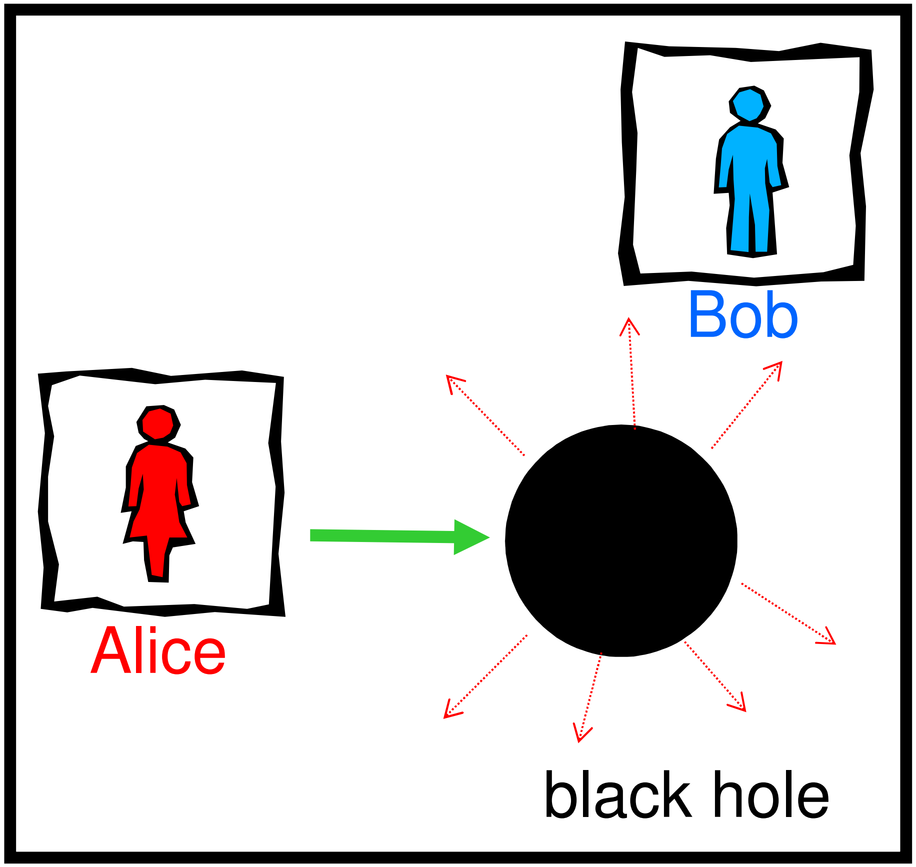
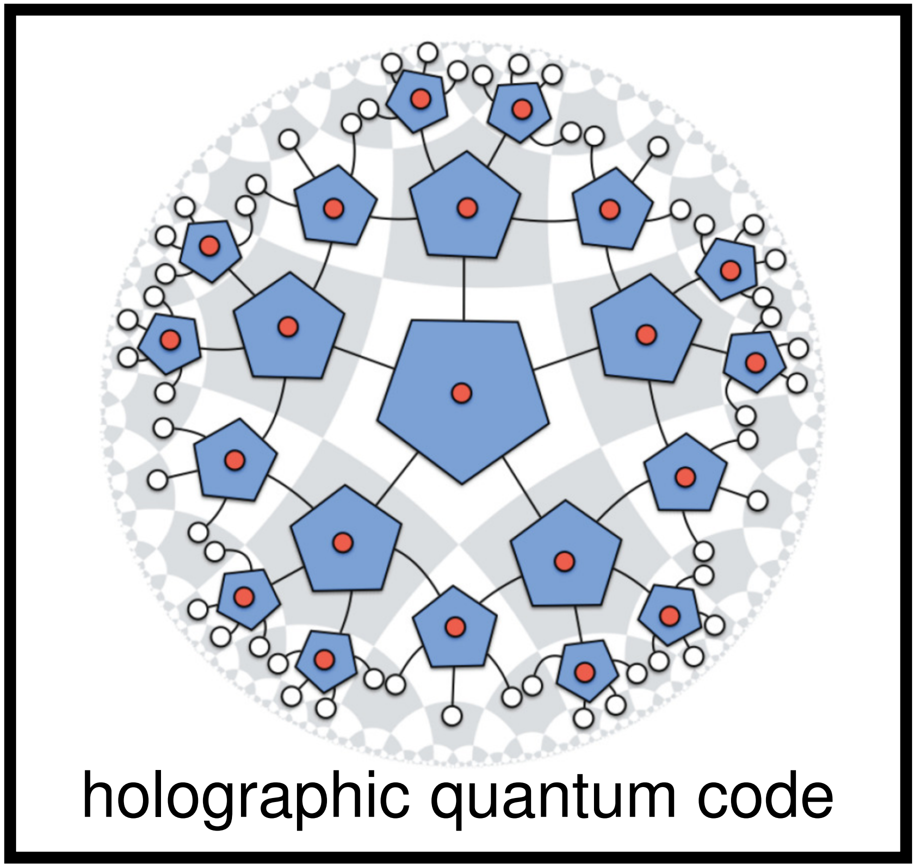
Quantum Information and Spacetime





INSTITUTE FOR QUANTUM INFORMATION AND MATTER

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GORDON AND BETTY
MOORE
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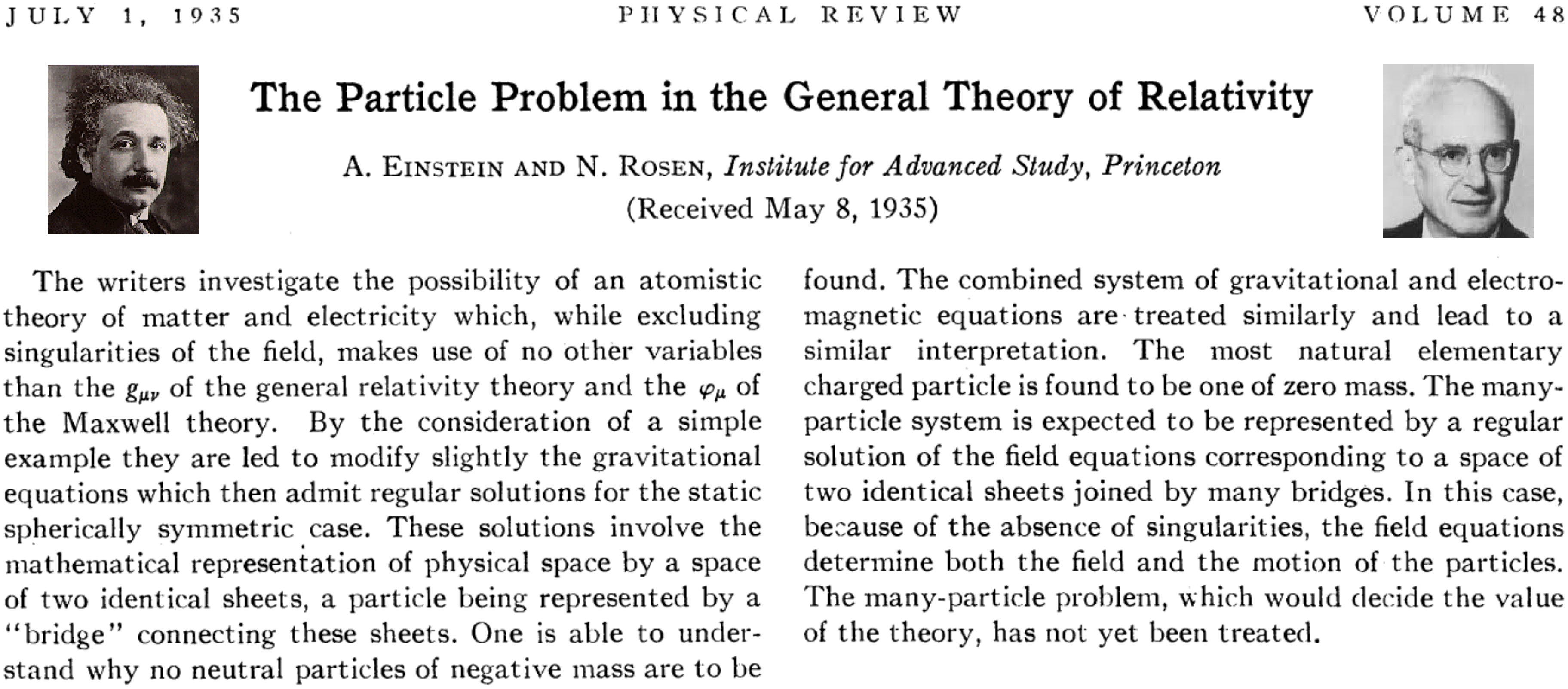
John Preskill
GR100
12 March 2016



JULY 1, 1935 PHYSICAL REVIEW VOLUME 48

The Particle Problem in the General Theory of Relativity

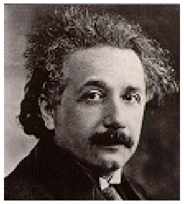
A. EINSTEIN AND N. ROSEN, *Institute for Advanced Study, Princeton*

(Received May 8, 1935)

The writers investigate the possibility of an atomistic theory of matter and electricity which, while excluding singularities of the field, makes use of no other variables than the $g_{\mu\nu}$ of the general relativity theory and the φ_μ of the Maxwell theory. By the consideration of a simple example they are led to modify slightly the gravitational equations which then admit regular solutions for the static spherically symmetric case. These solutions involve the mathematical representation of physical space by a space of two identical sheets, a particle being represented by a "bridge" connecting these sheets. One is able to understand why no neutral particles of negative mass are to be found. The combined system of gravitational and electromagnetic equations are treated similarly and lead to a similar interpretation. The most natural elementary charged particle is found to be one of zero mass. The many-particle system is expected to be represented by a regular solution of the field equations corresponding to a space of two identical sheets joined by many bridges. In this case, because of the absence of singularities, the field equations determine both the field and the motion of the particles. The many-particle problem, which would decide the value of the theory, has not yet been treated.

"… it does not seem superfluous to raise the question as to what extent the method of general relativity provides the possibility of accounting for atomic phenomena."

JULY 1, 1935 PHYSICAL REVIEW VOLUME 48



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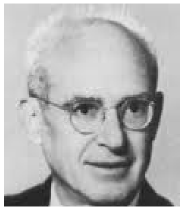

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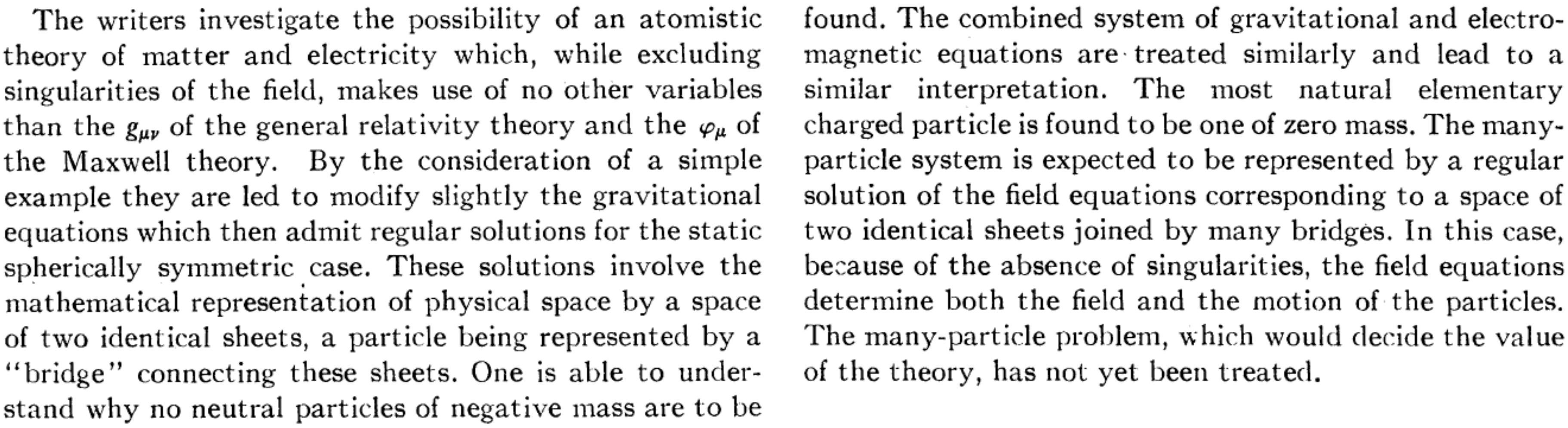

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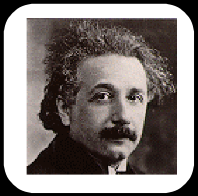
Einstein-Rosen bridge: "The four-dimensional space is described mathematically by two congruent parts or 'sheets',which are joined by a hyperplane r =2m in which g vanishes. We call such a connection between the two sheets a 'bridge'."

