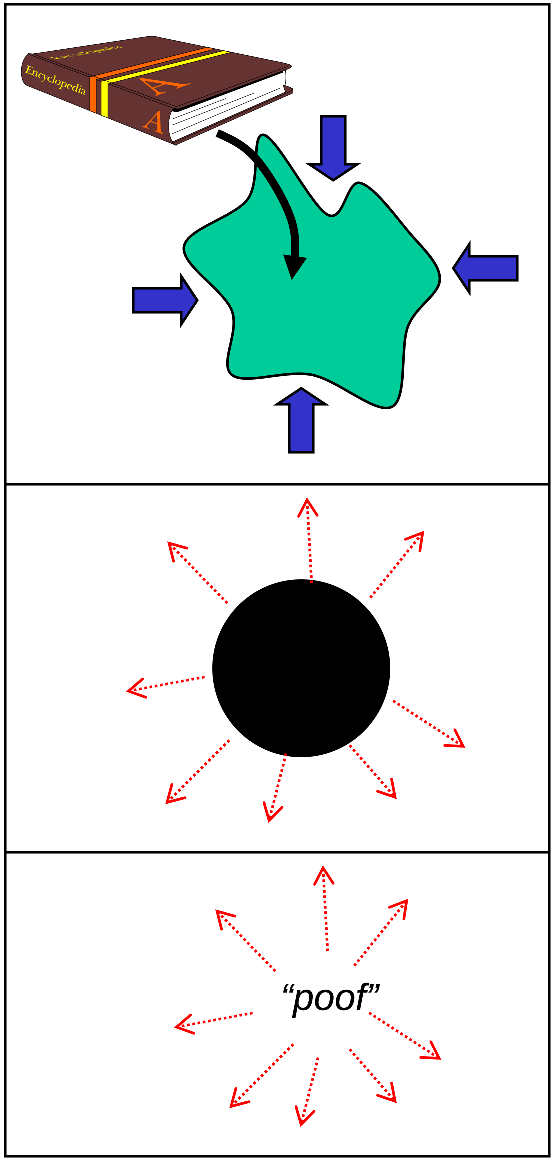
Strangely, black holes seem to be both very simple (have no hair), and yet also very complex (have enormous entropy, e.g., 10^{78} for a solar mass).

It is as though (qu)bits reside on the black hole horizon, one per each Planck unit of horizon area.



Black hole evaporation

Suppose we prepare a quantum state, encoding some information, as pressureless dust on the brink of gravitational collapse.



It collapses, and begins to emit Hawking radiation. This radiation is featureless, not dependent on the information encoded in the original collapsing body.

Eventually, all the mass is radiated away, and the black hole disappears. What happened to the information?

Other hot bodies emit thermal radiation. Such processes are *thermodynamically* irreversible but not *microscopically* irreversible.

But a black hole is different than other hot bodies, because it has an event horizon. Does that mean that this process is microscopically irreversible, that the information is lost not just in practice but in principle?

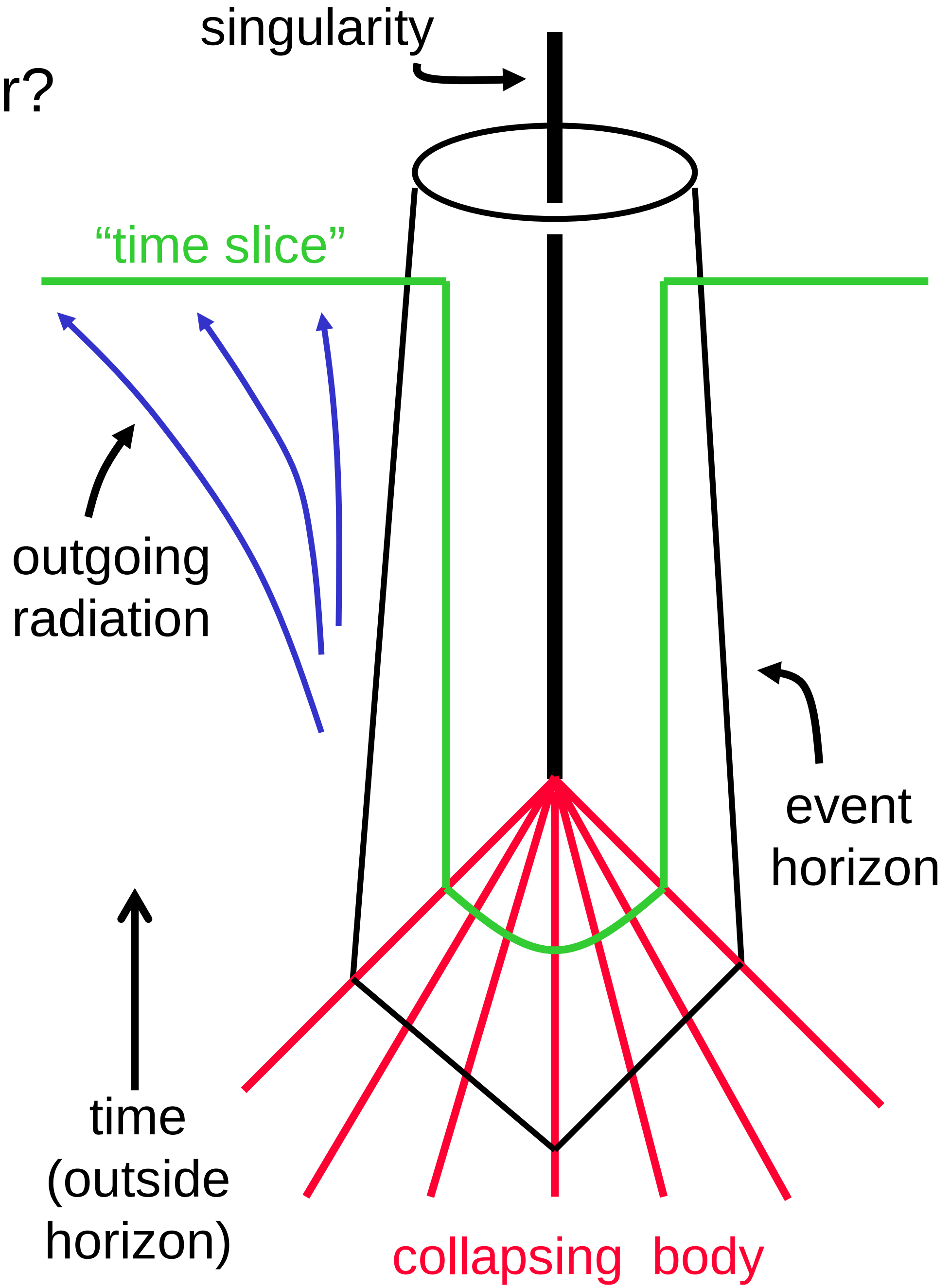
Information Puzzle:

Is a black hole a quantum cloner?

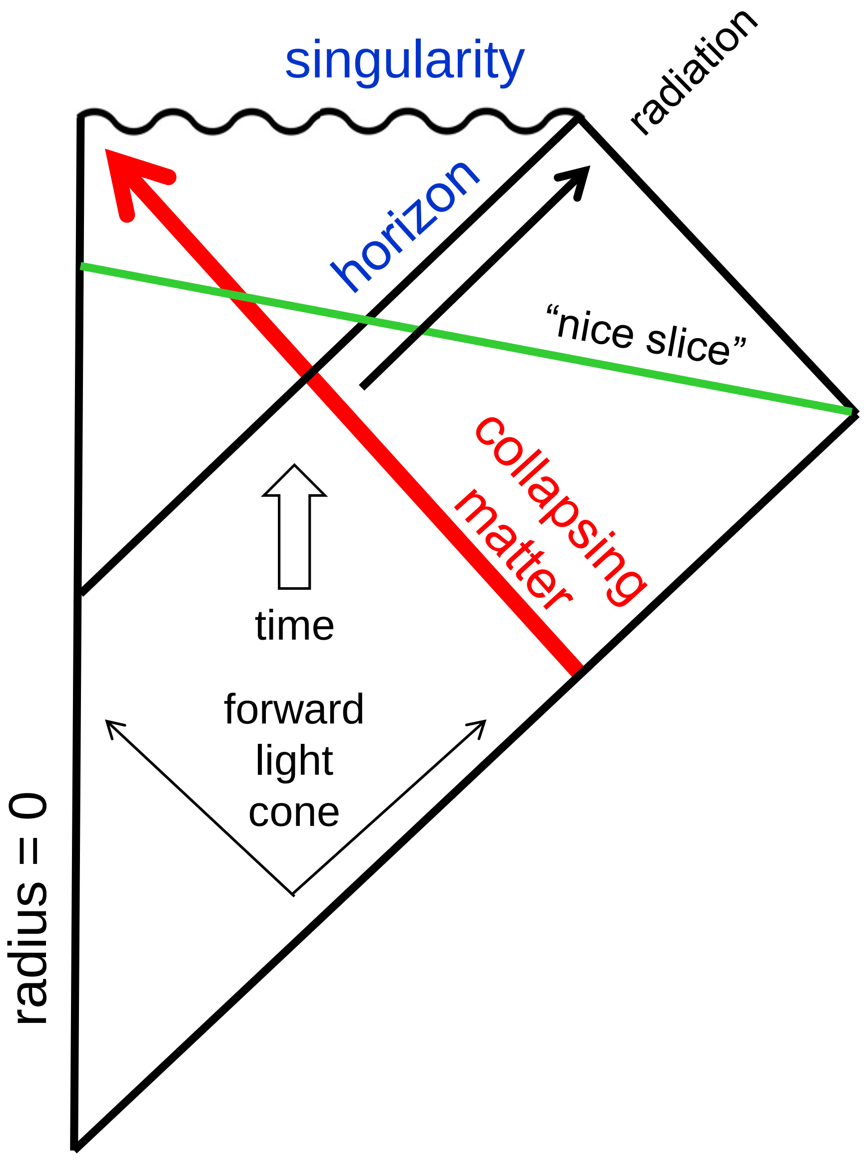
If information escapes from the black hole, then ..

The same (quantum) information is in two places at the same time!

We're stuck:
Either information is destroyed or cloning occurs. Either way, quantum physics needs revision.



Black hole as quantum cloner



The "nice slice" shown in green can be chosen to cross both the collapsing body behind the horizon and 99% of the escaping Hawking radiation outside the horizon.

Yet the slice only occupies regions of low curvature, where we would normally expect semiclassical physics to be reliable.

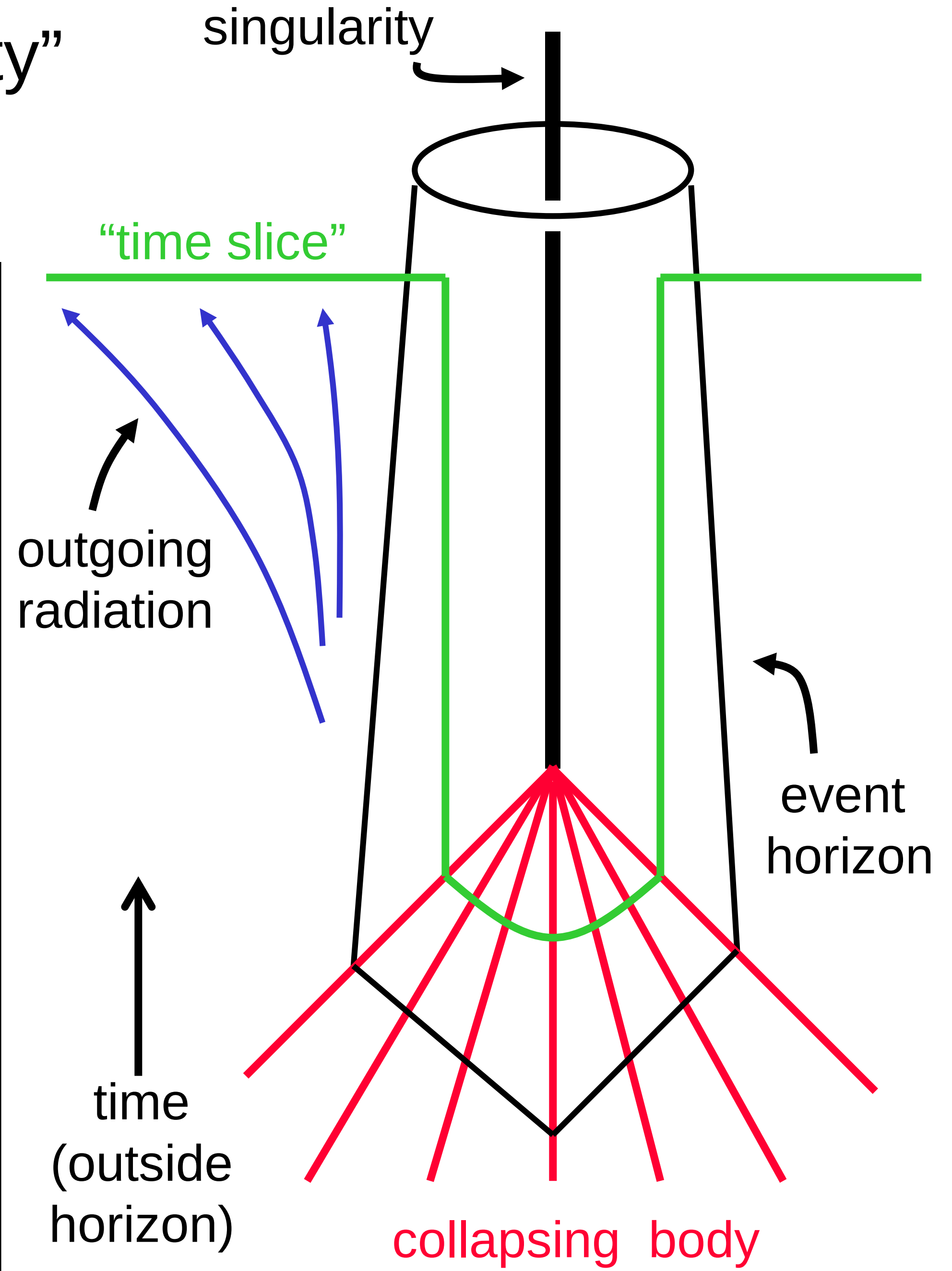
The same quantum information is in two different places at the same time.

“Black hole complementarity”

The inside and the outside are not two separate systems.

$$\mathcal{H} \neq \mathcal{H}_{\text{in}} \otimes \mathcal{H}_{\text{out}}$$

Rather, they are two different ways of looking at the *same* system. [Susskind 1993].



Black hole complementarity challenged

Three reasonable beliefs, not all true!

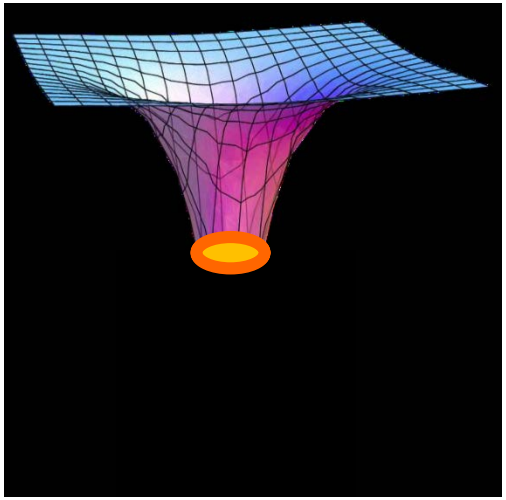
[Almheiri, Marolf, Polchinski, Sully (AMPS) 2012, Mathur 2009, Braunstein 2009]:

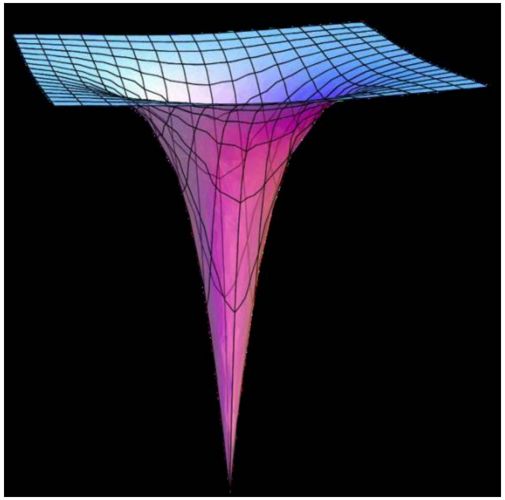
(1) The black hole "scrambles" information, but does not destroy it.