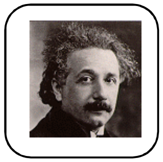


Albert Einstein

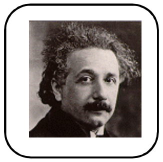
@einstein

Theoretical Physicist

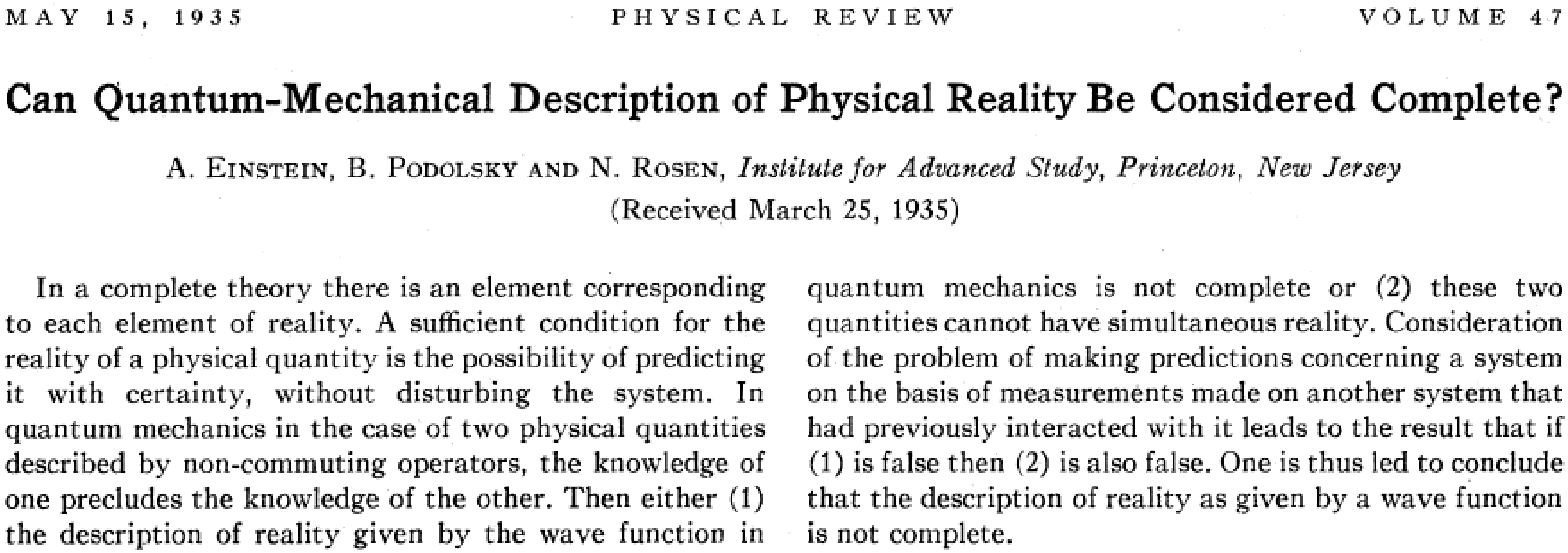
Tweets



Albert Einstein @einstein
Every field must adhere to the fundamental principle that singularities of the field are to be excluded.



Albert Einstein @einstein
Here is a possibility for a general relativistic theory of matter which is logically satisfying and which contains no new hypothetical elements.



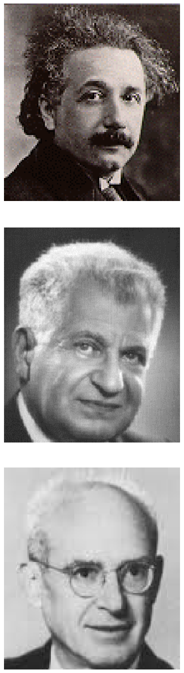
MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. Einstein, B. Podolsky and N. Rosen, *Institute for Advanced Study, Princeton, New Jersey*

(Received March 25, 1935)

In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting it with certainty, without disturbing the system. In quantum mechanics in the case of two physical quantities described by non-commuting operators, the knowledge of one precludes the knowledge of the other. Then either (1) the description of reality given by the wave function in quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system on the basis of measurements made on another system that had previously interacted with it leads to the result that if (1) is false then (2) is also false. One is thus led to conclude that the description of reality as given by a wave function is not complete.



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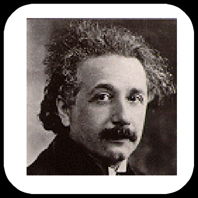

Albert Einstein
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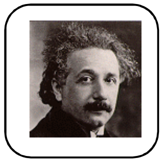
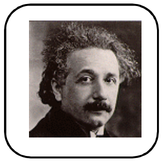
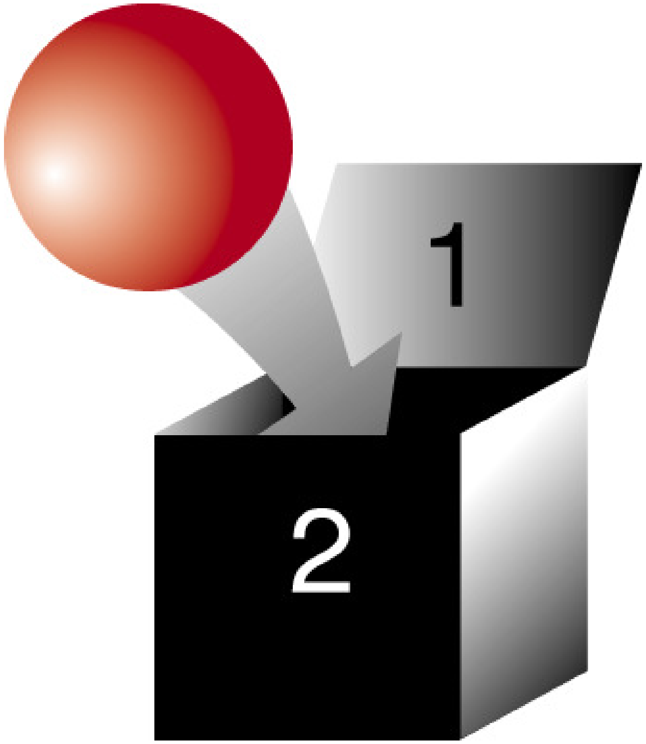


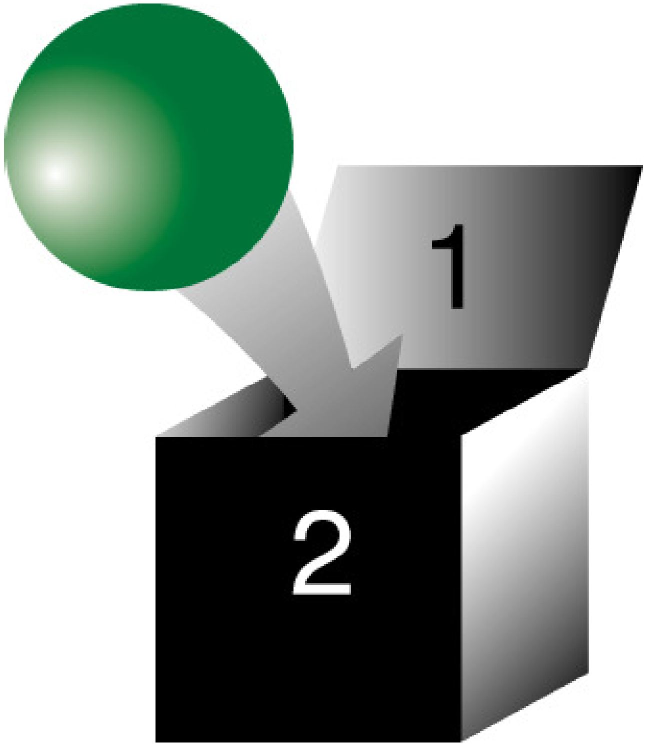
Albert Einstein @einstein
To judge the success of a physical theory, we may ask ourselves: (1) Is the theory correct? and (2) Is the description given by the theory complete?



Albert Einstein @einstein
The wave function does not provide a complete description of the physical reality… We believe, however, that such a theory is possible.

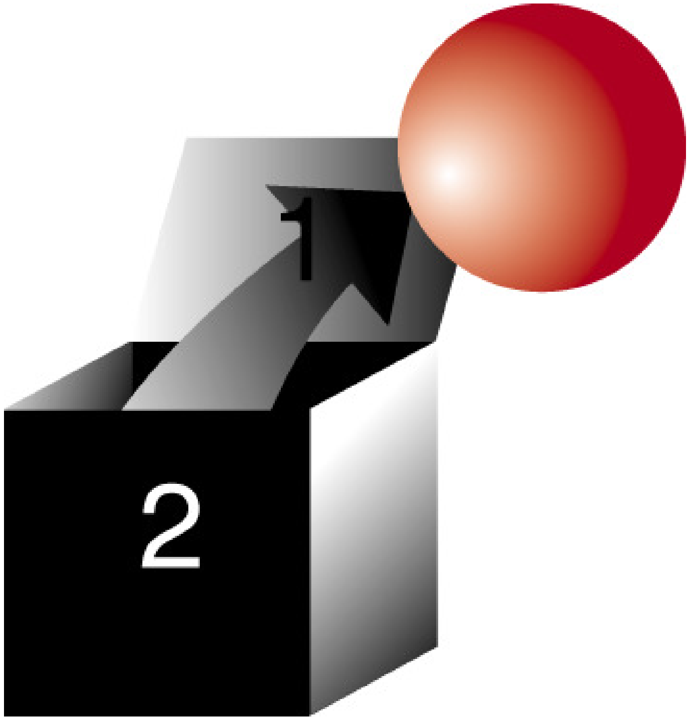
Classical Bit

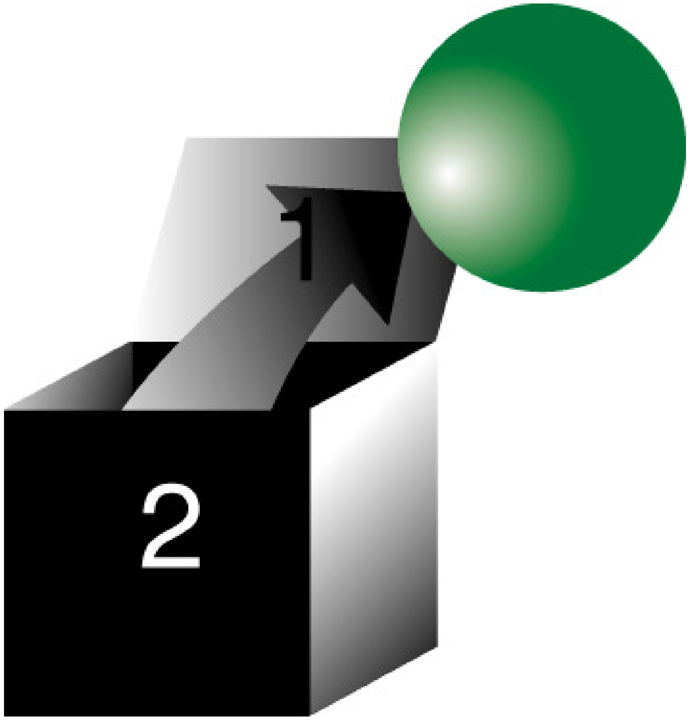




Classical Bit

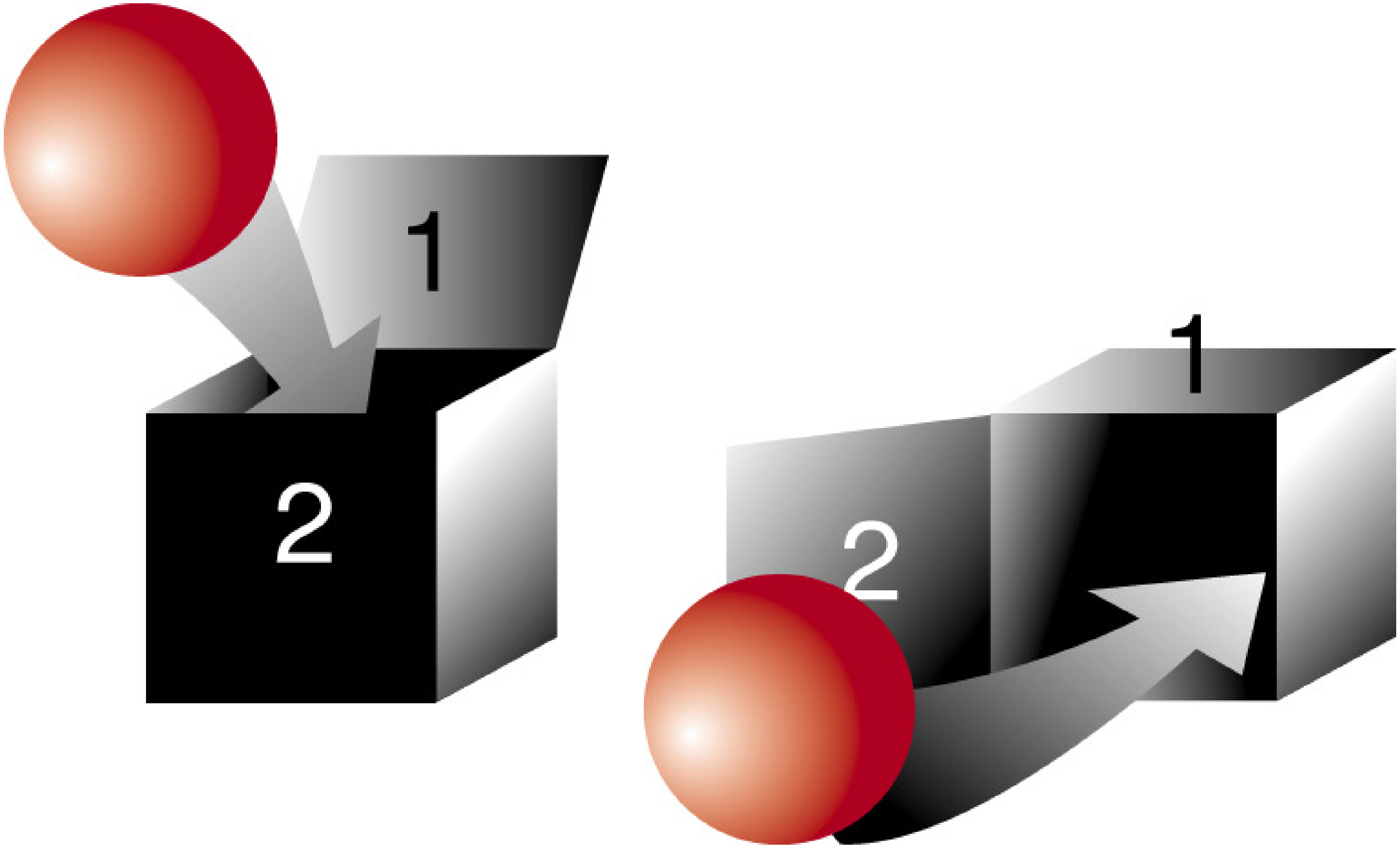
Classical Bit





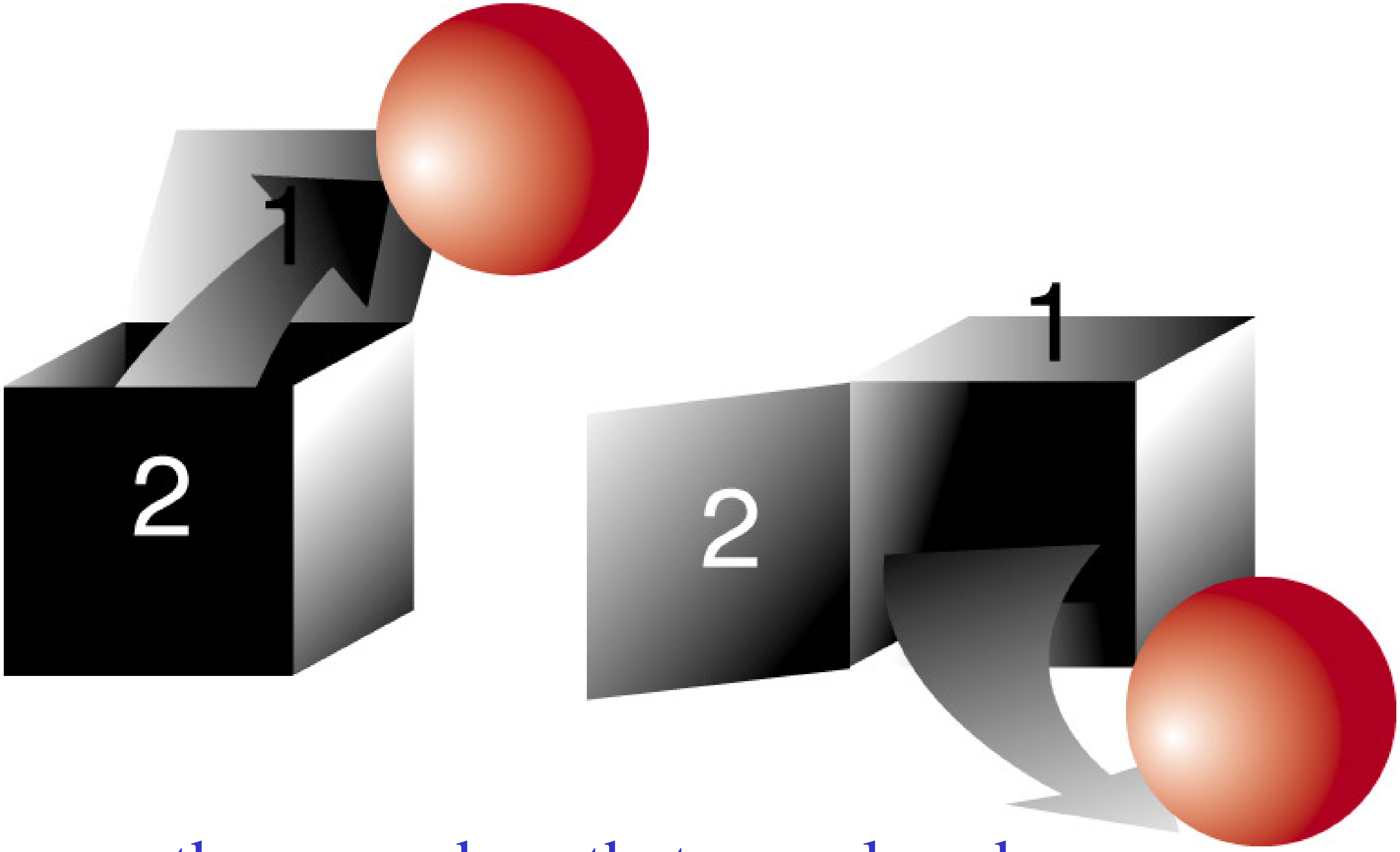
What went in, comes out.

Quantum Bit ("Qubit")



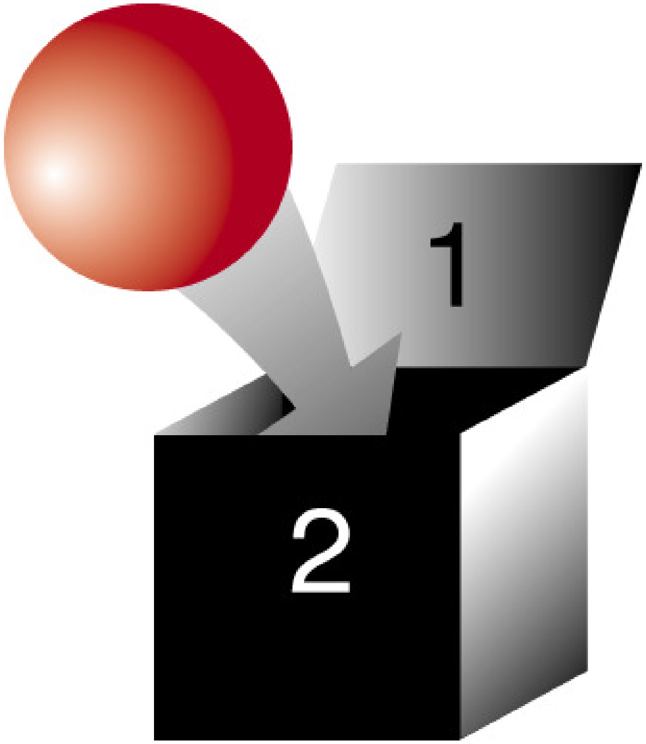
The two doors are two complementary observables, such as two ways to measure the polarization state of a photon.

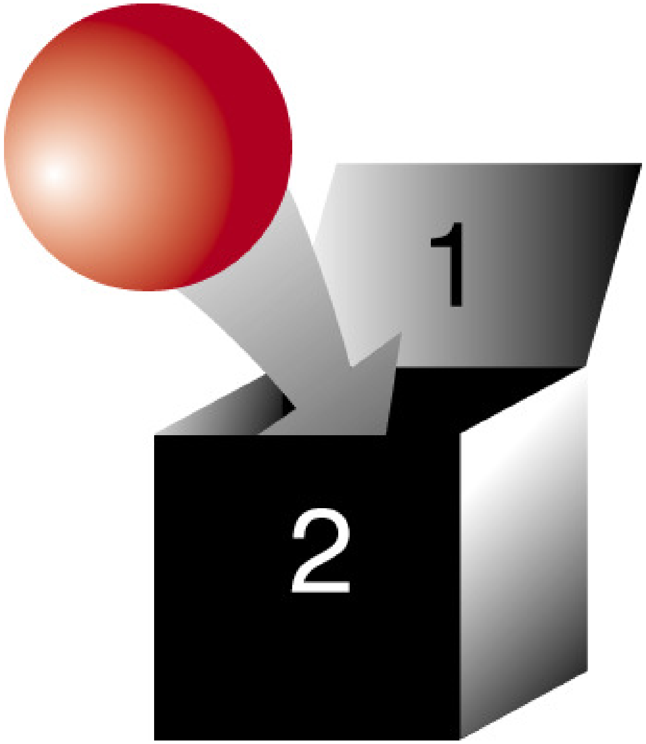
Quantum Bit (“Qubit”)



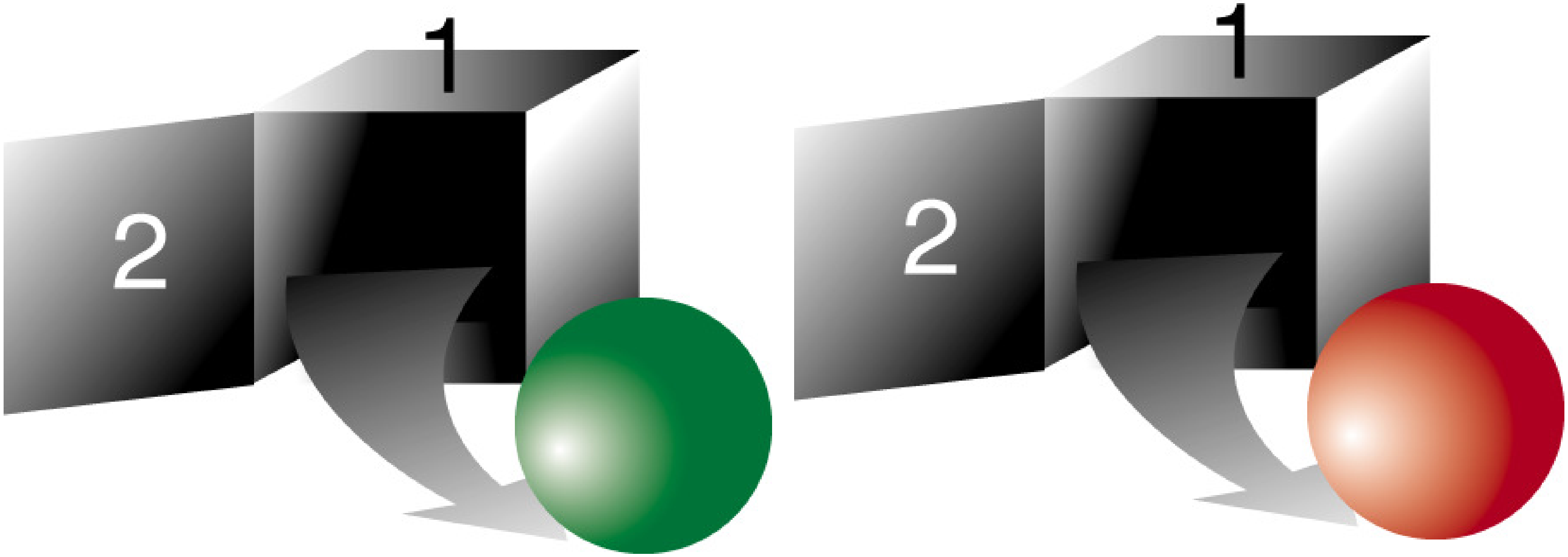
If you open the *same* door that you closed,
you can recover the bit from the box.