(2) An observer who falls through the black hole horizon sees nothing unusual (at least for a while).

(3) An observer who stays outside the black hole sees nothing unusual.

"Conservative" resolution:
A "firewall" at the horizon, rather than (2).





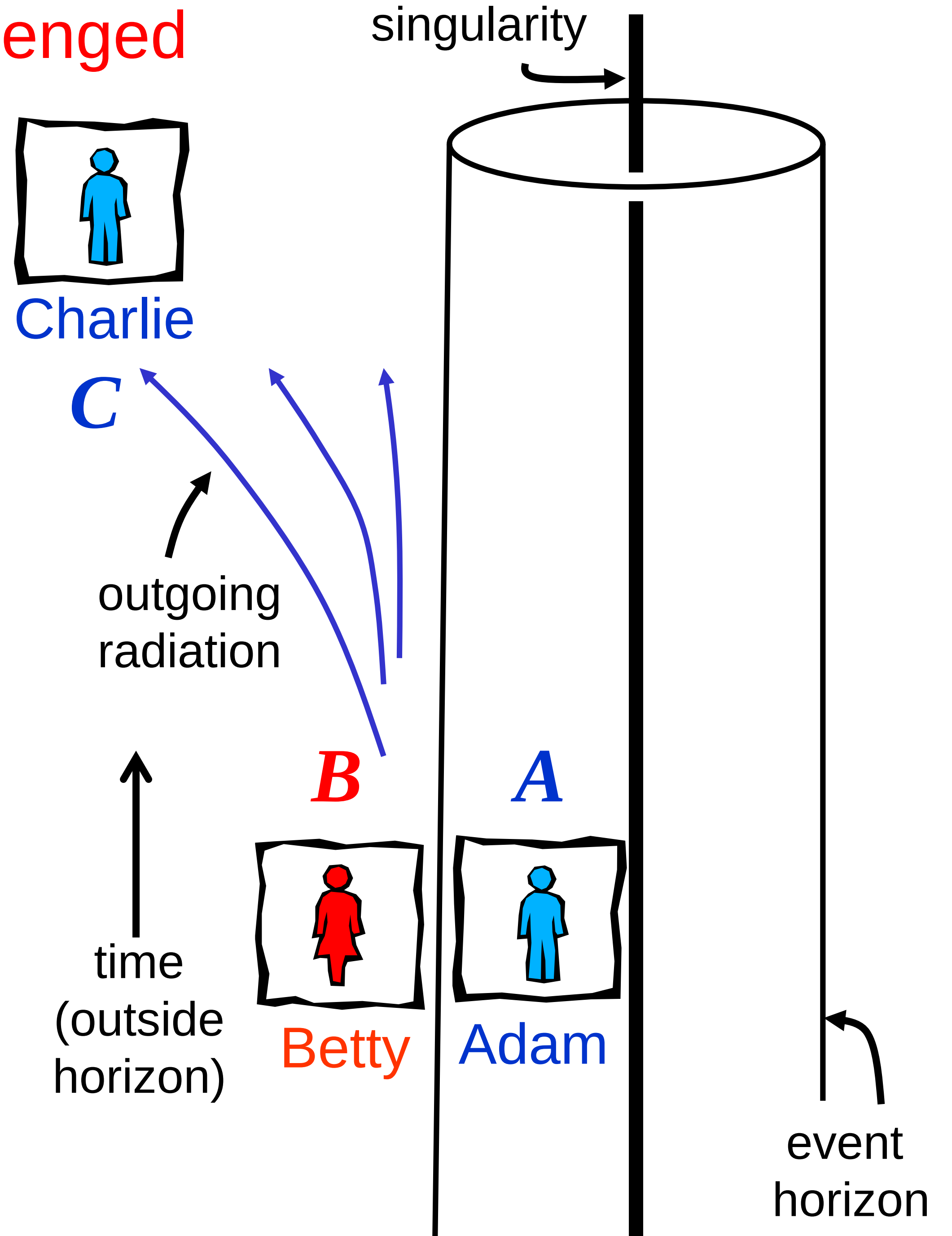
Complementarity Challenged

(1) For an old black hole, recently emitted radiation (B) is highly entangled with radiation emitted earlier (C) by the time it reaches Charlie.

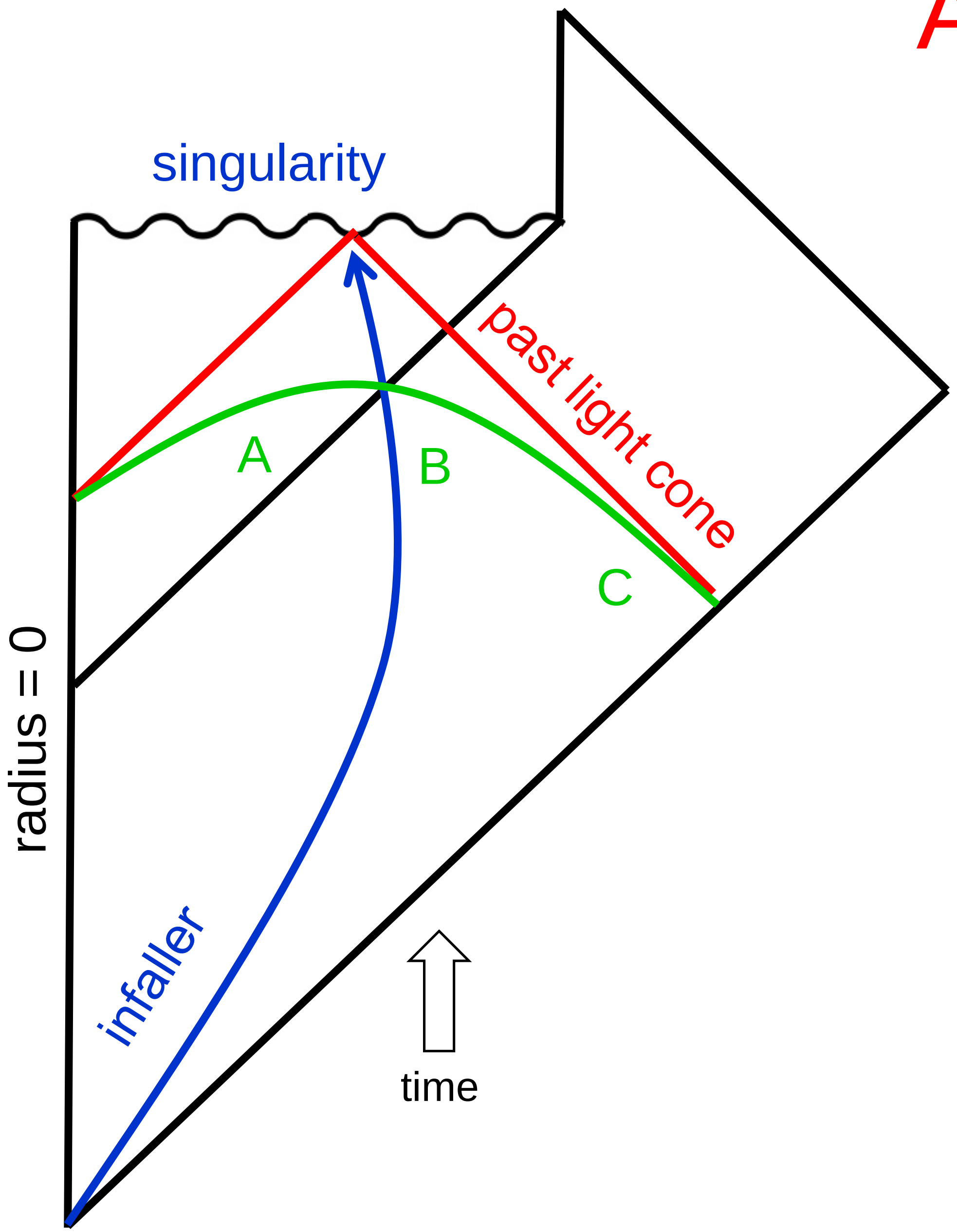
(2) If freely falling observer sees vacuum at the horizon, then the recently emitted radiation (B) is highly entangled with modes behind the horizon (A).

(3) If B is entangled with C by the time it reaches Charlie, it was already entangled with C at the time of emission from the black hole.

Monogamy of entanglement violated!

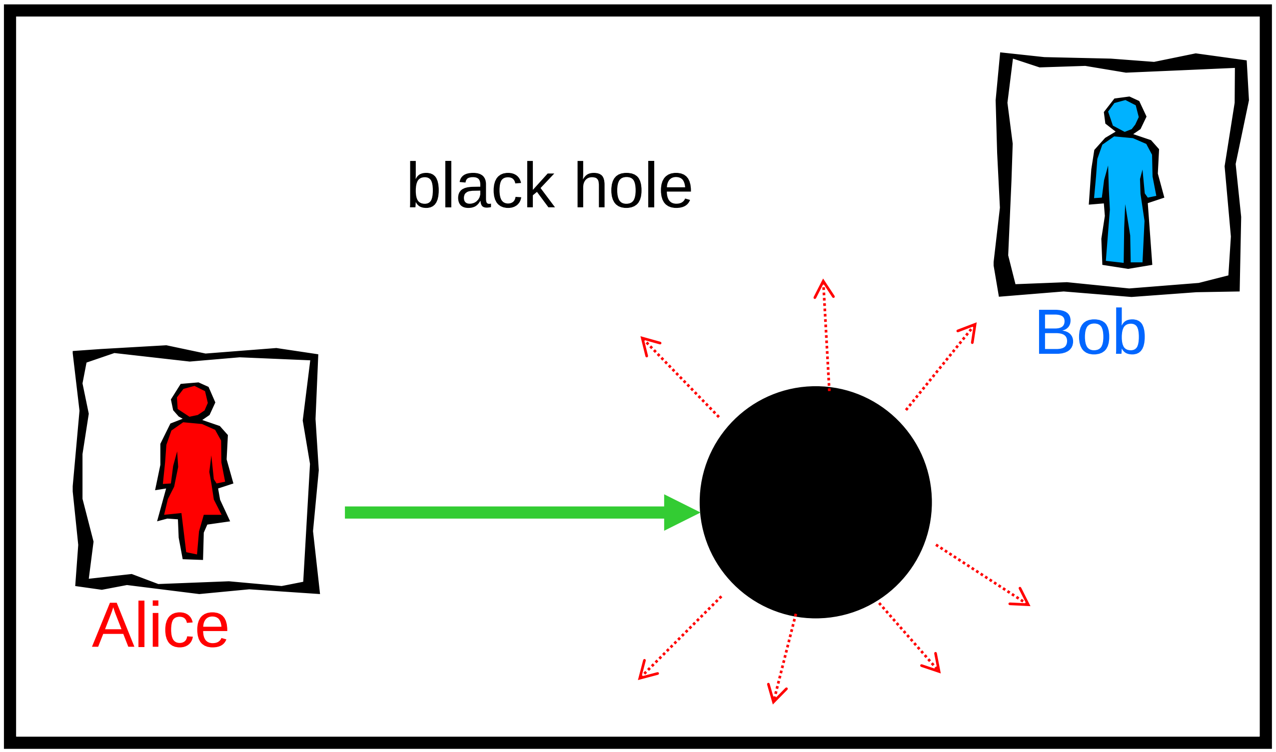


AMPS experiment



Now a single infalling agent, when still a safe distance from the singularity, can be informed that both the AB and BC entanglement have been confirmed, hence *verifying* a violation of the monogamy of entanglement.

What's inside a black hole?



What’s inside a black hole?

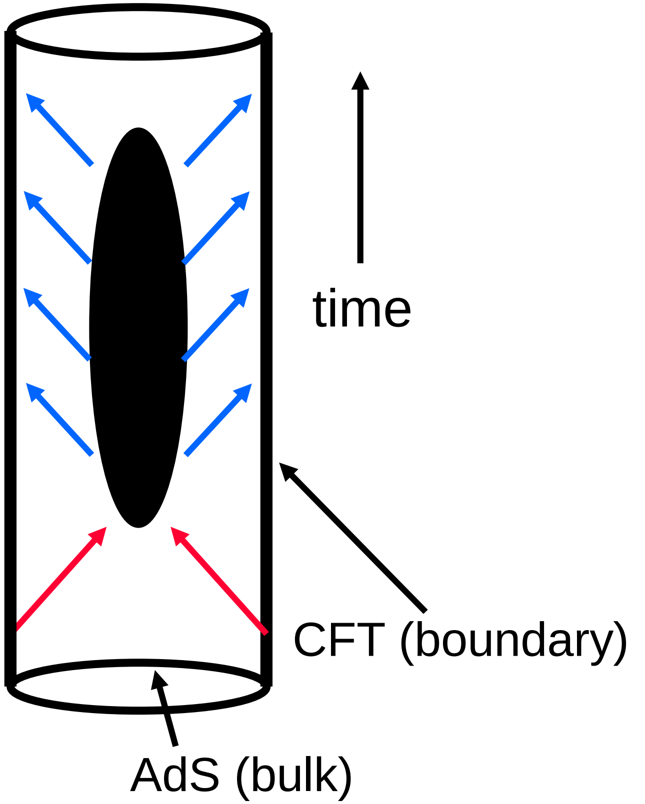
A. An unlimited amount of stuff.

B. Nothing at all.

C. Some of the same stuff that is also (far) outside the black hole.

D. None of the above.

A black hole in a bottle



We can describe the formation and evaporation of a black hole using an "ordinary" quantum theory on the walls of the bottle, where information has nowhere to hide (*Maldacena 1997*).

A concrete realization of the "holographic principle" (*'t Hooft, Susskind 1994*).

So at least in the one case where we think we understand how quantum gravity works, a black hole seems not to destroy information!

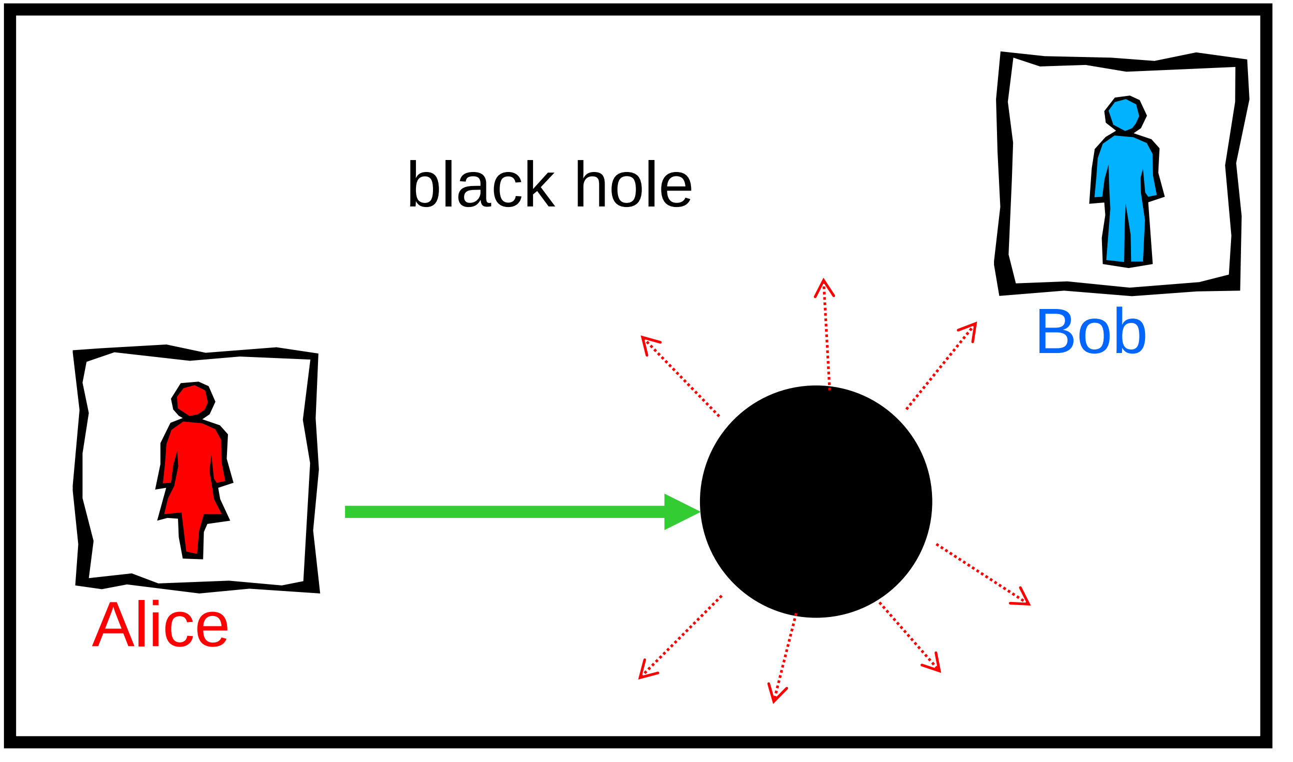
Even so, the mechanism by which information can escape from behind a putative event horizon remains murky.