Quantum Bit (“Qubit”)

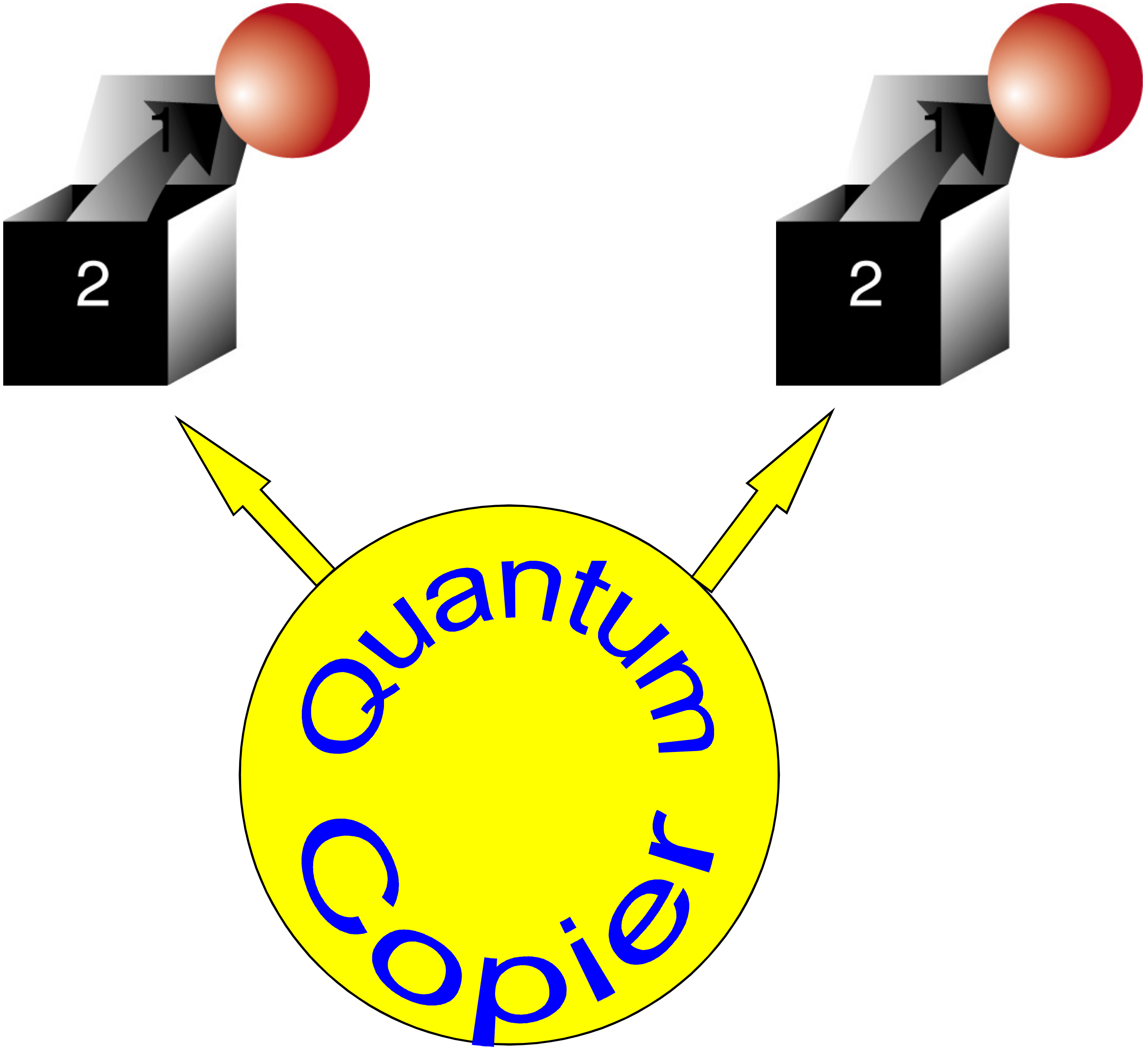


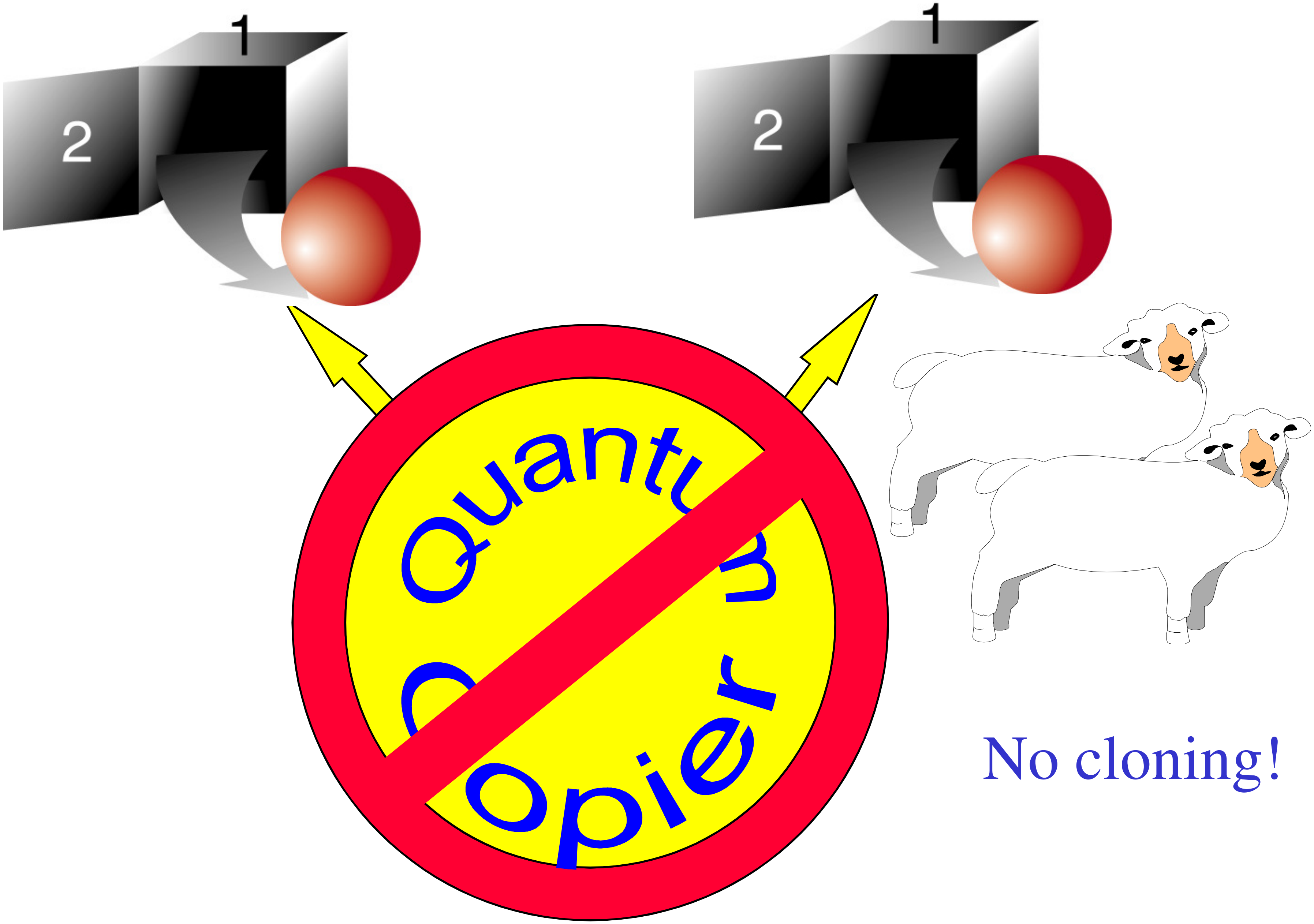


Quantum Bit (“Qubit”)



If you open a *different* door than you closed, the color is *random* (red 50% of the time and green 50% of the time).

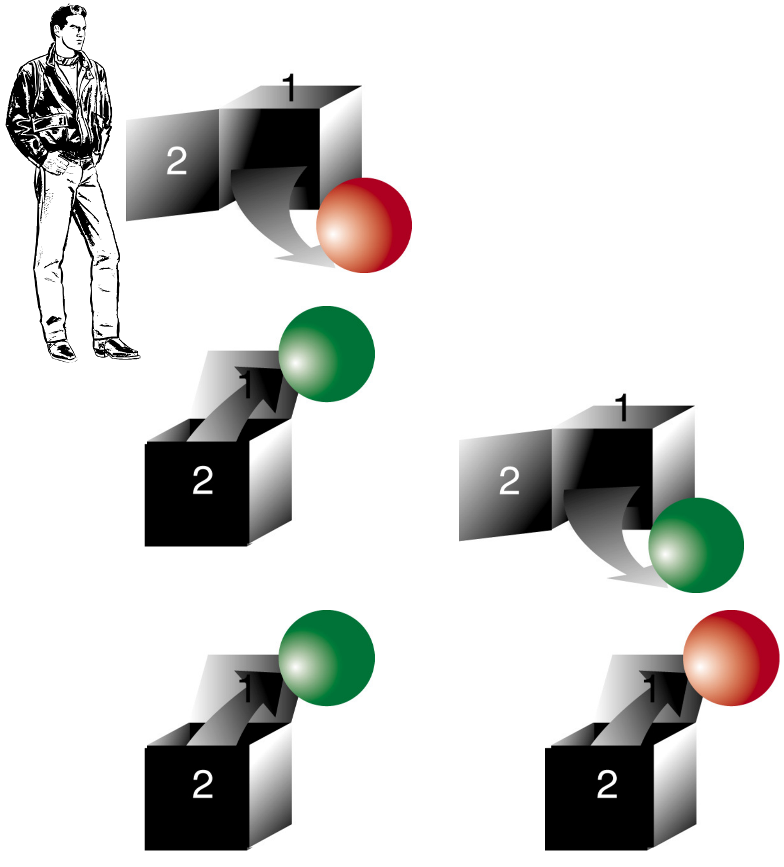

1
2
1
2
Quantum Copier



No cloning!