Indeed, it is not clear whether or how the boundary theory describes the experience of observers who cross into the black hole interior, or even if there is an interior!

End of Lecture 1

Beginning of Lecture 2

What's inside a black hole?



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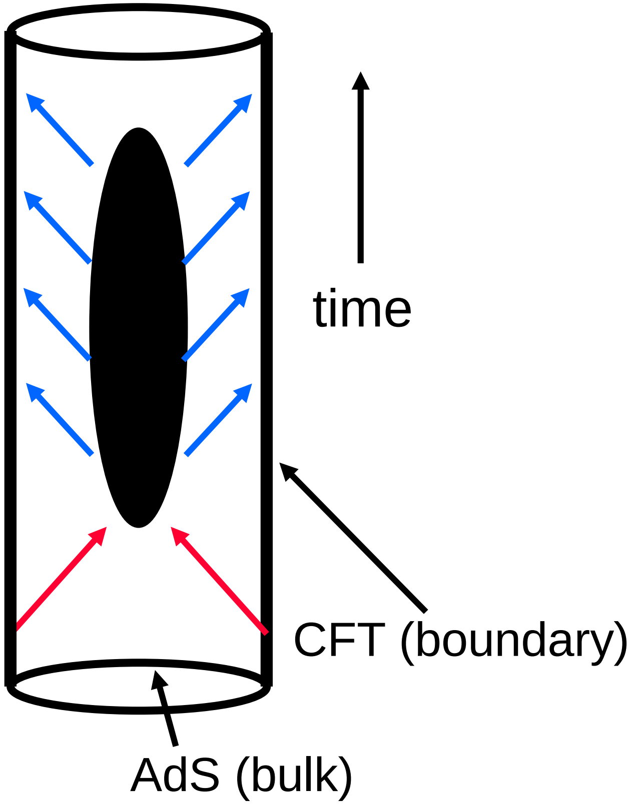

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Bulk/boundary duality: an *exact* correspondence

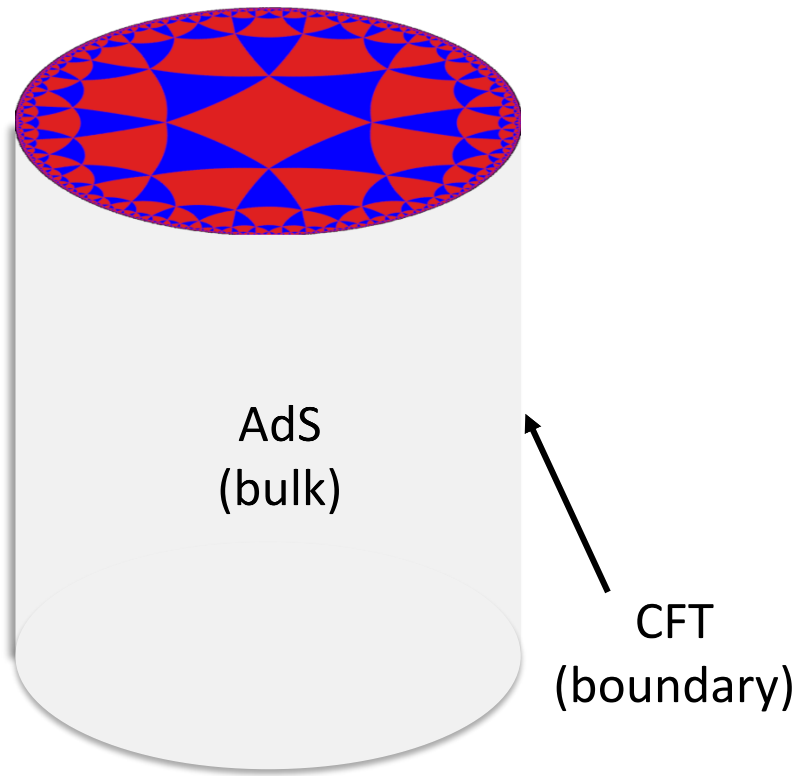
Weakly-coupled gravity in the bulk $\leftrightarrow$ strongly-coupled conformal field theory on boundary.

Complex dictionary maps bulk operators to boundary operators.

Emergent radial dimension can be regarded as an RG scale.

Semiclassical (sub-AdS scale) bulk locality is highly nontrivial.

Geometry in the bulk theory is related to entanglement structure of the boundary theory.

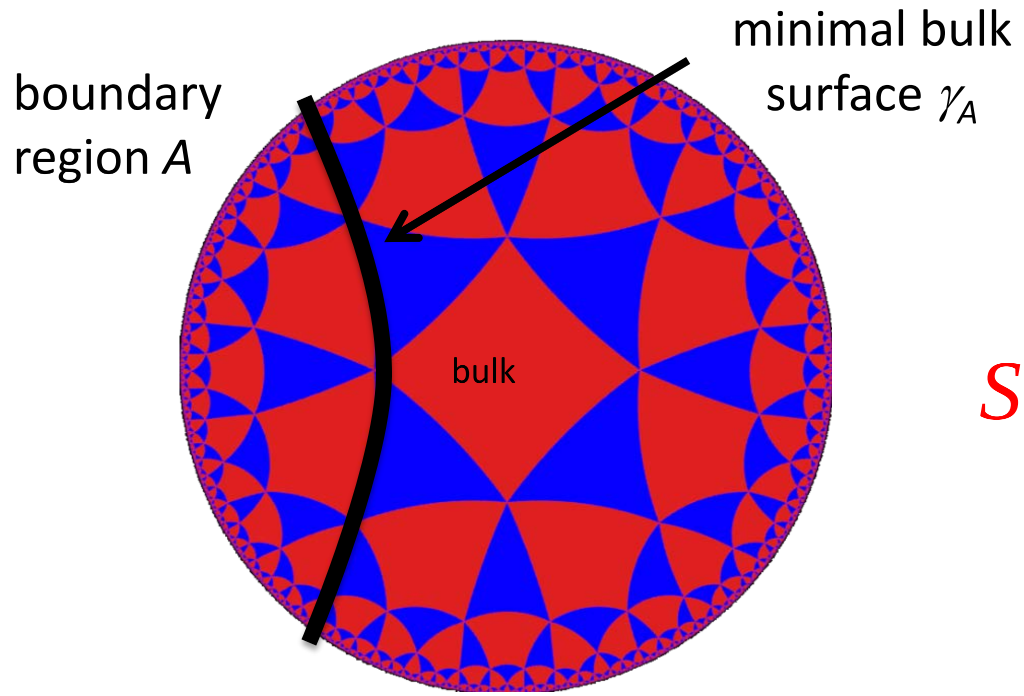


Many boundary fields ("large N"), so AdS curvature large compared to Planck scale.

Strong coupling on boundary, so AdS curvature large compared to the string scale.

(Maldacena 1997)

Holographic entanglement entropy



$$S(A) = \frac{1}{4G}\,\mathrm{Area}(\gamma_A) + \cdots$$

To compute entropy of region A in the boundary field theory, find minimal area of the bulk surface γ_A with the same boundary.

(Ryu,Takayanagi 2006. Hubeny, Rangamani, Takayanagi 2007.)

(How can area, an observable, be equal to entropy, which is not a linear operator? It's important that the formula is not exact…)

Geodesics on Hyperbolic Disk

Metric (boundary at z = 0),
L is AdS curvature scale:

$$ds^2 = L^2 \frac{dy^2 + dz^2}{z^2}$$

Geodesic is semicircle:

$$(y, z) = \frac{R}{2}(\cos\phi, \sin\phi)$$

Geodesic is infinitely long. Regulate by putting boundary at *z* = *a*. Then for boundary interval of length R:

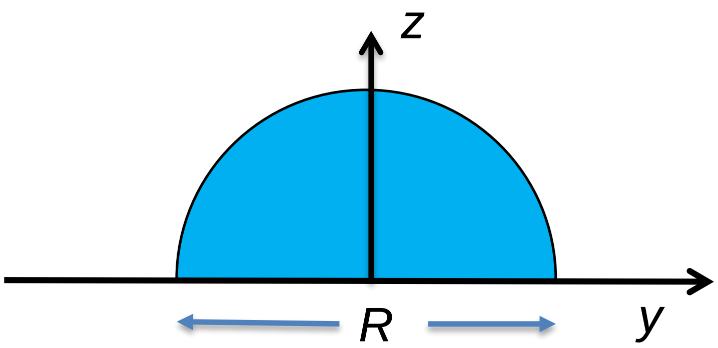
$$\text{Geodesic Length} = 2L\ln(R/2a)$$

Fastest way to reach the other end of the boundary interval is to dive deep into the bulk, because:

$$dz = dr e^{r/L}$$

where *r* is proper distance into the bulk.

The geodesic is infinitely long, just as the entanglement entropy is infinite. The UV cutoff on the boundary corresponds to an IR cutoff in the bulk.



For a larger boundary region, the geodesic probes more deeply into the bulk. The radial direction of the bulk geometry corresponds to the scale of the boundary theory. (Short boundary distance means large bulk radius.)

Ryu-Takayanagi Formula

$$\frac{\text{Geodesic Length}}{4G} = \frac{2L}{4G}\log\left(\frac{R}{a}\right)$$

$$S = \frac{c}{3}\log\left(\frac{R}{a}\right)$$

$$c = \frac{3L}{2G}$$

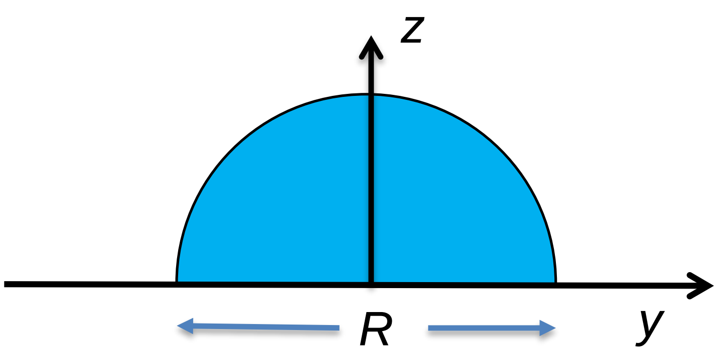
The emergent bulk dimension is a scale of the boundary theory.

The UV cutoff on the boundary is an IR cutoff in the bulk.

Short-distance boundary physics is long-distance bulk physics.

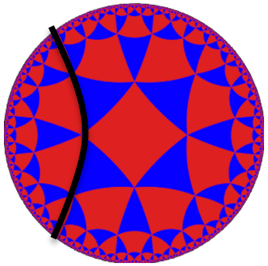
A conformal field theory on the boundary is needed for a deep bulk.

A boundary field theory with a mass gap has exponentially decaying correlations, and *S* = constant for *R* larger than correlation length.



That would mean that the bulk has finite extent in the z direction.

Ryu-Takayanagi (RT) formula



How we do know the RT formula is right?

There is a derivation, using path integral methods. I won't go into that here, but one important lesson from the derivation is that RT is not exact. It is the leading term in a systematic expansion in powers of Newton's gravitational constant G. The next-to-leading terms are also well understood. These corrections become more important when we consider shorter distances and higher energies in the CFT.

We can also check it in a number of ways. These checks are limited, because many computations in the strongly coupled CFT are beyond our ability.

One simple check: If the boundary is in a pure state, and we divide the boundary into two subsystems, then both subsystems have the same entropy. (The two boundary regions share the same minimal surface.)

Subadditivity and strong subadditivity of entropy are also easy to check.

We can go further, and find further entropy inequalities which are implied by RT but don't hold for general states. These are quite interesting, because they inform us about how quantum theories and states with dual geometries have special properties.

Mutual information

As shown, consider three consecutive regions A, B, C. What is the mutual information of A and C?

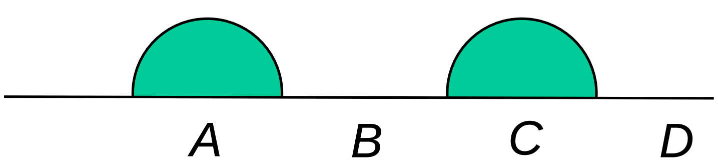
There are two extremal surfaces. RT picks out the one with smaller area.

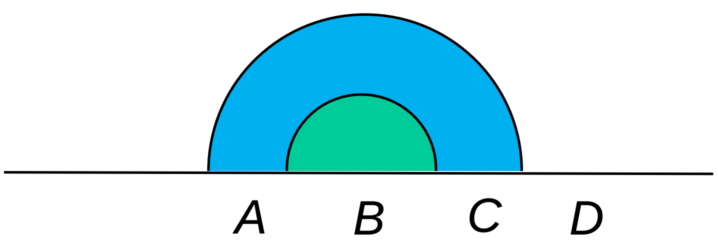
For the first choice, $S(AC) = S(A) + S(C)$, and $I(A;C) = 0$. The marginal states are uncorrelated.

The second choice will be favored if $S(ABC) + S(B) < S(A) + S(C)$.
Then $I(A:C) = S(A) + S(C) - S(AC) = S(A) + S(C) - S(ABC) - S(B) > 0$.
This proves subadditivity.

In fact in this second case, the quantum Markov property (quantum conditional independence) is satisfied: For pure ABCD, $S(BD) = S(AC) = S(B) + S(ABC) = S(B) + S(D)$.
So … $I(B;D) = 0$.

We can divide AC into two subsystems, where one purifies B, the other purifies D.
If B is erased, there is a local (Petz) recovery map taking AC to ABC.
This is a first hint that holographic states are interesting error-correcting codes.

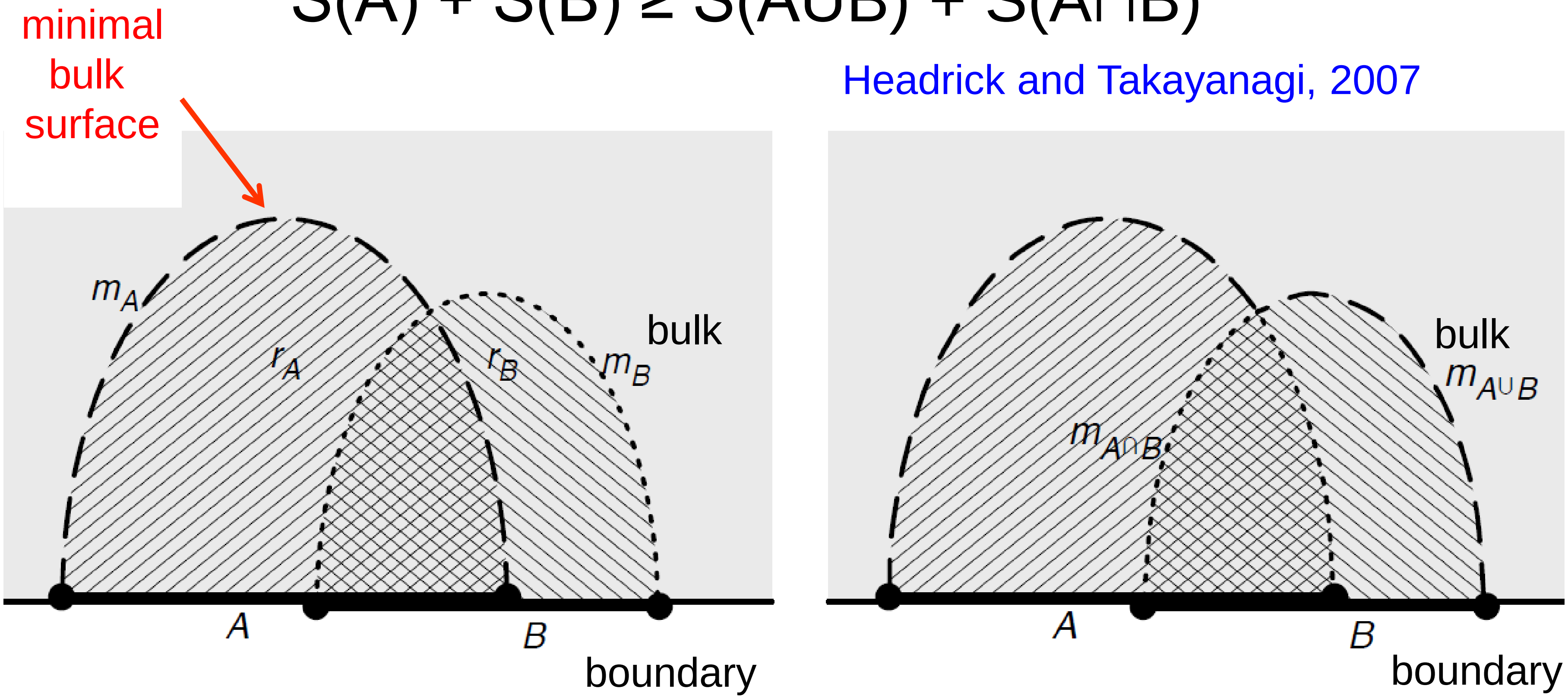




Strong subadditivity from holography

$$S(A) + S(B) \geq S(A \cup B) + S(A \cap B)$$

Headrick and Takayanagi, 2007



Tripartite Info: $I(A;B) + I(A;C) \leq I(A;BC)$

(monogamy of mutual information for disjoint A, B, C). True for holographic theories, not in general. Indicates that boundary state is highly entangled.

Hayden, Headrick, Maloney, 2011

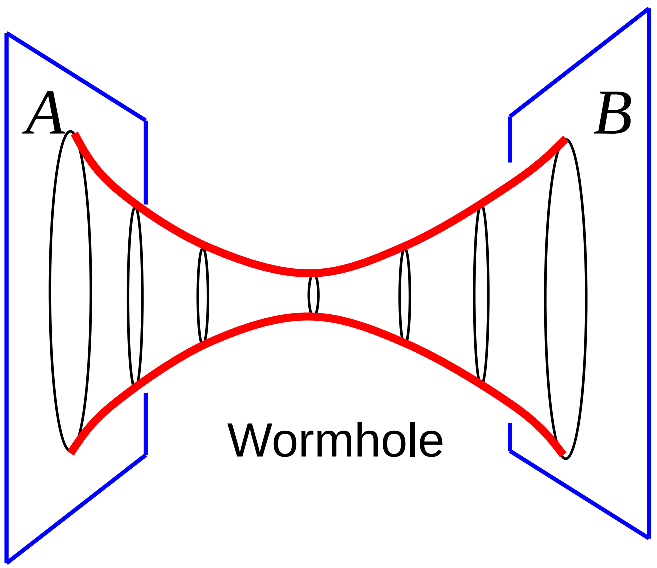
The "two-sided" AdS black hole

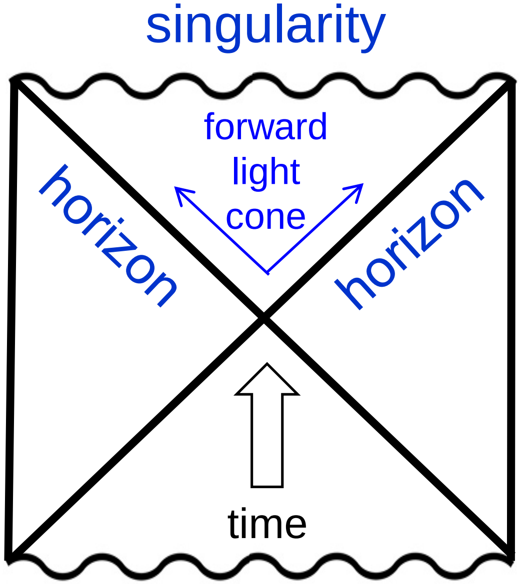
The AdS/CFT correspondence gives us a new laboratory for studying black holes.

Black holes which are small compared to the AdS curvature scale evaporate completely, but large black holes persist indefinitely.

The "extended" black hole solution actually describes two asymptotic regions, which are connected by a "wormhole" which grows longer (but keeps the same width) as time advances.

The quantum black hole has a temperature, and remains in thermal equilibrium with a gas of particles at the same temperature as the black hole.





The "two-sided" AdS black hole

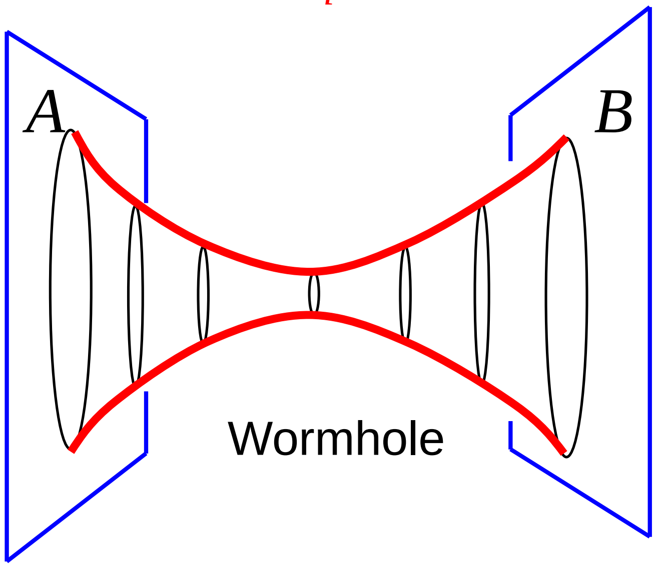
The AdS black hole has two boundaries, and hence corresponds to the quantum state of two strongly coupled CFT's, one on each boundary.

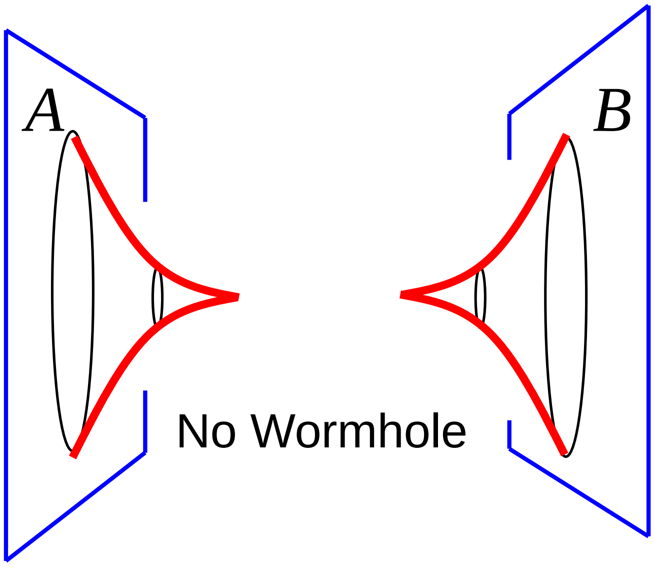
This state is the entangled thermofield double (TFD) of the two CFT's. Tracing out one CFT, we obtain a thermal state of the other CFT.

$$|\psi\rangle_{AB} = \frac{1}{\sqrt{Z}} \sum_i e^{-\beta E_i/2} |E_i\rangle \otimes |E_i\rangle$$

$$\Rightarrow \rho_A = \frac{1}{Z} \sum_i e^{-\beta E_i} |E_i\rangle\langle E_i|$$

A product state is dual to a disconnected geometry. An entangled state is dual to a wormhole.





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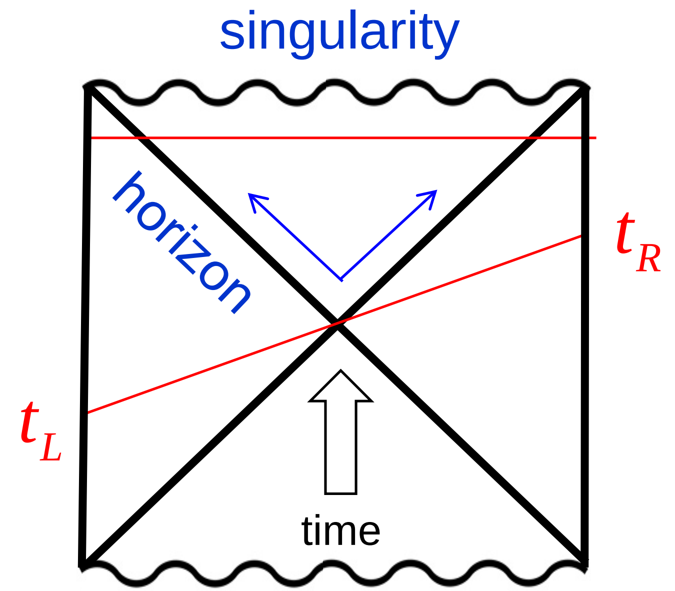
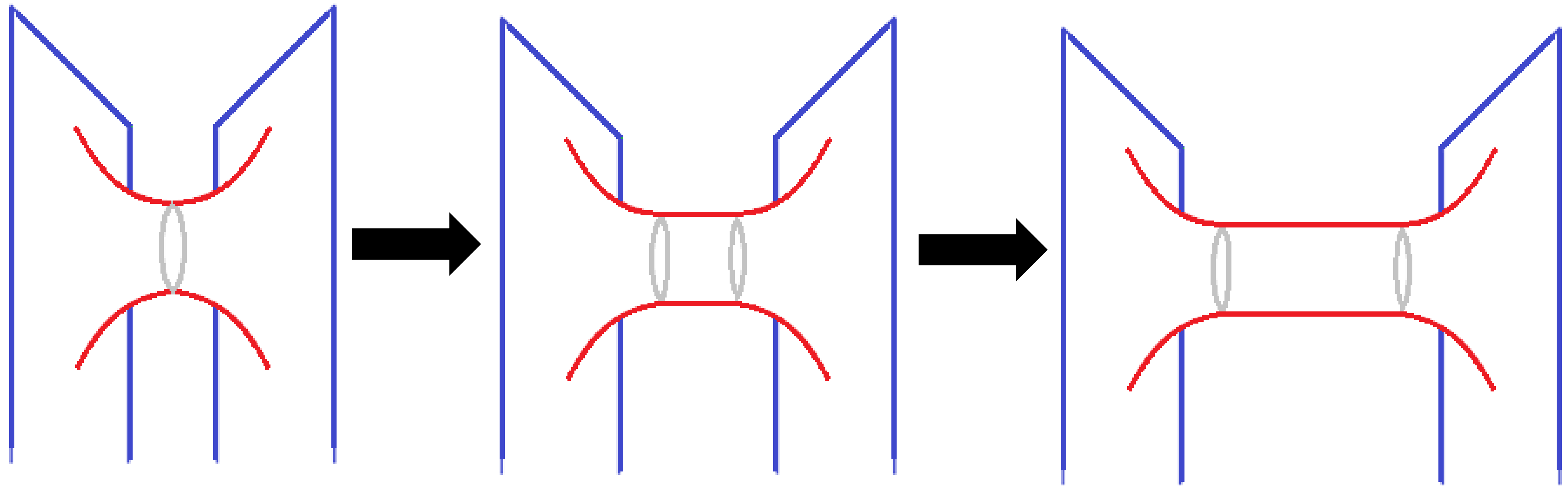


As the two-side black hole evolves, it remains maximally entangled; the marginal state on the right or left side does not change. But the relative phases in the superposition evolve. The evolution effects only the geometry inside the horizon, where the solution to the Einstein equations is not stationary: the wormhole neck grows longer:

$$|\psi(t_L, t_R)\rangle_{AB} = \frac{1}{\sqrt{Z}} \sum_i e^{-\beta E_i/2} e^{-i(t_L + t_R)E_i} \, | E_i \rangle \otimes | E_i \rangle$$

If time runs forward on right and backward on right, state does not evolve (boost symmetry of solution).



Black hole

A CFT at a high temperature corresponds to a large black hole in the bulk. For a 1+1 dimensional CFT, we know that $S = (\pi c/3)\, RT$. We can check agreement.

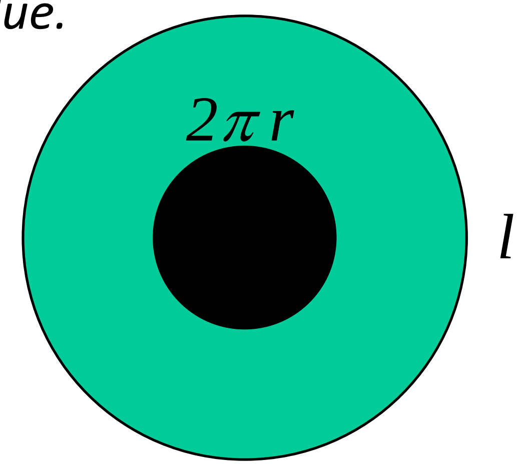
We consider black hole to be maximally entangled with a reference system (perhaps another black hole). The entanglement entropy of the CFT with the reference system counts the black hole microstates.

We need to know something about the BTZ black hole in the limit of high temperature: $r/L = l\, T >> 1$.
Here $2\pi r$ is BH circumference, T is temperature, L is the AdS curvature scale, and l is circumference of boundary. We can compute this by considering the proper acceleration near the horizon (which determines the local Unruh temperature), and then finding its red shifted value.

Entropy of the boundary, according to RT, is
$S = 2\pi r / 4G$.

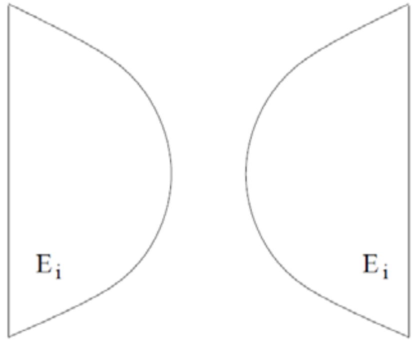
According to CFT thermodynamics, it is
$S = (\pi c / 3)\, l\, T = (\pi c / 3)\, r / L$

This confirms $c = (3/2)\,(L / G)$.