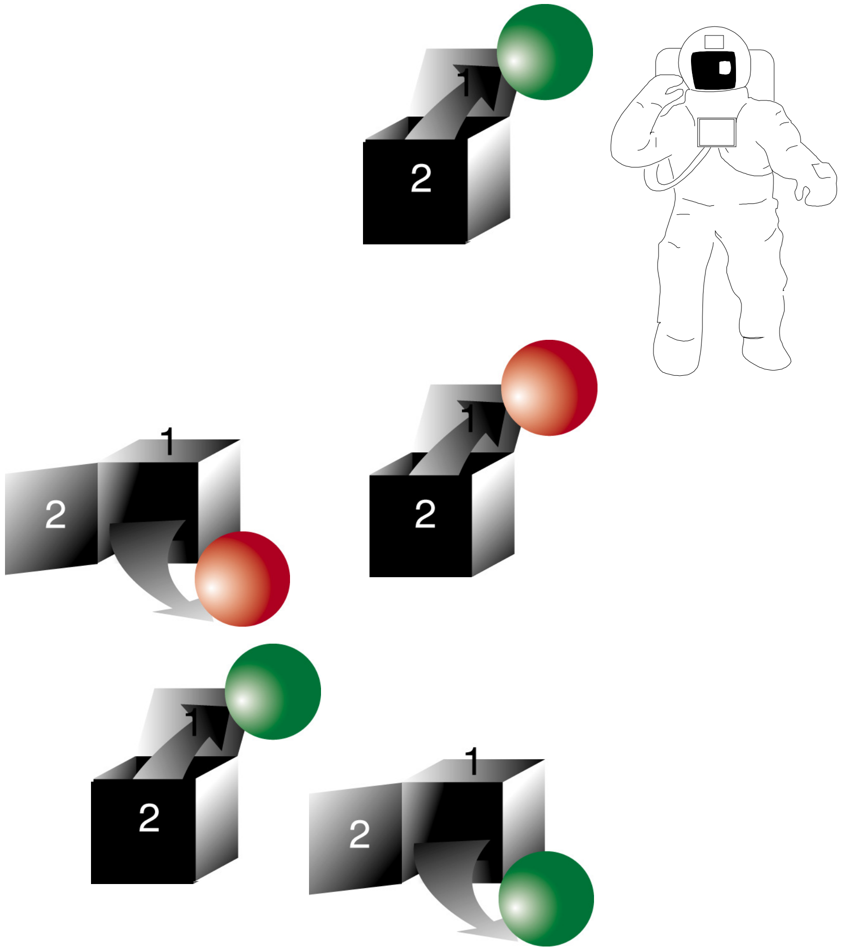
Quantum Correlations

Pasadena



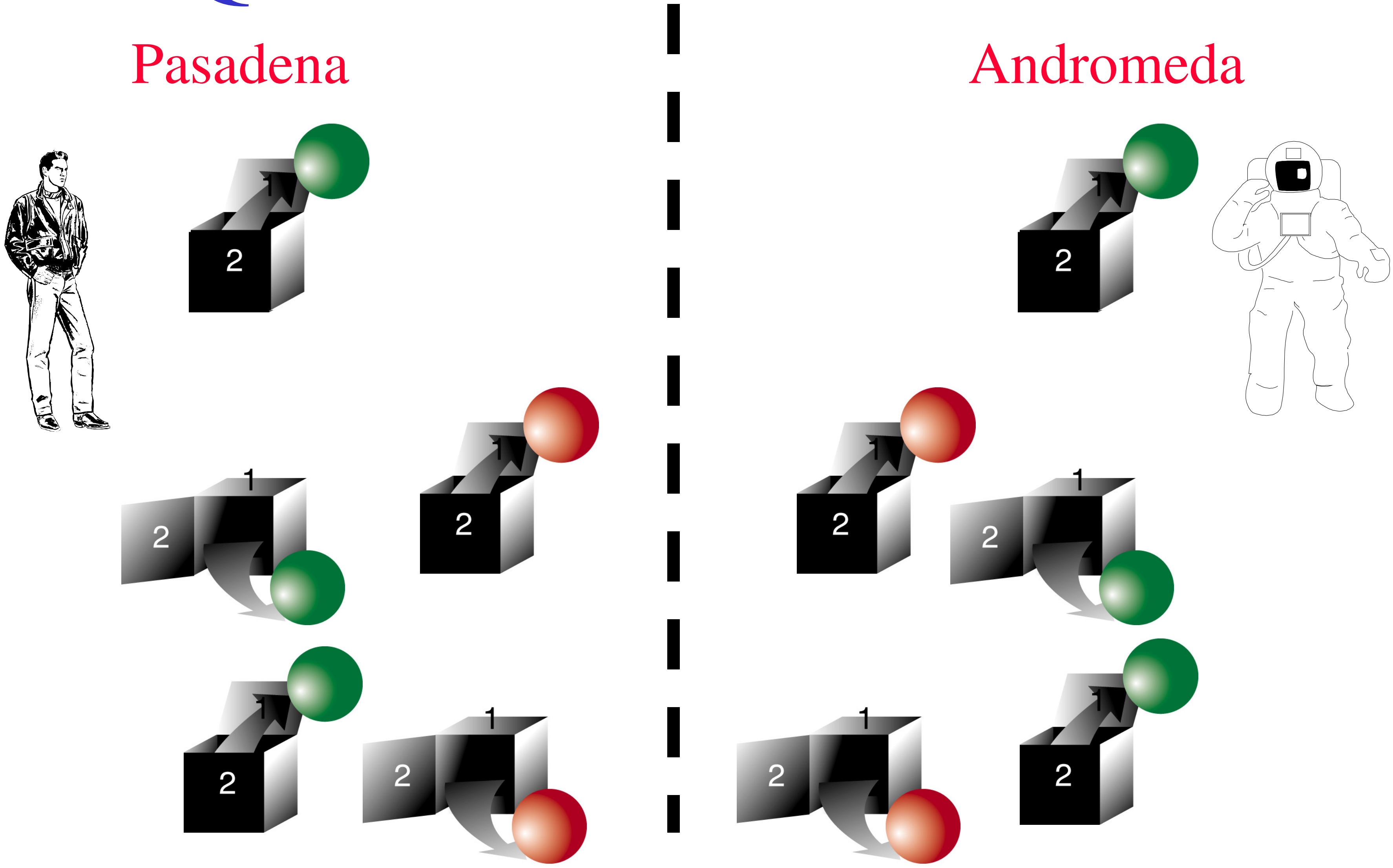
Open either door in Pasadena, and the color of the ball is *random.*

Andromeda



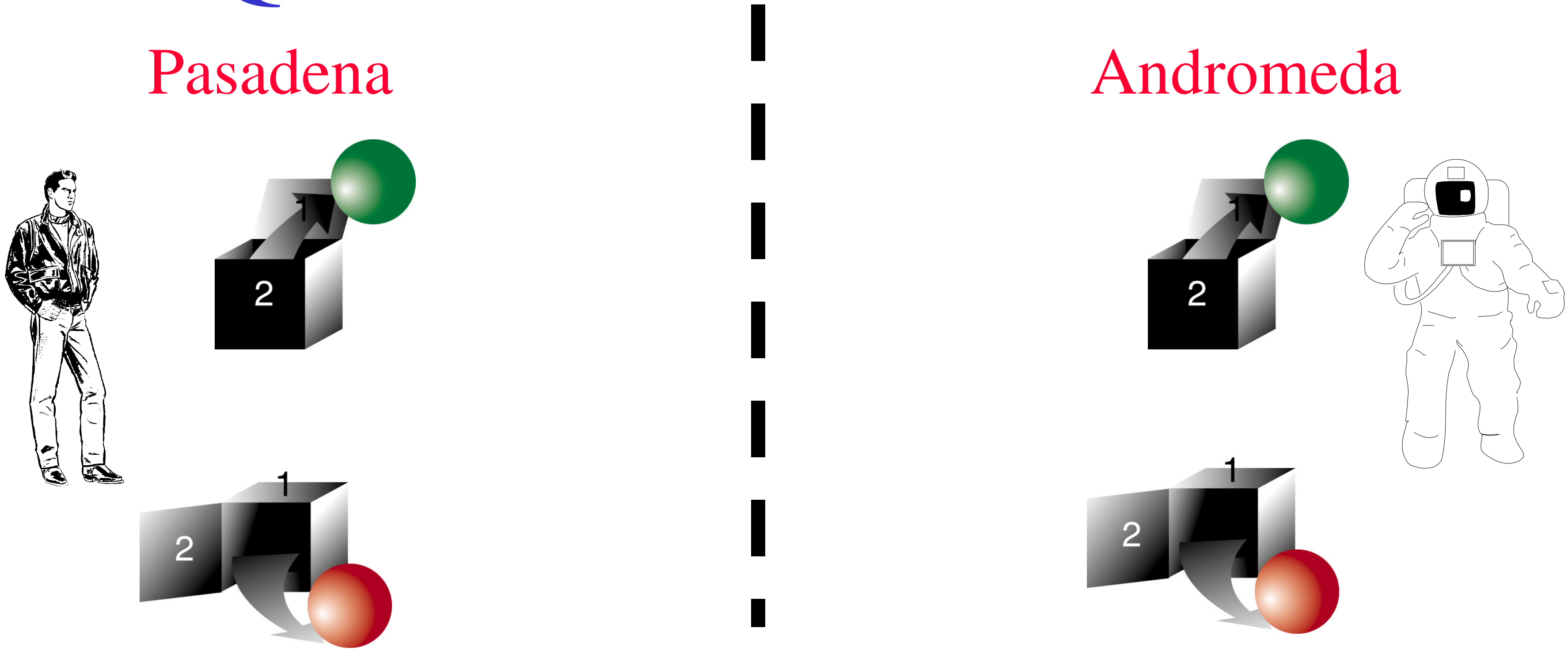
Same thing in Andromeda.

Quantum Correlations



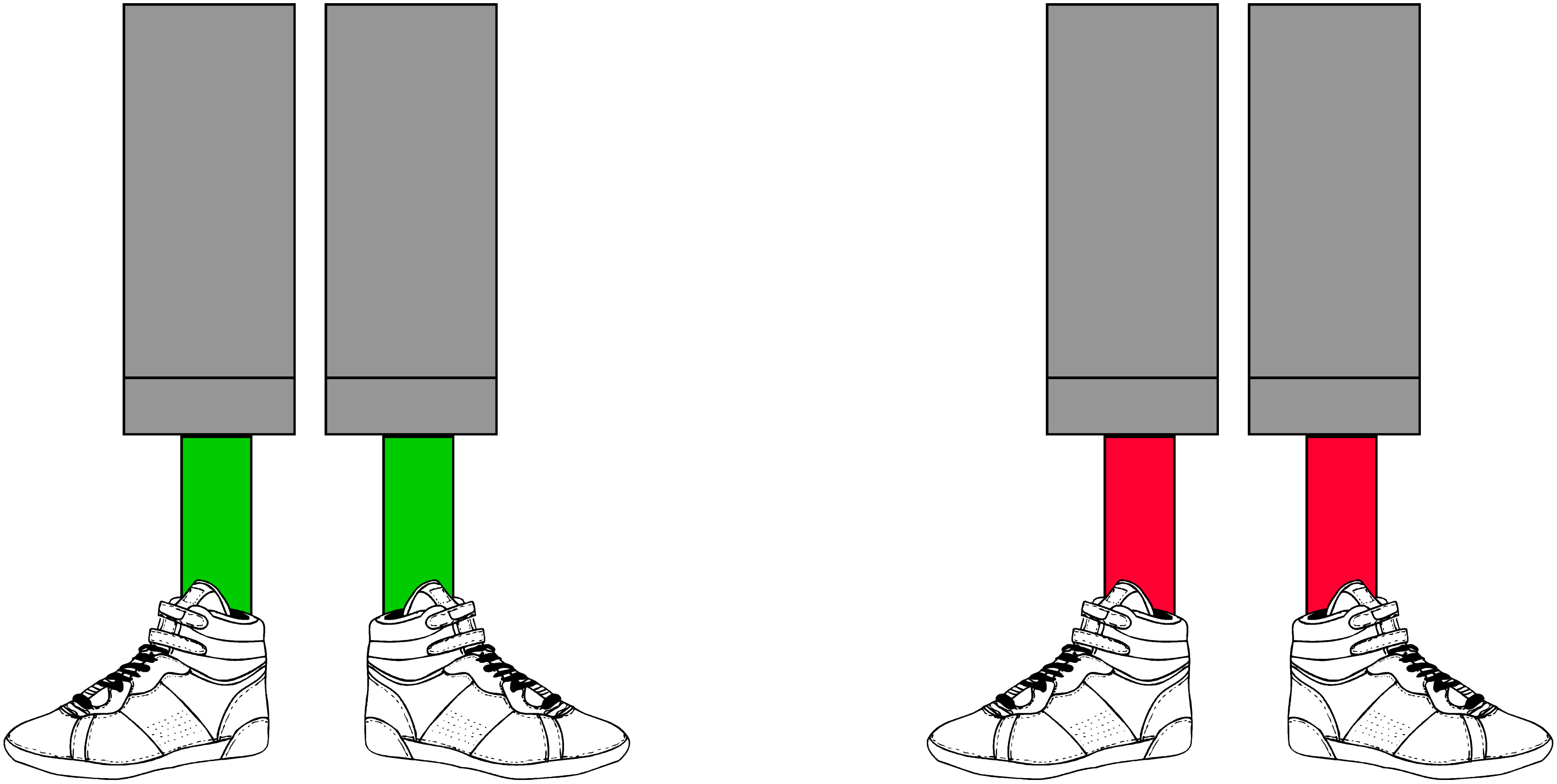
But if we both open the same door, we always find the same color.

Quantum Correlations

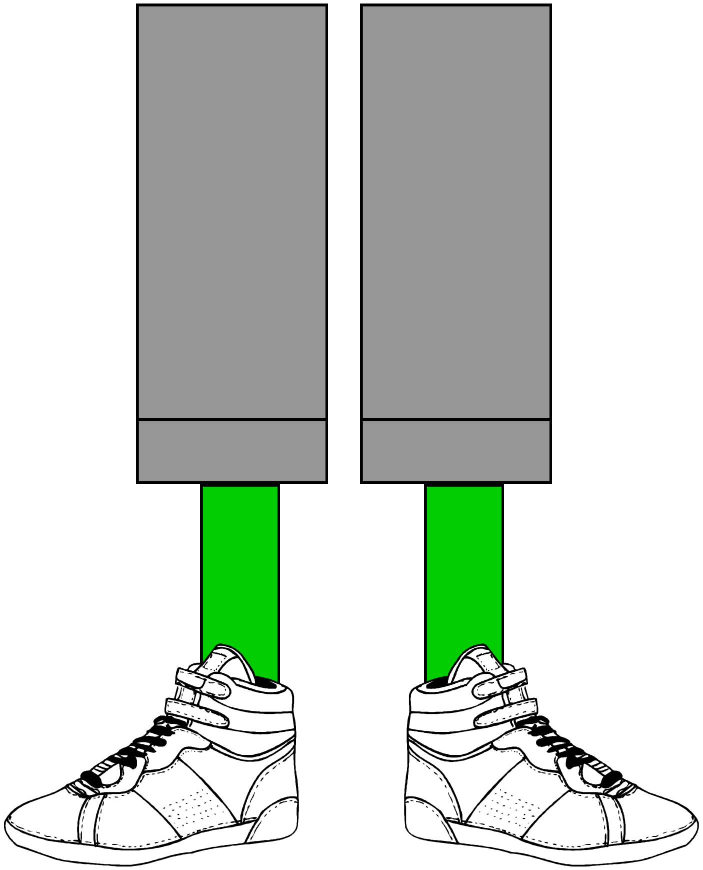


Quantum information can be *nonlocal*, shared equally by a box in Pasadena and a box in Andromeda.