Building spacetime from quantum entanglement

$$\sum_i e^{-\beta E_i/2}$$



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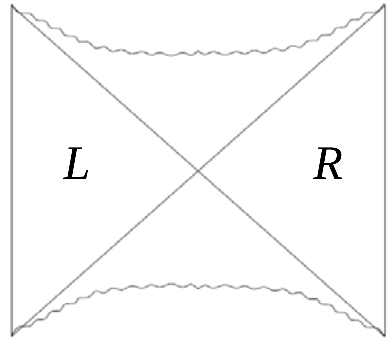
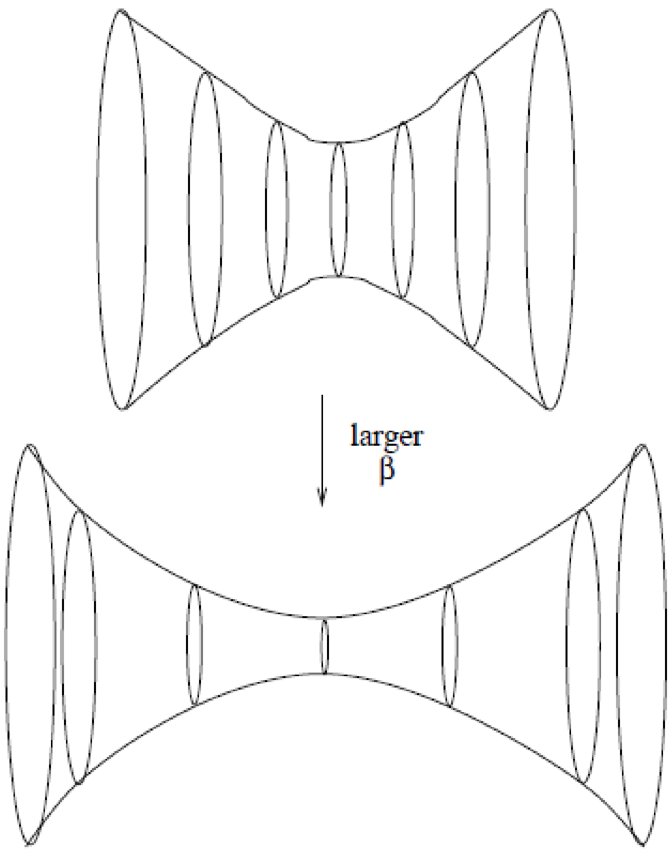
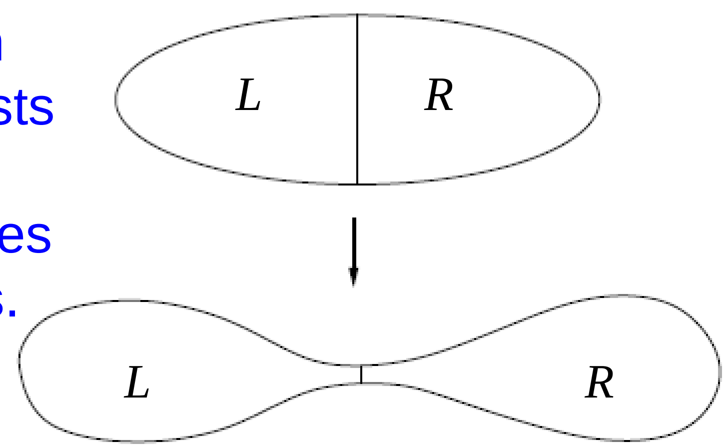


$$\sum_i e^{-\beta E_i/2} \, | E_i \rangle \otimes | E_i \rangle$$



Suppose we try to reduce the entanglement between two boundary hemispheres using a quantum computer. By RT, the bulk geometry acquires a narrow neck, eventually breaking off as the state becomes a product state (Van Raamsdonk 2010).

Breaking vacuum entanglement costs energy. The back reaction dismantles space into pieces.

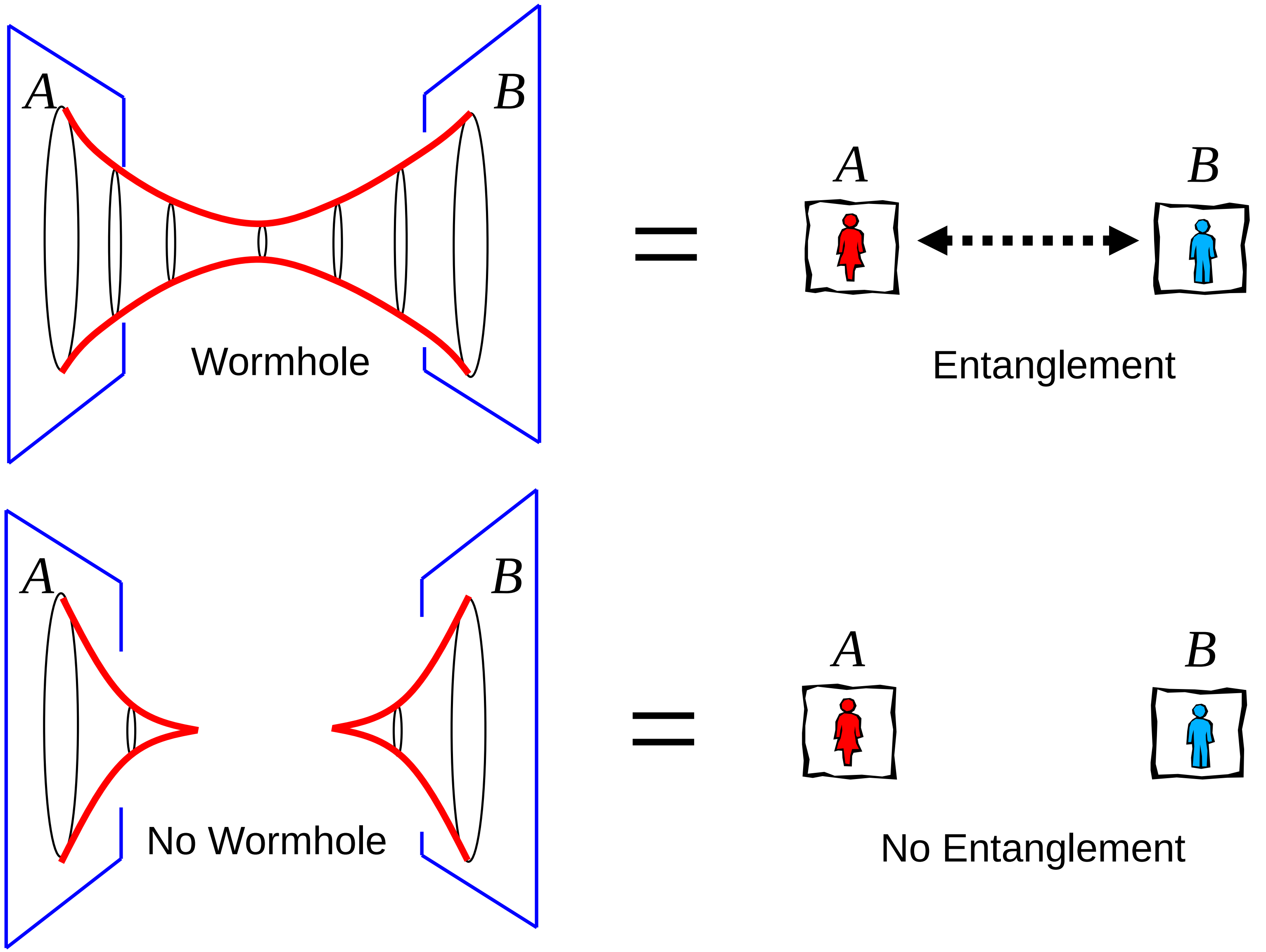


Entanglement is the "glue" that holds space together.

If, with your quantum computer, you transformed the highly entangled vacuum state to a product state, then space would fall apart into tiny pieces.

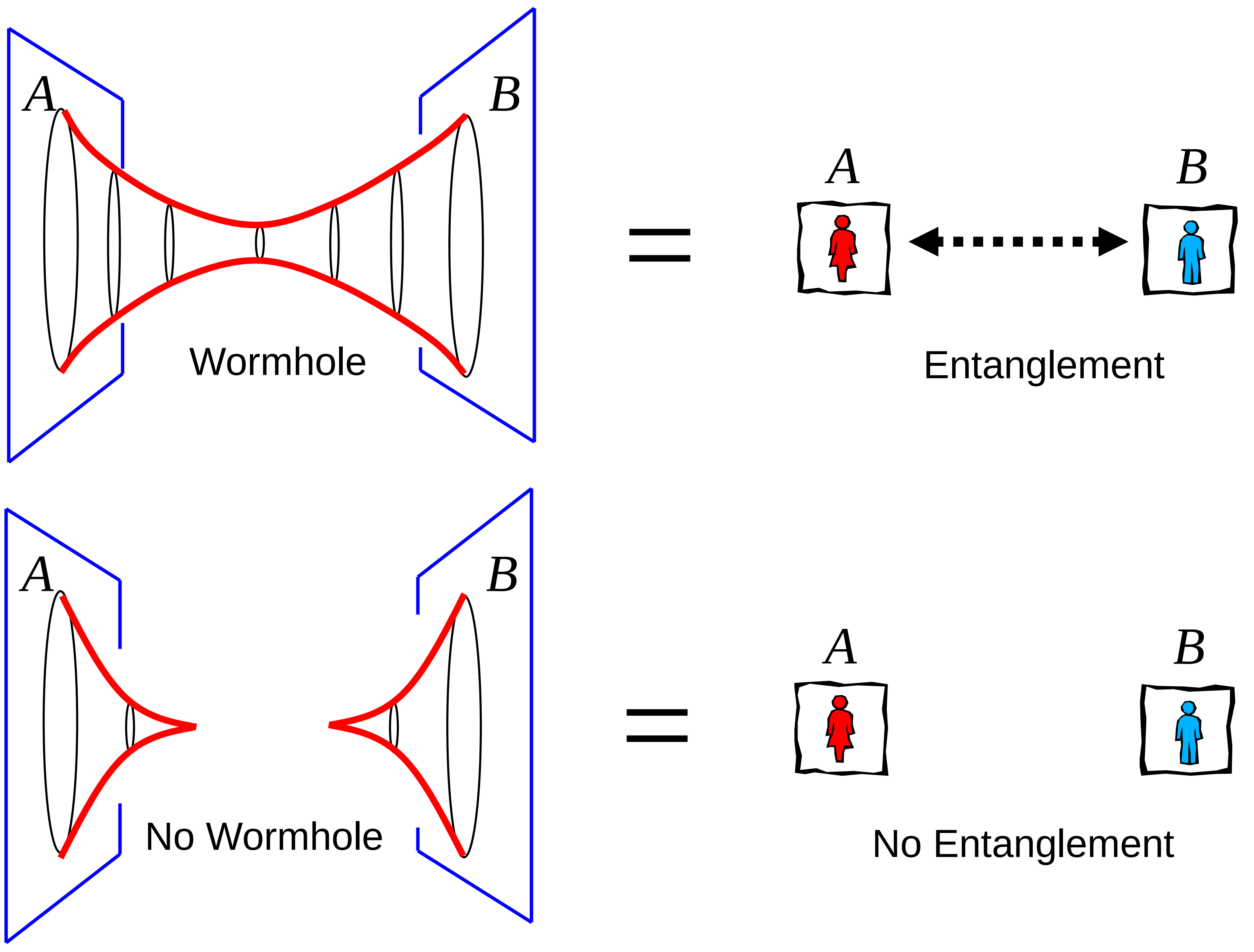
This would require an enormous amount of energy.

Building spacetime from quantum entanglement



[Maldacena 2003, Van Raamsdonk 2010, Maldacena-Susskind 2013]

ER = EPR



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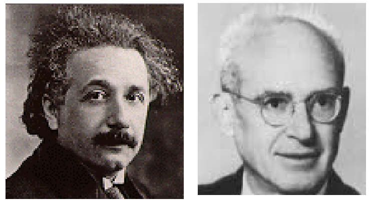
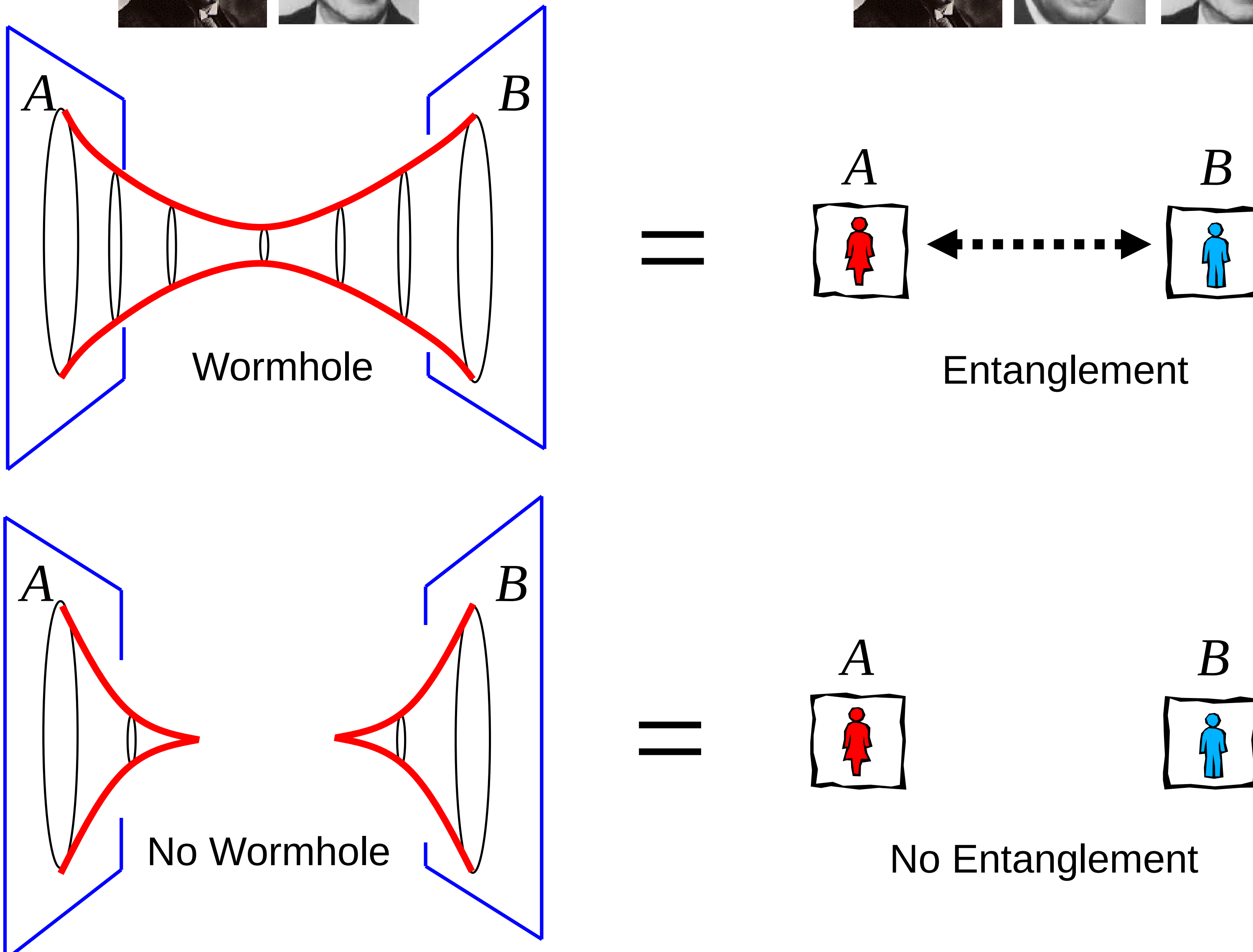
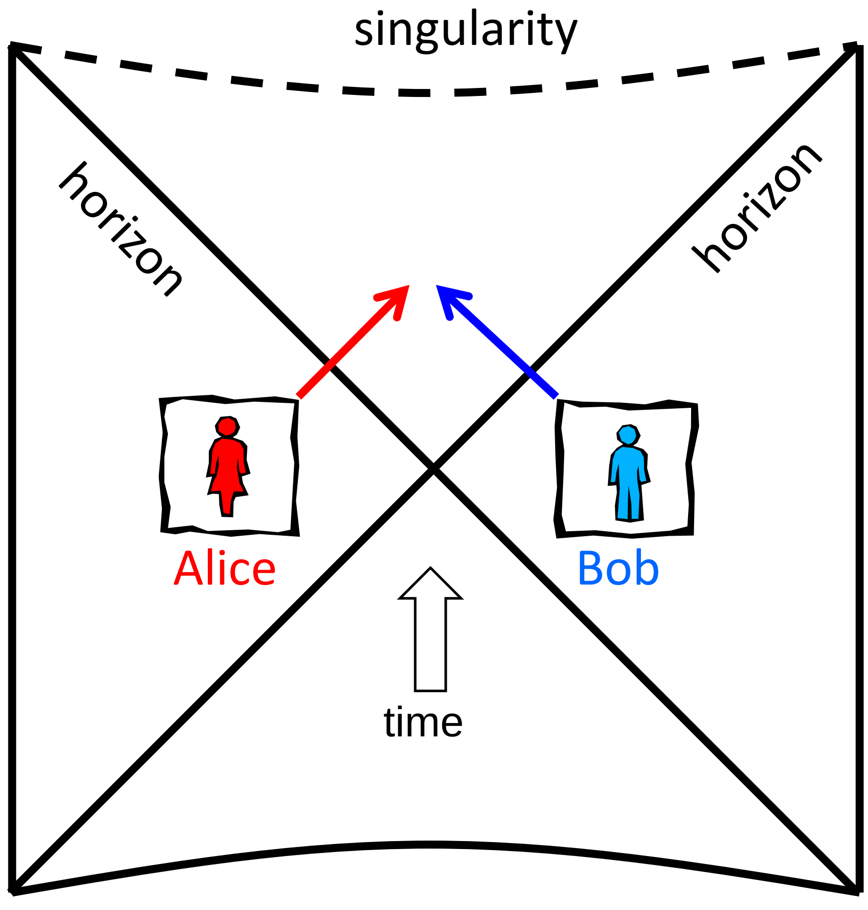




[Maldacena 2003, Van Raamsdonk 2010, Maldacena-Susskind 2013]

Love in a wormhole throat



Alice and Bob are in different galaxies, but each lives near a black hole, and their black holes are connected by a wormhole. If both jump into their black holes, they can enjoy each other’s company for a while before meeting a tragic end.

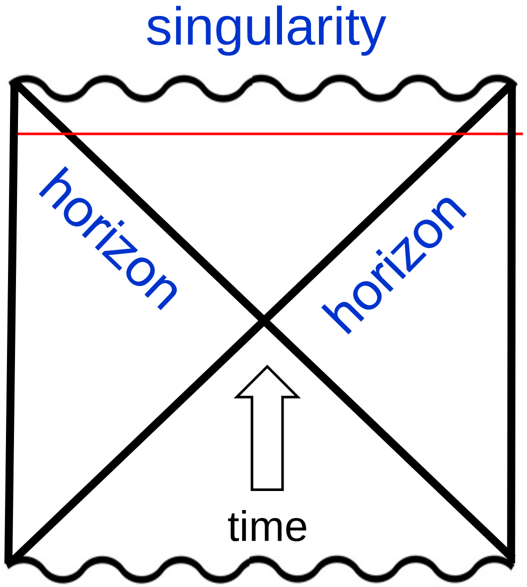
AMPS and the TFD

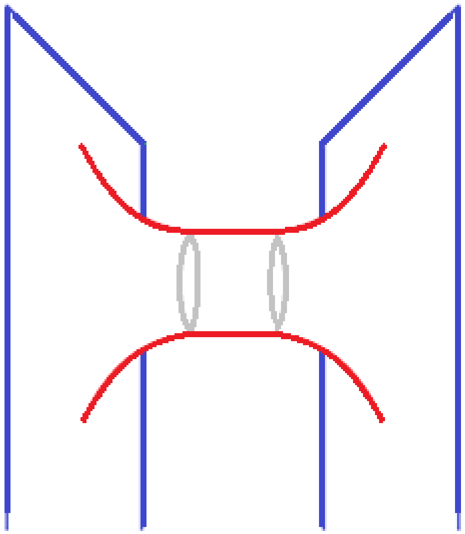
In the thermofield double (TFD) state, the AdS black hole on the right is maximally entangled with another system (the black hole on the left), yet its horizon is smooth. How do we reconcile with the AMPS argument?

The answer is clear in this case: Hawking radiation from the right BH can be maximally entangled with modes on the other side of the horizon, and with another system, because both are the *same* system (the left black hole).

We may boldly assert that this is the resolution in general: the interior geometry of the black hole is actually constructed from the system which is maximally entangled with the black hole.

We can imagine gravitationally collapsing the system entangled with the black hole, then applying a one-sided unitary to obtain the TFD. Identifying the radiation emitted long ago with the black hole interior seems wildly nonlocal, and just about audacious enough to be on the right track.





Wormholes and complexity

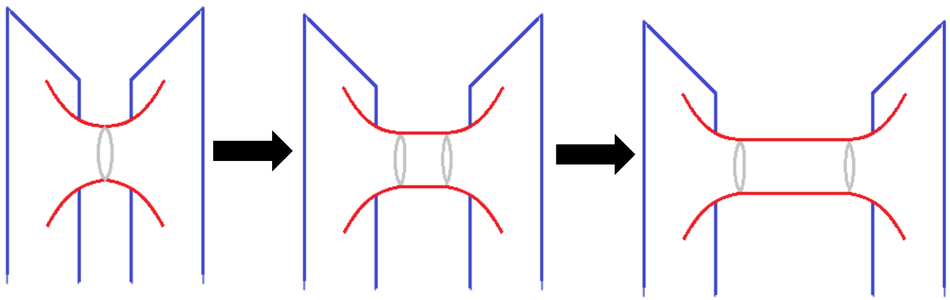
Complexity of a quantum state is the size of the minimal quantum circuit that prepares the state, starting with a product state. Generic states have exponential complexity. It takes exponential time to prepare such a generic state under evolution governed by a local Hamiltonian.

In a chaotic system, we expect the complexity to increase linearly with time. The time scale is fixed by the energy of the system, e.g., its temperature *T*. We may anticipate

$$\frac{d}{dt}\left(\text{complexity}\right) \approx Tn/\hbar \approx (T/\hbar)\times \text{entropy}$$

Susskind (2014) suggested interpreting the growing length of the wormhole (in suitable units) as a measure of complexity in the thermofield double. Brown *et al.* 2015 made this conjecture more precise:

$$\frac{d}{dt}\left(\text{complexity}\right) \approx 2M/\pi\hbar$$



where *M* is the black hole mass. (This matches the maximal gate speed allowed by the Margolus-Levitin theorem.)

Wormholes and complexity

$$\frac{d}{dt}(\text{complexity}) \approx \frac{2Mc^2}{\pi\hbar} \approx \frac{2(D-1)}{D}\frac{TS}{\pi\hbar} \quad \text{after} \quad t_* = \frac{\hbar\beta}{2\pi}\log S$$

(D spacetime dimensions)

A 1 gram black hole performs 10^{48} ops per second. That's fast. Current technology is wasteful, locking up most of the energy unproductively in the rest mass of atoms.

It takes the scrambling time t_* to reach this asymptotic rate of complexity increase. That's the time required for a local perturbation to spread throughout the whole system.

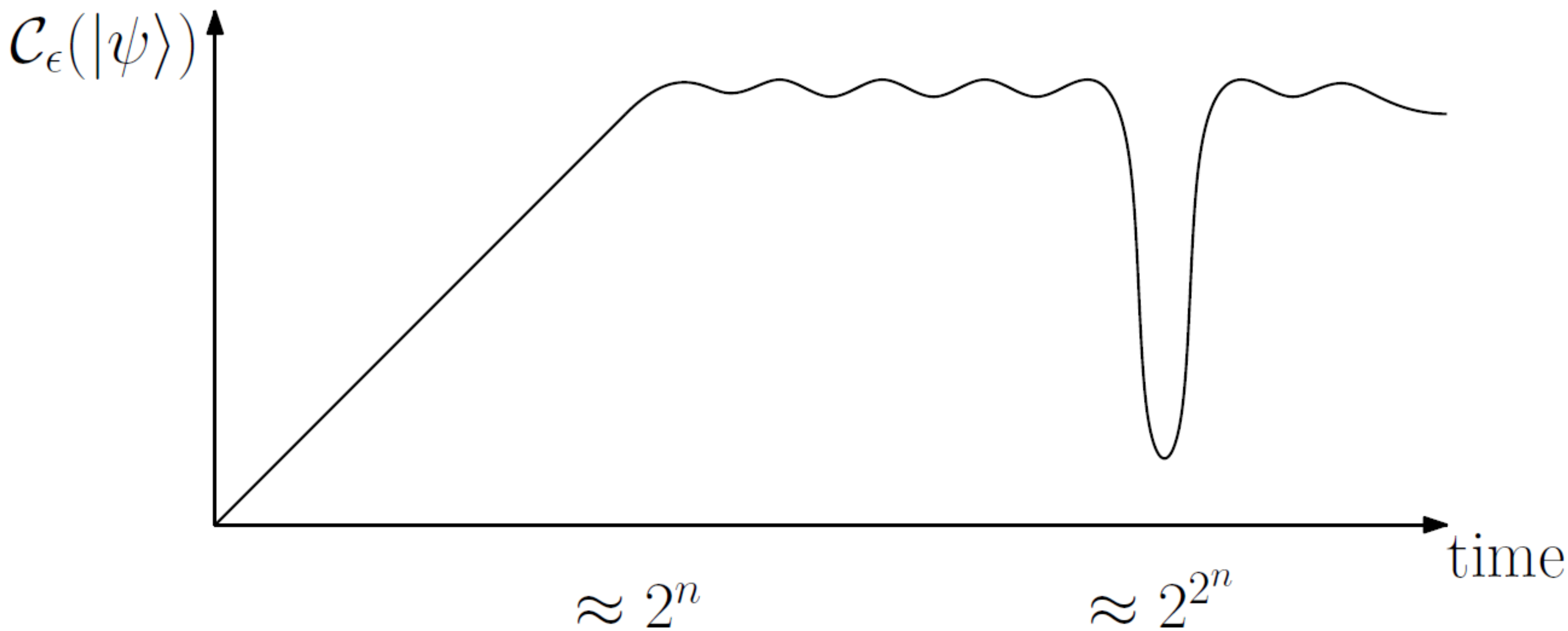
A check on the result: Consider perturbing the CFT at time $-t$ by applying a local operator. This should increase the complexity of the state (at t=0) by $2(t - t_*)dC/dt$. Imagine propagating backward for time t, applying perturbation, then forward for time t, and allowing time t_* for the effect of the perturbation to spread.

The corresponding picture in the bulk is that the perturbation produces a shock wave which lengthens the wormhole (Shenker and Stanford 2013). We can check that the additional wormhole length agrees with expected increase in complexity.

But how, precisely, should the complexity be defined microscopically? That is still unclear.

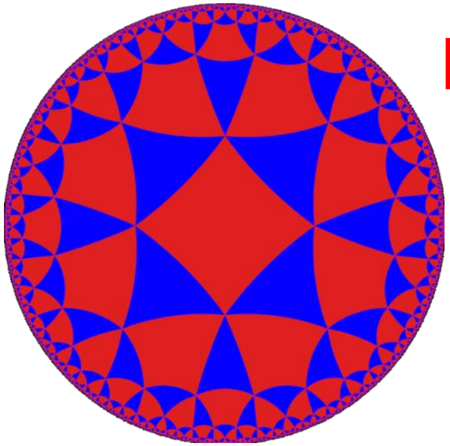
Increasing complexity

We expect (though we can't prove) that in an n-qubit chaotic quantum system the complexity will continue to increase linearly until the elapsed time is exponential in n. The volume of Hilbert space is doubly exponential in n, so we expect it takes a doubly exponentially long time to reach another atypical state with low complexity. (See Aaronson 2016.)



Susskind (2015) suggests that (real) black holes have smooth horizons while the complexity is rising, but might become firewalls when complexity saturates. Then throwing just one qubit into the black hole doubles its maximal complexity, making the horizon transparent for another exponentially long time!

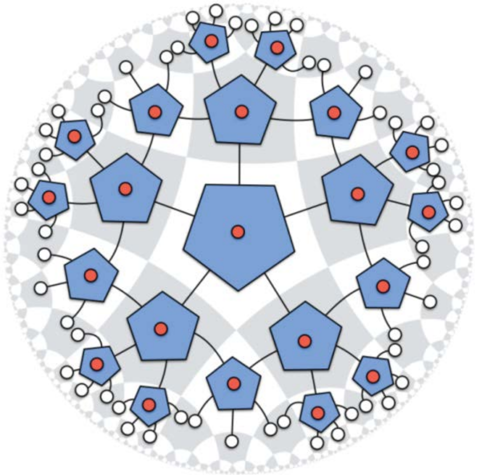
Two amazing ideas:



Holographic correspondence

Quantum error correction

Are they closely related?



-- Spacetime as a quantum error-correcting code.
-- Scrambled encoding on boundary, protected against erasure.
-- Entanglement seems to be the glue holding space together.
-- Illustrates the surprising unity of physics.
-- Toward accessible experiments probing quantum gravity?

Almheiri, Dong, Harlow (2015)
Pastawski, Yoshida, Harlow, Preskill (2015)
Hayden, Nezami, Qi, Thomas, Walter, Yang (2016)

Logical operator = “precursor”

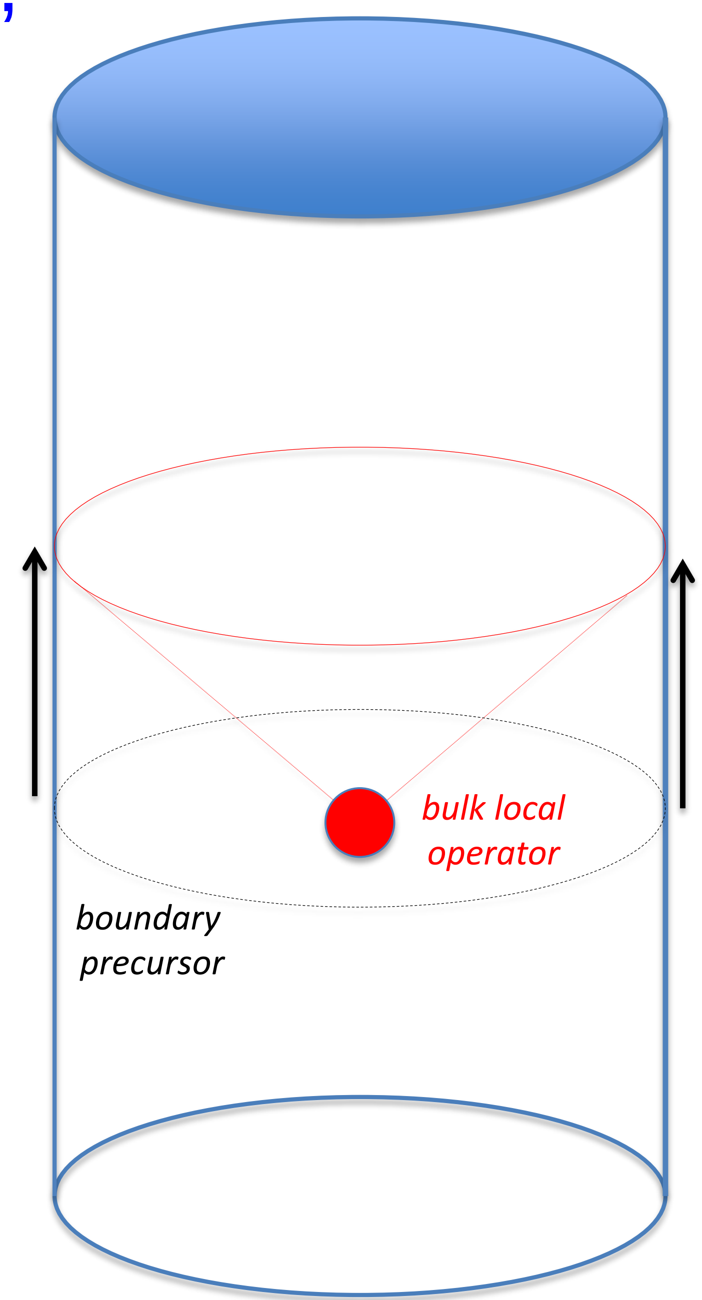
A local operator in the bulk spacetime produces a disturbance which propagates causally in the bulk.

The effect of this bulk operator becomes locally detectable on the boundary at a later time.