This phenomenon, called *quantum entanglement*, is a crucial feature that distinguishes quantum information from classical information.



Classical Correlations



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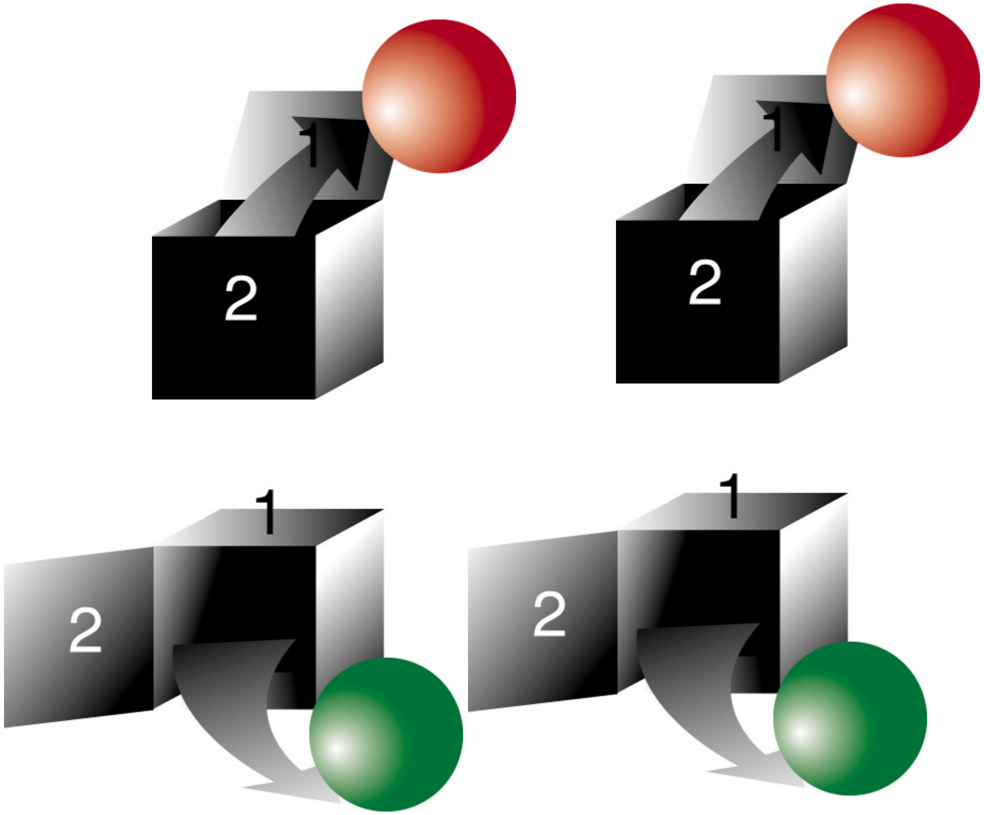
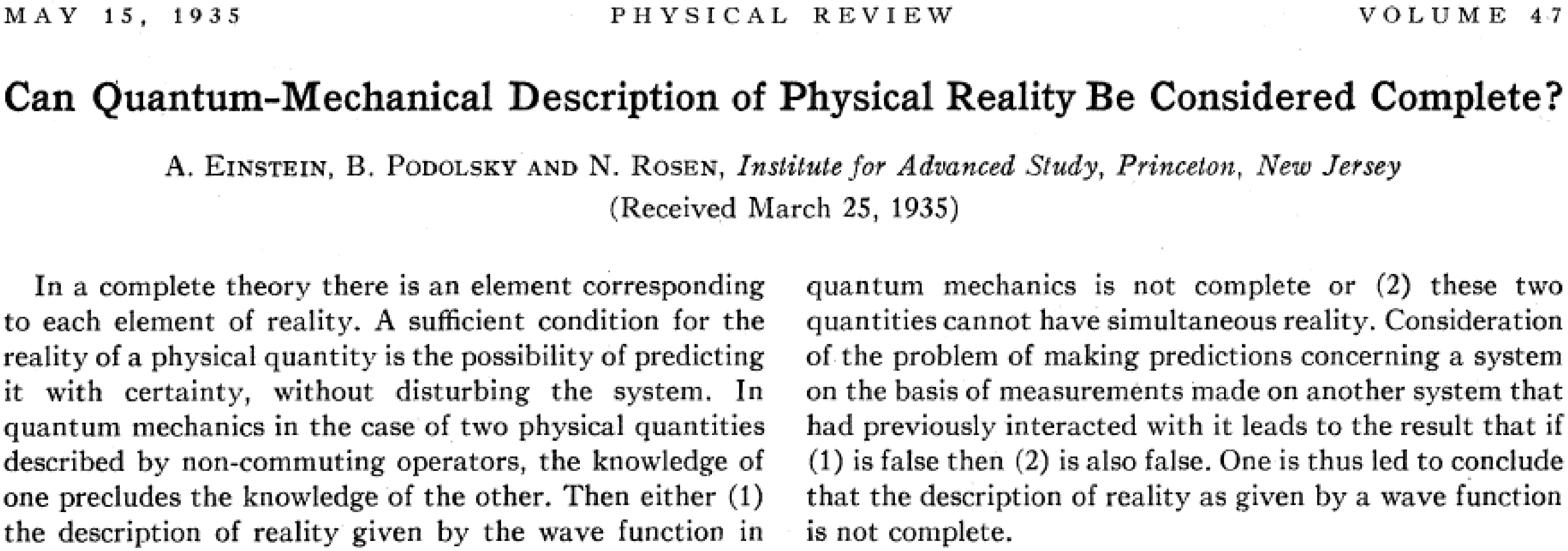


Quantum Correlations

Aren’t boxes like soxes?



MAY 15, 1935 PHYSICAL REVIEW VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

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(Received March 25, 1935)

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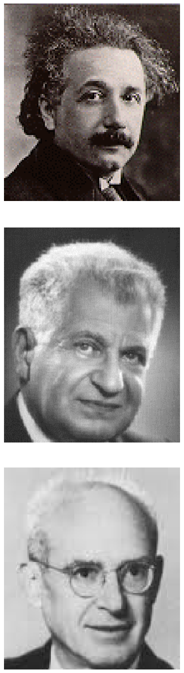

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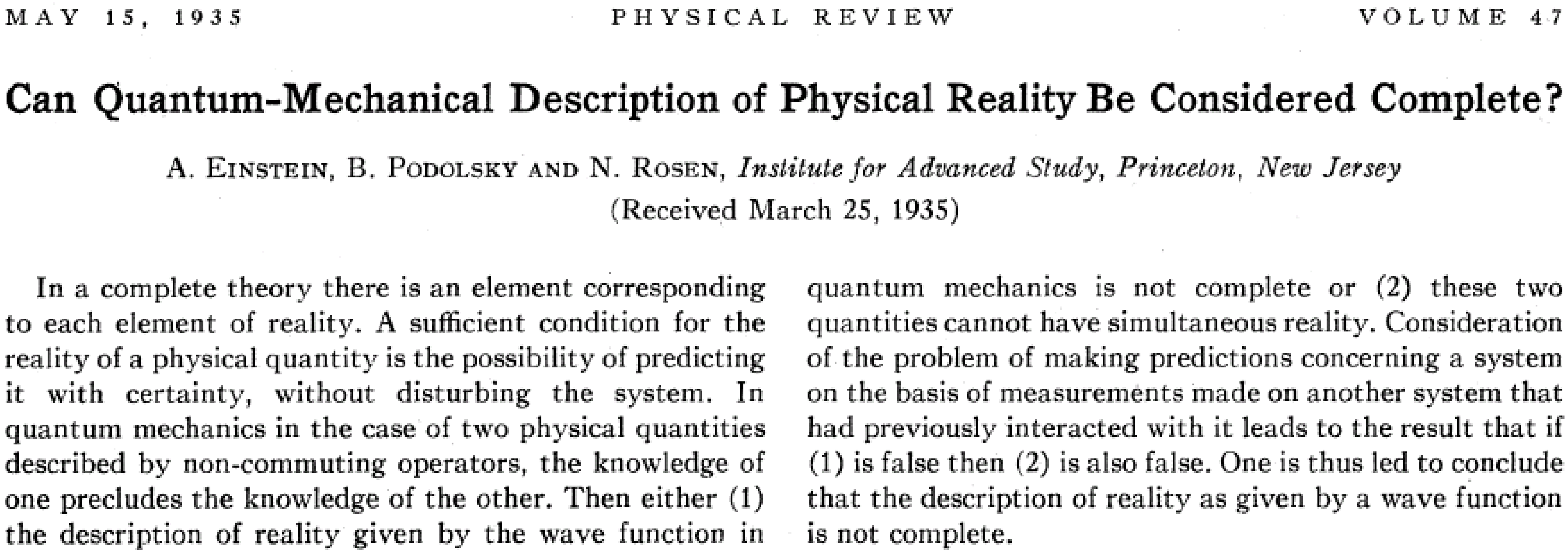

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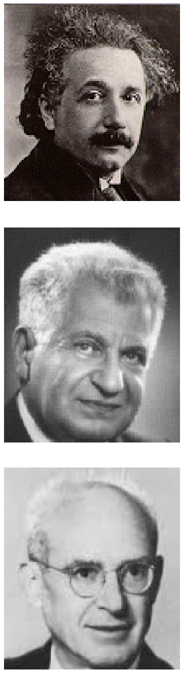
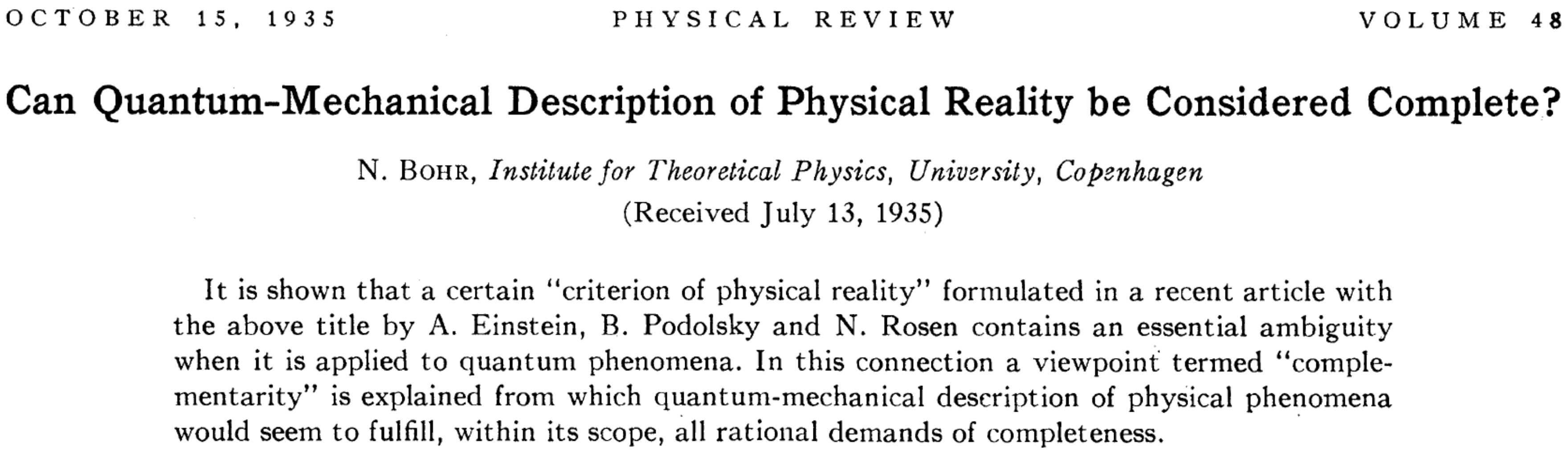


“If, without in any way disturbing a system, we can predict with certainty … the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.”



OCTOBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Can Quantum-Mechanical Description of Physical Reality be Considered Complete?

N. BOHR, *Institute for Theoretical Physics, University, Copenhagen*

(Received July 13, 1935)

It is shown that a certain "criterion of physical reality" formulated in a recent article with the above title by A. Einstein, B. Podolsky and N. Rosen contains an essential ambiguity when it is applied to quantum phenomena. In this connection a viewpoint termed "complementarity" is explained from which quantum-mechanical description of physical phenomena would seem to fulfill, within its scope, all rational demands of completeness.