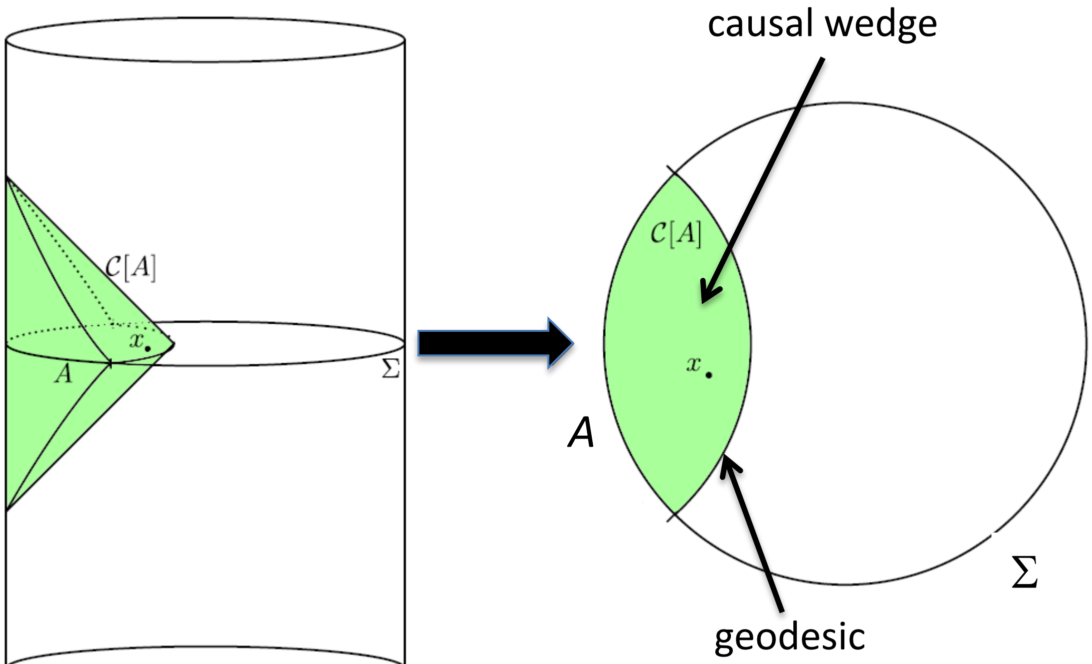
The bulk operator corresponds to a nonlocal “precursor” operator on the boundary.

The precursor is more and more nonlocal for bulk operators deeper and deeper in the bulk.

We interpret the precursor as the logical operator acting on a quantum code, with better protection against error for bulk operators deeper inside the bulk.



AdS-Rindler reconstruction



Bulk time slice contains point *x* in the bulk and boundary time slice Σ.

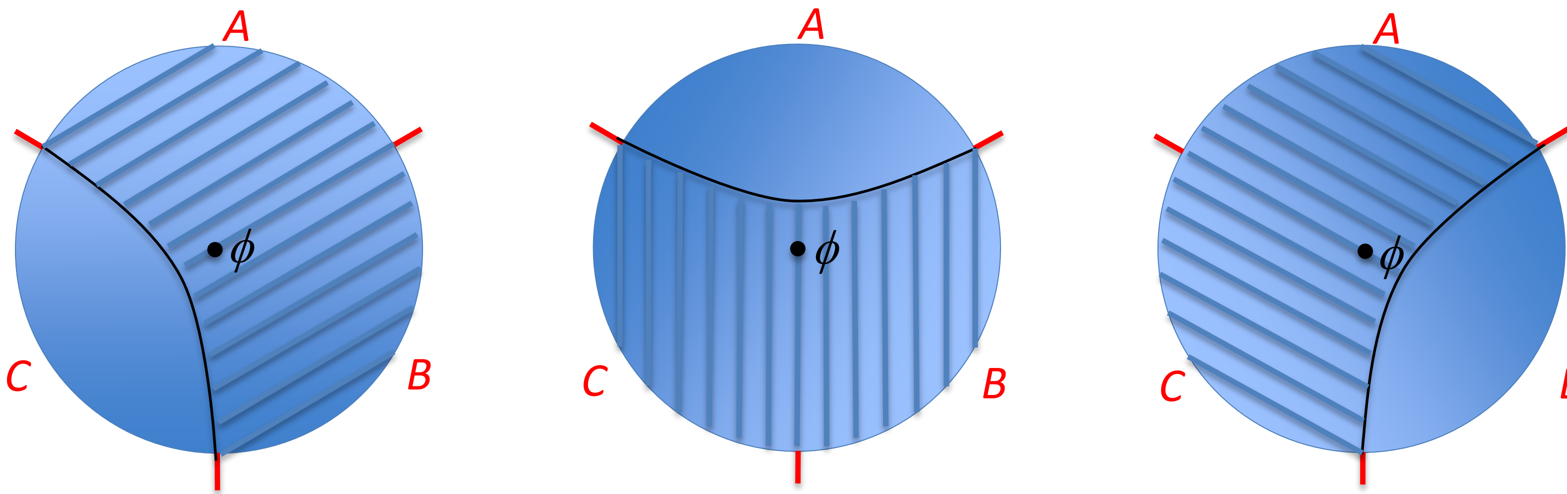
A local operator acting at *x* can be reconstructed on the boundary region *A* if *x* lies within the *causal wedge C[A]* of *A*, the bulk region bounded by *A* and the bulk geodesic with the same boundary as *A*.

Classical bulk field equations are "causal" in the *radial* direction. Boundary data in the "backward" light cone of *x* suffices to determine a bulk operator at *x* (*Hamilton-Kabat-Lifschytz-Lowe = HKLL*). This can be systematically corrected order by order in 1/N.

Furthermore we can use the boundary equations to squash the boundary wedge down to the time slice Σ.

This reconstruction is highly ambiguous – each bulk point lies in many causal wedges.

Causal wedge puzzle



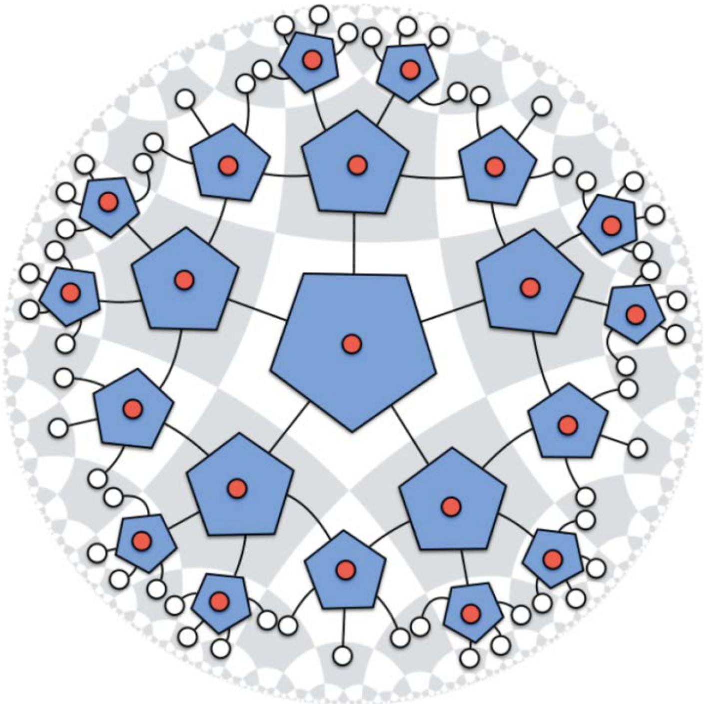
The ambiguity of the AdS-Rindler reconstruction poses an interesting puzzle.

Divide boundary into three disjoint sets *A, B, C* as shown. The bulk operator ϕ resides in *C[AB],* hence can be reconstructed on *AB* and commutes with any boundary operator in *C*.

We can also reconstruct ϕ on *BC* (so it commutes with operators in *A*) or on *AC* (so it commutes with operators in *B*). Hence the reconstructed operator commutes with all local boundary operators, and must be a multiple of the identity (local field algebra is irreducible).

Resolution (*Almheiri-Dong-Harlow 2015*): These three reconstructions yield physically inequivalent boundary operators, all with the same action on the code subspace. *Holographic codes concretely realize this proposal.*

Holographic Quantum Error-Correcting Codes



Holographic codes demonstrate the idea that *geometry emerges from entanglement*.

A tensor network realization of holography, based on a uniform tiling of the bulk. (Lattice spacing comparable to AdS curvature scale. No dynamics.)

Physical variables of a quantum code reside on the boundary, logical operators (those preserving the code space) reside in the bulk.

There is an explicitly computable dictionary, and computable boundary entanglement structure. Local operators deep in the bulk are mapped to highly nonlocal operators on the boundary.

This dictionary is not complete --- the bulk Hilbert space (code space) is a proper subspace of the boundary Hilbert space, and the bulk operators preserve this subspace. E.g. we may think of them as operators which map low-energy states to low-energy states in the boundary CFT.

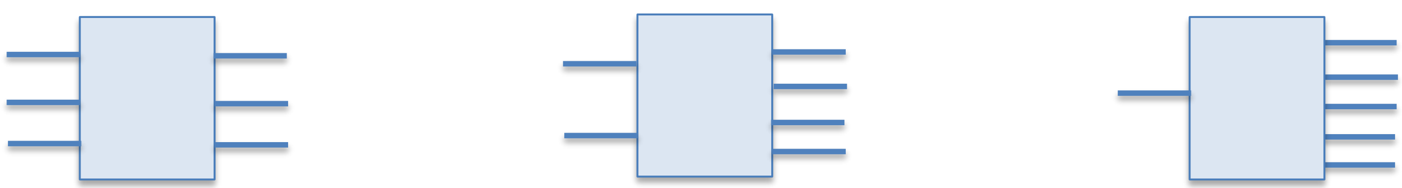
Perfect tensors

The tensor T arises in the expansion of a pure state of $2n$ v-dimensional "spins" in an orthonormal basis.

$$|\psi\rangle = \sum_{a_1, a_2, \ldots, a_{2n}} T_{a_1 a_2 \ldots a_{2n}} \, | a_1 a_2 \ldots a_{2n} \rangle$$

T is perfect if the state is maximally entangled across *any* cut, i.e. for any partition of the $2n$ spins into two sets of n spins. (State is *absolutely maximally entangled*.)

By transforming kets to bras, T also defines $3 \to 3$ unitary, $2 \to 4$ and $1 \to 5$ isometries.



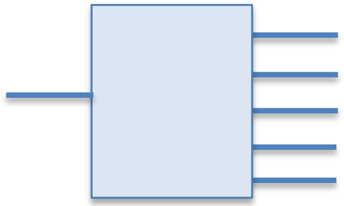
$$\sum_{a_1, \ldots a_6} T_{a_1 \ldots a_6} \, | a_4 a_5 a_6 \rangle \langle a_1 a_2 a_3 | \qquad \sum_{a_1, \ldots a_6} T_{a_1 \ldots a_6} \, | a_3 a_4 a_5 a_6 \rangle \langle a_1 a_2 | \qquad \sum_{a_1, \ldots a_6} T_{a_1 \ldots a_6} \, | a_2 a_3 a_4 a_5 a_6 \rangle \langle a_1 |$$

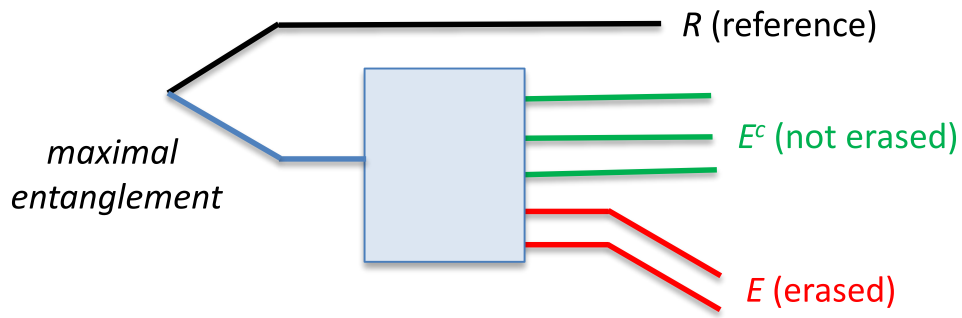
These are the isometric encoding maps (up to normalization) of quantum error-correcting codes. The $2 \to 4$ map encodes two qubits in a block of 4, and corrects 1 erasure. The $1 \to 5$ map encodes one qubit in a block of 5, and corrects 2 erasures.

Erasure correction

The 1→5 isometric map encodes one qubit in a block of 5, and corrects two erasures.

$$\sum_{a_1,\ldots a_6} T_{a_1\ldots a_6} |a_2 a_3 a_4 a_5 a_6\rangle\langle a_1|$$





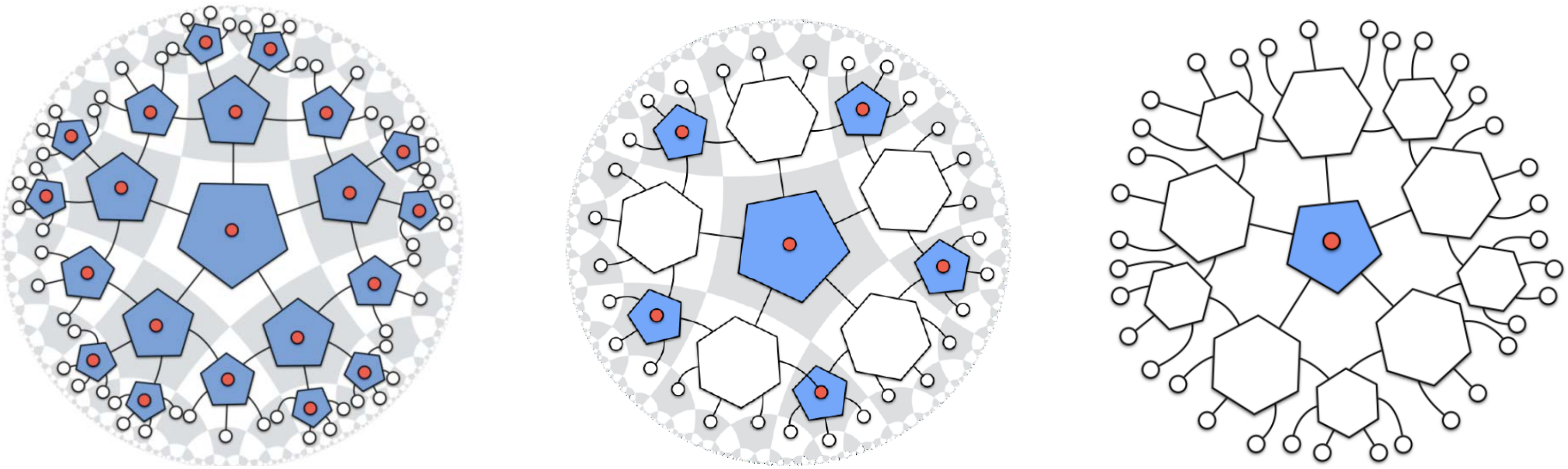
We say qubits are erased if they are removed from the code block. But we know *which* qubits were erased and may use that information in recovering from the error.

Consider maximally entangling a *reference qubit R* with the encoded qubit. Suppose two physical qubits (the subsystem *E*) are removed, while their complement E^c is retained.

Because the tensor *T* is perfect, *RE* is maximally entangled with E^c, hence *R* is maximally entangled with a subsystem of E^c. Thus the logical qubit can be decoded by applying a unitary decoding map to E^c alone; *E* is not needed.

Likewise, we may apply any logical operator to the encoded qubit by acting on E^c alone. (The logical operation can be *cleaned* so it has no support on the erased qubits.)

Holographic quantum codes



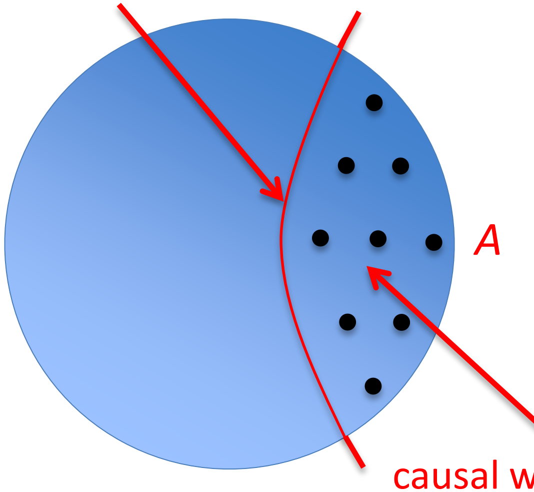
pentagon code — pentagon/hexagon code — one encoded qubit

Holographic quantum error-correcting codes are constructed by contracting perfect tensors according to a tiling of hyperbolic space by polygons.