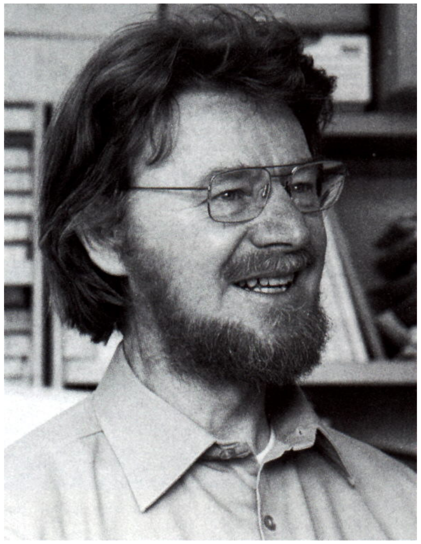
"there is … no question of a mechanical disturbance of the system under investigation during the critical last stage of the measuring procedure. But even at this stage there is essentially the question of an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system."

"Another way of expressing the peculiar situation is: the best possible knowledge of a *whole* does not necessarily include the best possible knowledge of its *parts* … I would not call that *one* but rather *the* characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought…

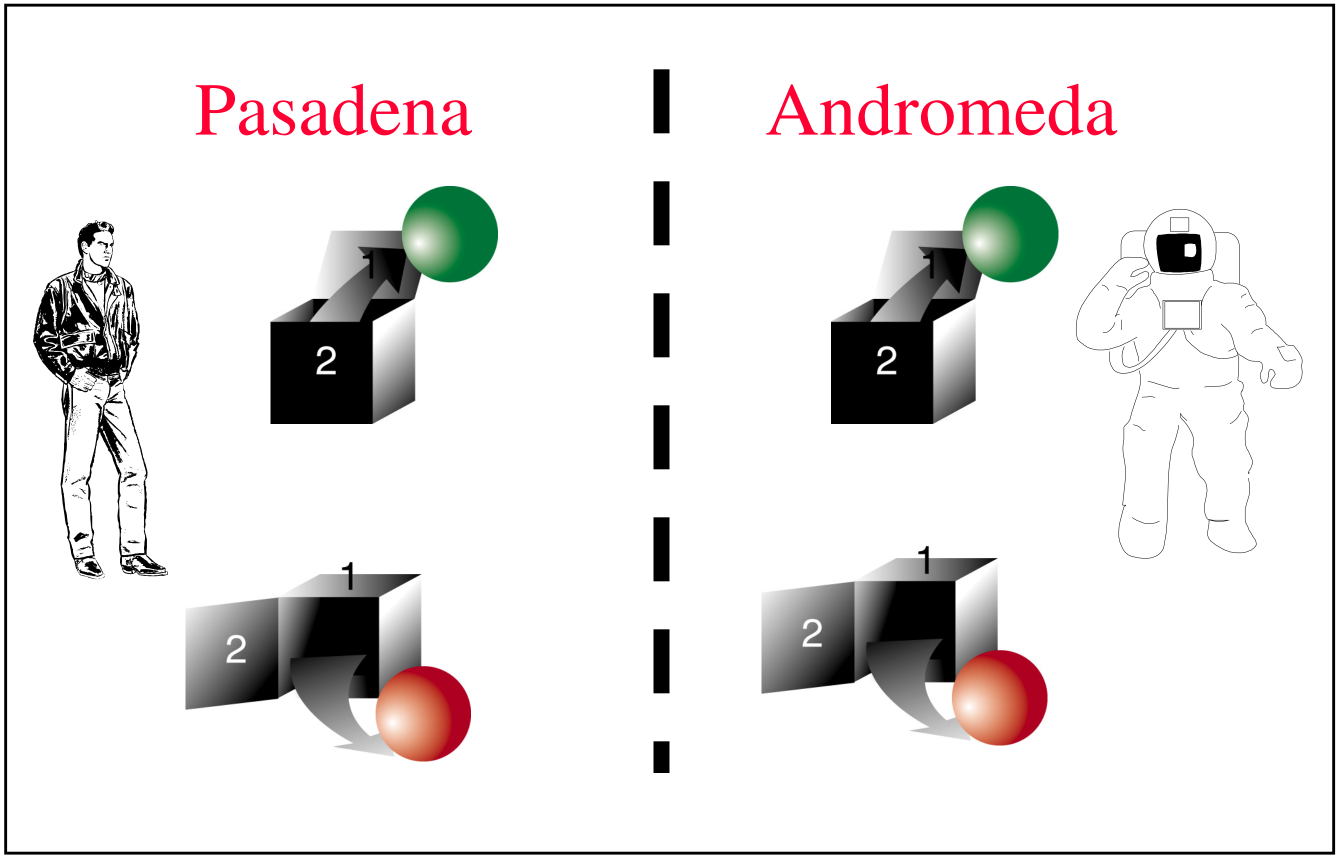
By the interaction the two representatives [quantum states] have become *entangled*."

Erwin Schrödinger, *Proceedings of the Cambridge Philosophical Society*, submitted 14 August 1935

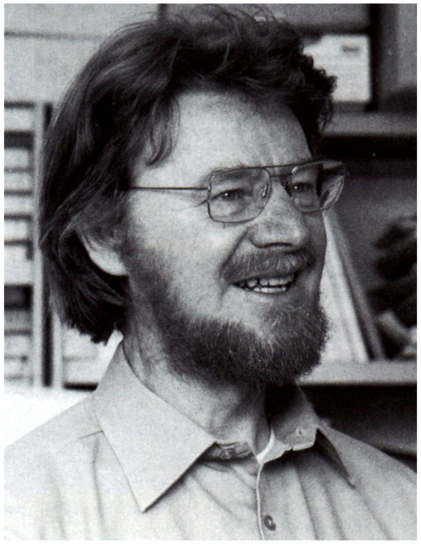
Quantum Entanglement



Bell ‘64



Quantum information can be *nonlocal*; quantum correlations are a stronger resource than classical correlations.



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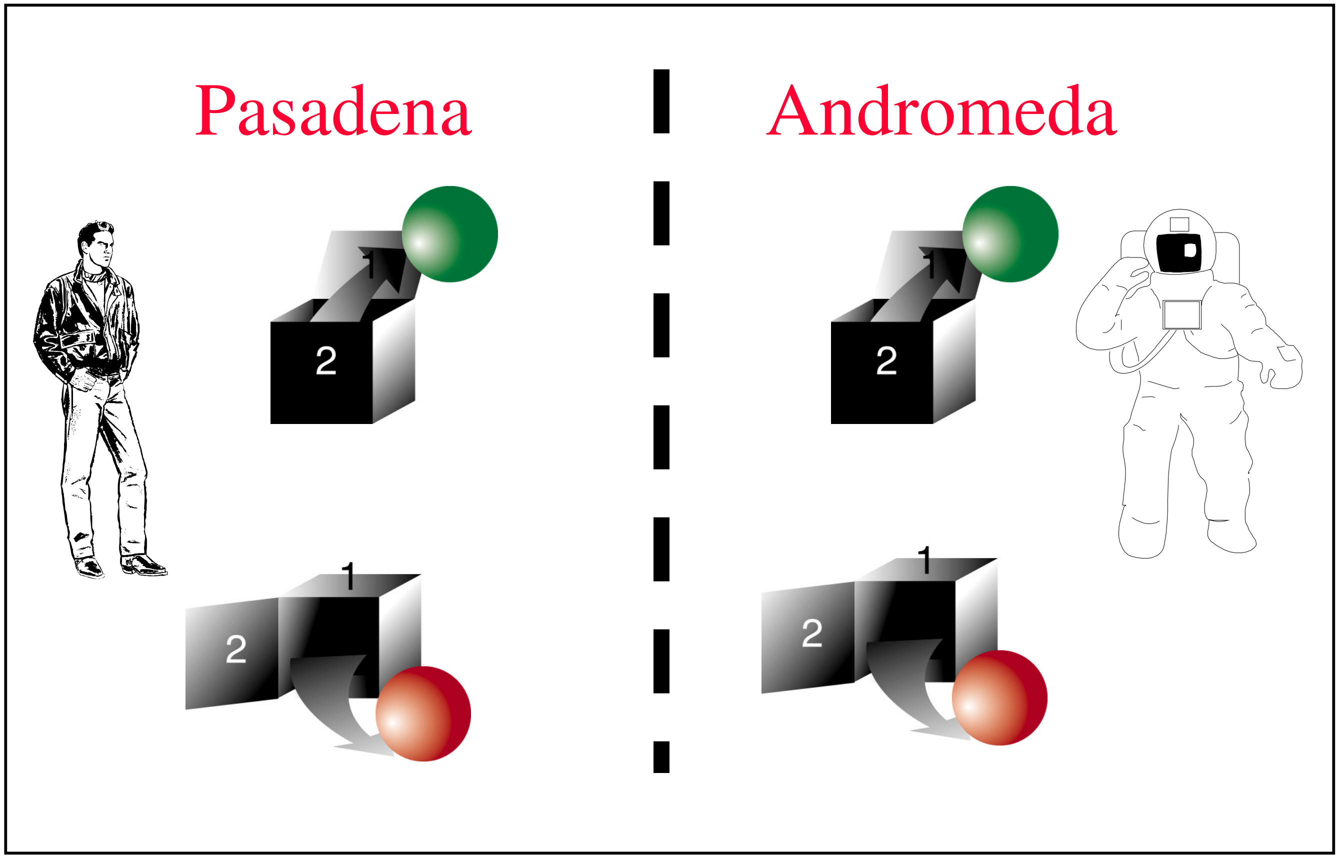
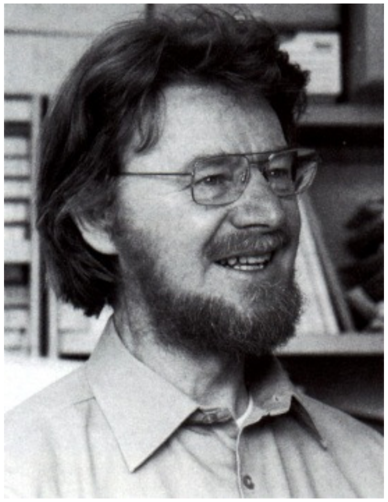
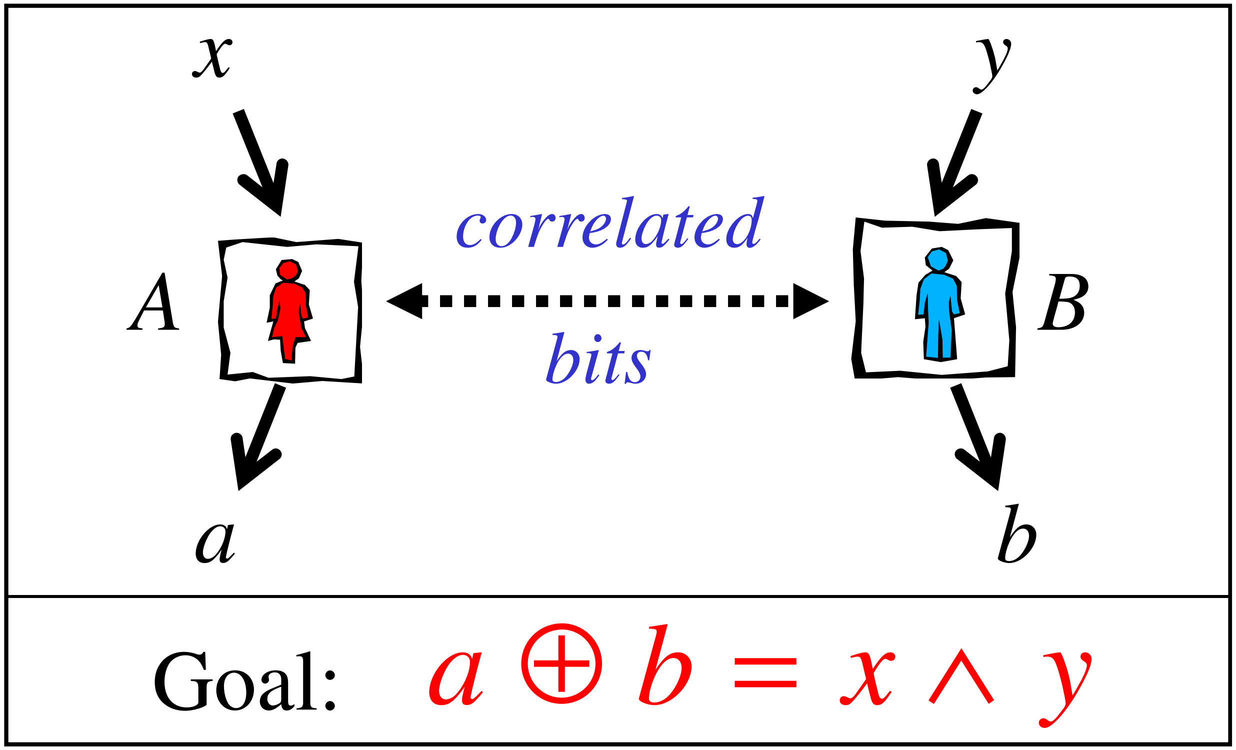




Quantum entanglement

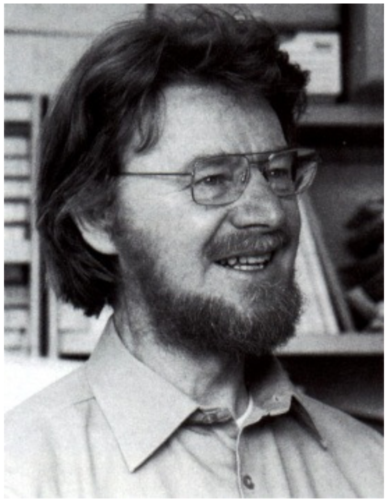
Alice and Bob play a cooperative two-player game.