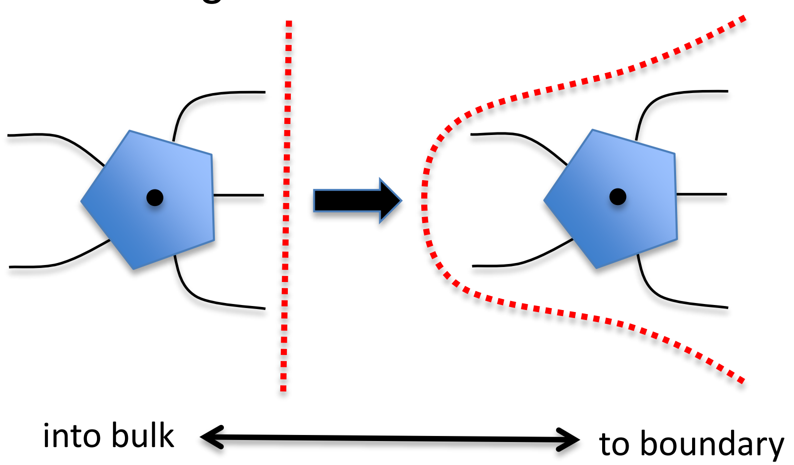
The code is an isometric embedding of the bulk Hilbert space into the boundary Hilbert space, obtained by composing the isometries associated with each perfect tensor.

"Greedy" causal wedge

There is an analog of the AdS-Rindler reconstruction in holographic codes. For a connected region *A* on the boundary there is a corresponding *greedy geodesic* $\gamma_A{}^*$ and *greedy causal wedge C[A].* Bulk operators contained in *C[A]* can be reconstructed on *A*.



A given bulk operator is contained in many different causal wedges; it is protected against erasure of the physical qubits outside the causal wedge. Operators deeper in the bulk have better protection against erasure.

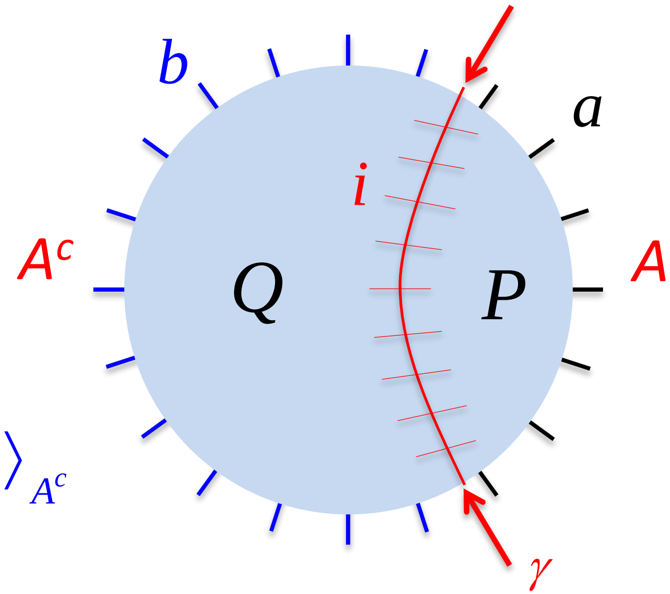


To construct the greedy geodesic, start with *A*, and push into the bulk a cut bounded by ∂A, step by step: if at least three of the tensor's legs cross the cut, move the cut further into the bulk past the tensor. After each step we have an isometry mapping indices which cross the cut (and bulk indices) to *A*.

The greedy geodesic coincides with true geodesic (minimal cut) in some cases, differs slightly in other cases.

Ryu-Takayanagi Formula

Consider a *holographic state* $|\psi\rangle$ (no dangling bulk indices), and a geodesic cut γ_A through the bulk with indices on the cut labeled by i. Indices of A are labeled by a and indices of A^c labeled by b.



$$|\psi\rangle = \sum_{a,b,i} |a\rangle_A \otimes |b\rangle_{A^c} P_{ai}\ Q_{bi} = \sum_i |P_i\rangle_A \otimes |Q_i\rangle_{A^c}$$

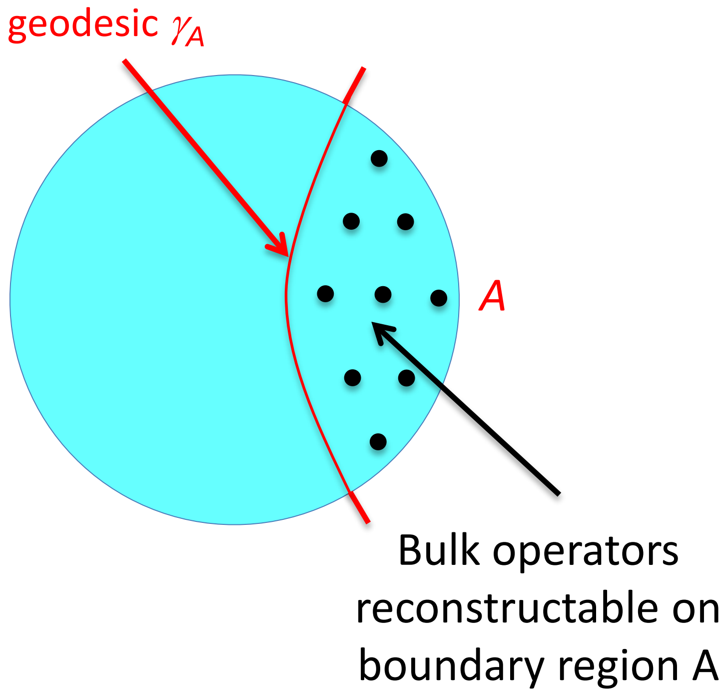
For a holographic state on a tiling with *nonpositive curvature*, the tensors P and Q are both *isometries*, if A is connected (*max-flow min-cut argument*).

If each internal index takes v values, there are $v^{|\gamma|}$ terms in the sum over i. and the vectors $\{|P\rangle_i\}, \{|Q\rangle_i\}$ are orthonormal. Therefore

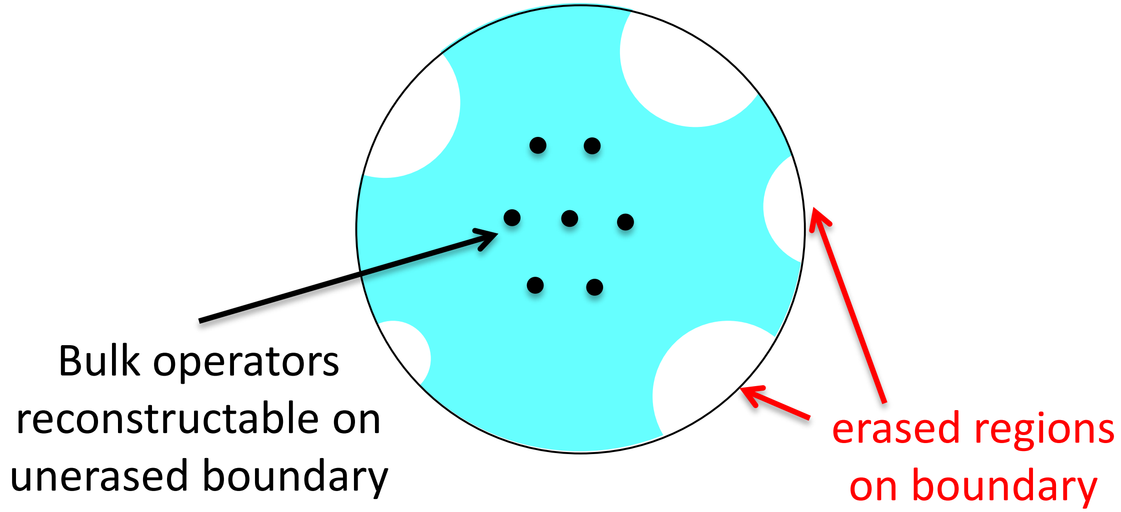
$$S(A) = |\gamma_A| \log v$$

Spacetime as an error-correcting code

For a connected region *A* on the boundary there is a corresponding *geodesic* γ_A . Bulk operators in the wedge between *A* and γ_A can be reconstructed on the boundary in region *A*.



Operators deeper in the bulk have better protection against erasure on the boundary.



Bulk operators at the center of the bulk are robust against erasure of up to half of the boundary qubits.

Almheiri, Dong, Harlow (2015). Pastawski, Yoshida, Harlow, Preskill (2015).

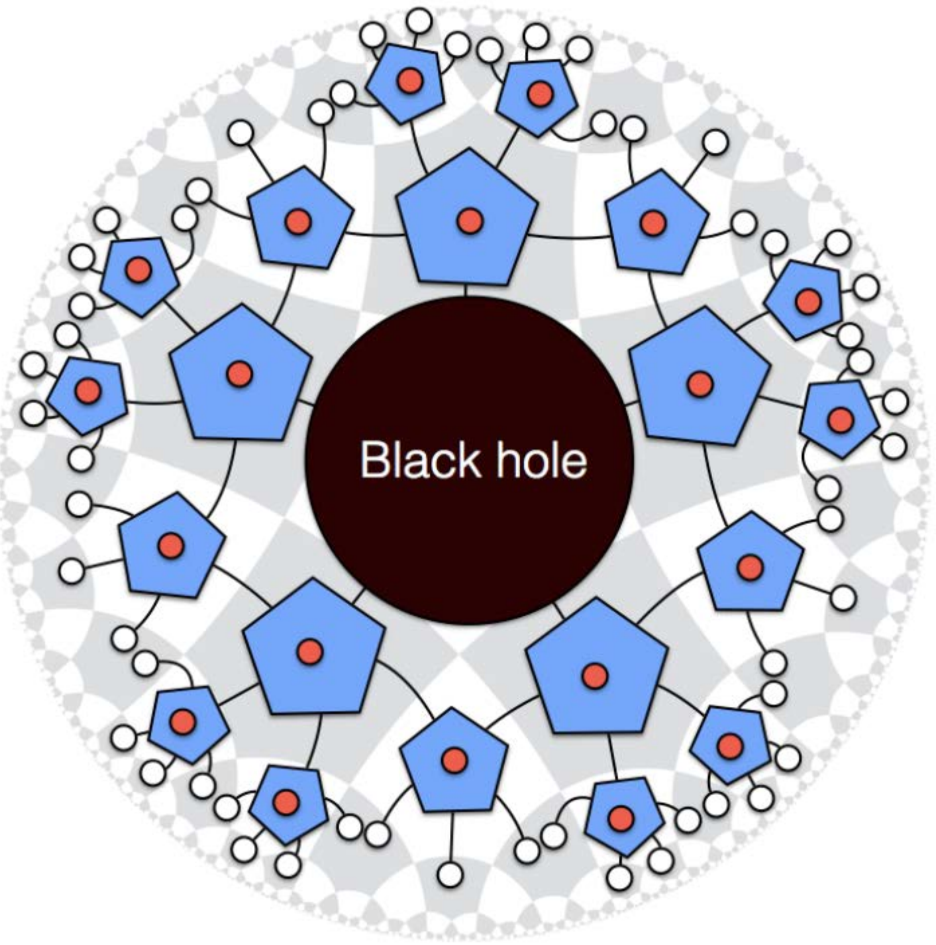
Holographic black holes

-- Most boundary states correspond to large black holes in the bulk.

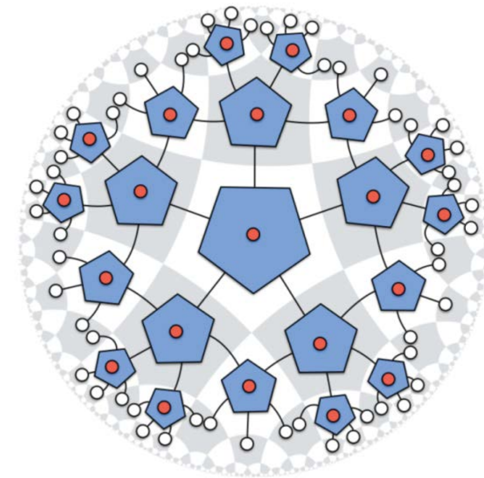
-- Bulk local operators acting outside the black hole can be reconstructed on the boundary.

-- Uncontracted bulk indices at the horizon, the black hole microstates, are also mapped to the boundary.

-- Encoding isometry becomes trivial as black hole grows to fill the whole bulk.



Holographic quantum codes



-- Nicely capture some central features of full blown gauge/gravity duality, and provide an explicit dictionary relating bulk and boundary observables.

-- Realize the Ryu-Takayanagi relation between boundary entanglement and bulk geometry (with small corrections in some cases).

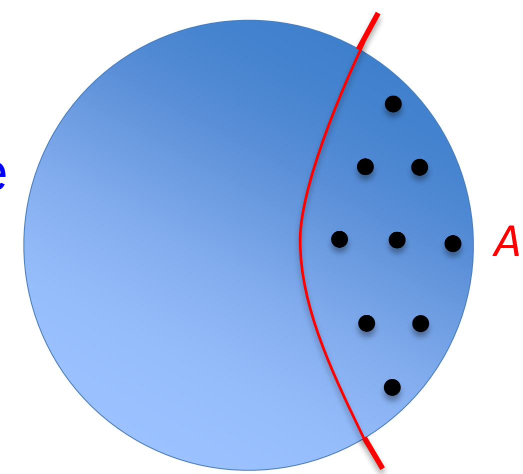
-- In what (approximate) sense is a conformal field theory a quantum error-correcting code?

-- Why does bulk locality hold (approximately) at sub-AdS curvature scales?

-- How is the code affected by real time evolution of the boundary?

-- Extending quantum error correction ideas to emergent geometry beyond AdS/CFT?

-- Other applications of these code constructions?



Quantumists ≈ Biologists

quantum gravity = life

boundary theory = chemistry

quantum information theorists = chemists

quantum gravity theorists = biologists

what we want = molecular biology

black hole information problem = fruit fly

understanding the big bang = curing cancer

Slide concept stolen from Juan Maldacena

Ooguri: I see that this new joint activity between quantum gravity and quantum information theory has become very exciting. Clearly entanglement must have something to say about the emergence of spacetime in this context.

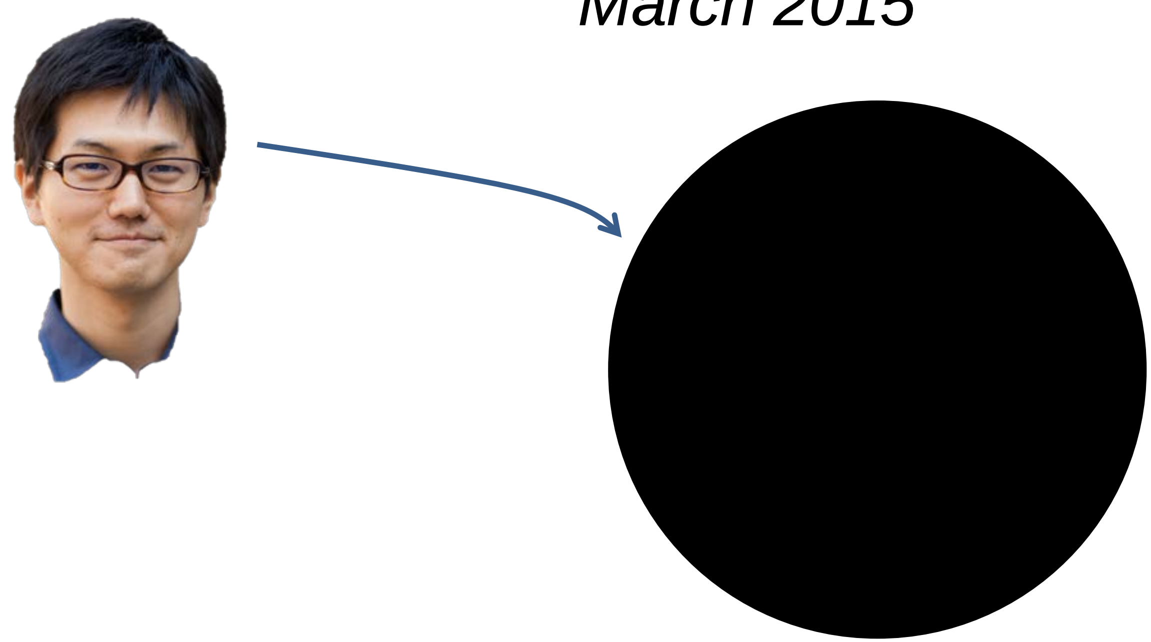
Witten: I hope so. I'm afraid it's hard to work on, so in fact I've worked with more familiar kinds of questions.

Kavli IPMU News
December 2014

Notices of AMS
May 2015

“Now is the time for quantum information scientists to jump into .. black holes”

Beni Yoshida
QuantumFrontiers.com
March 2015



End of Lecture 2