Goal: $a \oplus b = x \wedge y$

If they share correlated classical bits and play their best strategy, they win with probability 75% (averaged over the inputs they receive).

Quantum entanglement



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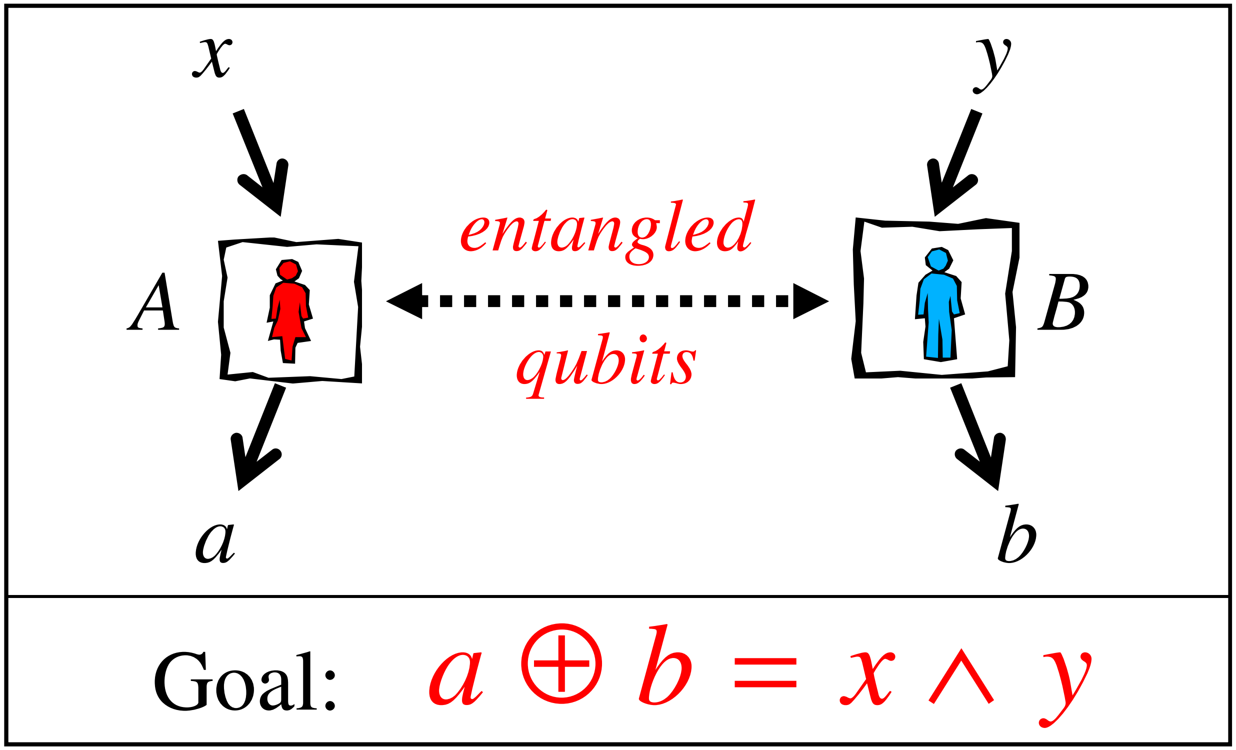
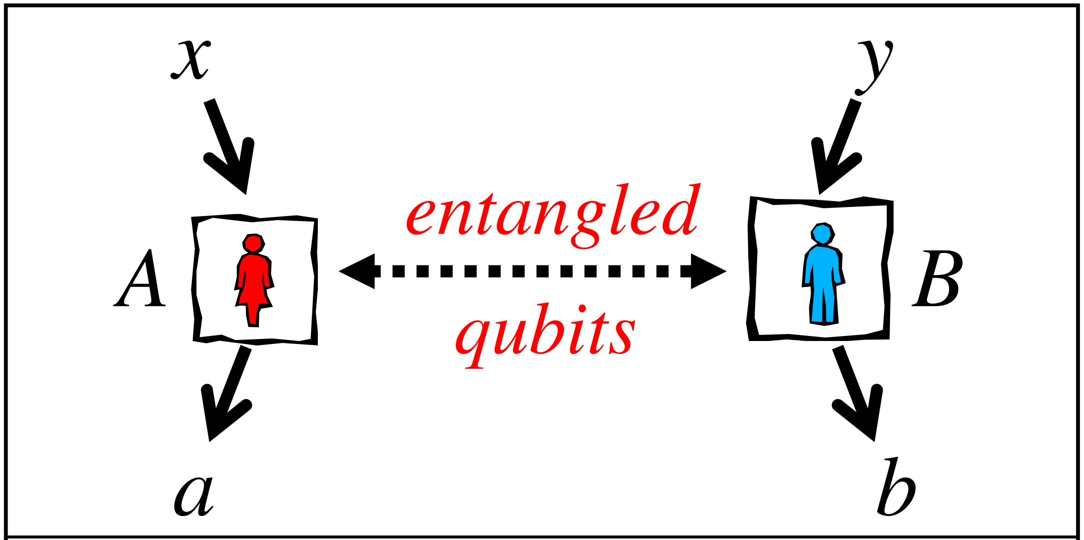


Goal: $a \oplus b = x \wedge y$

If they share entangled qubits and play their best strategy, they win with probability 85.4% (averaged over the inputs they receive).

Quantum entanglement

In experimental tests, physicists have played the game and have won with probability above 75%.



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Quantum correlations are a stronger resource than classical correlations.

Aspect

Quantum entanglement

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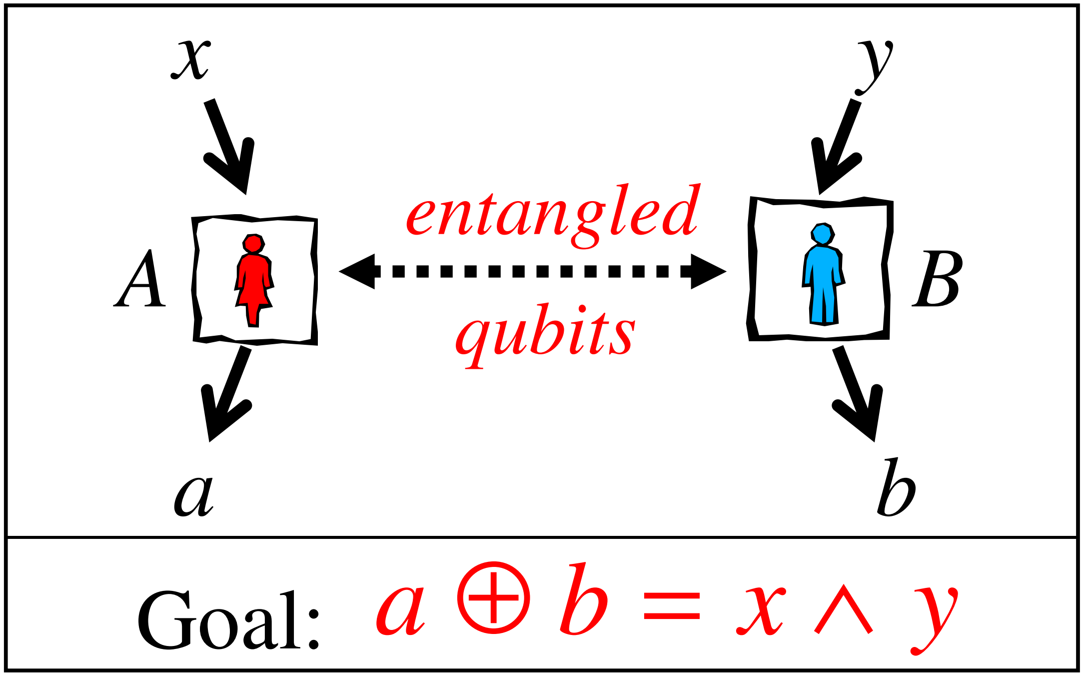

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* Spooky action at a distance!!

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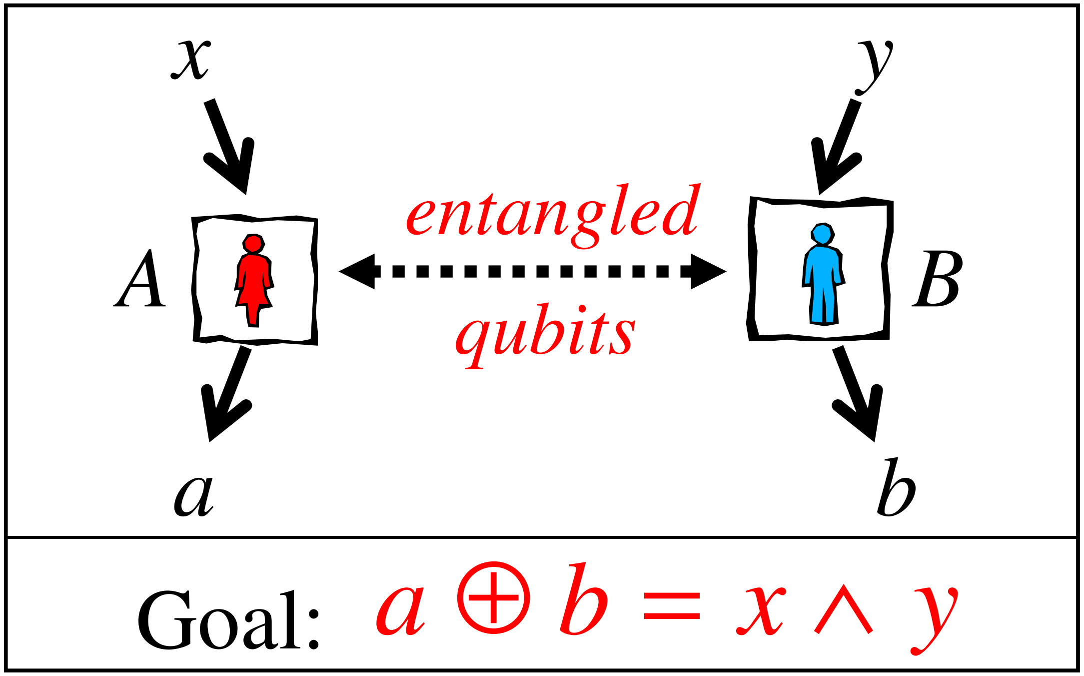

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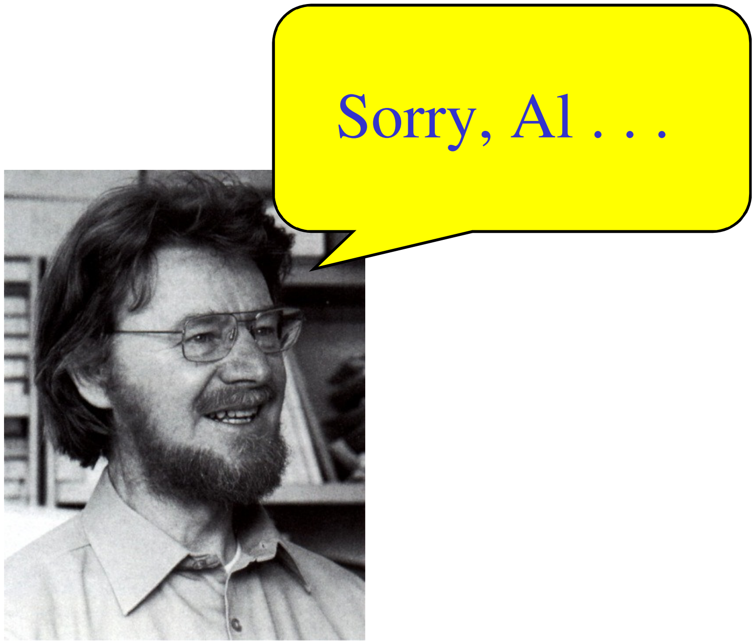

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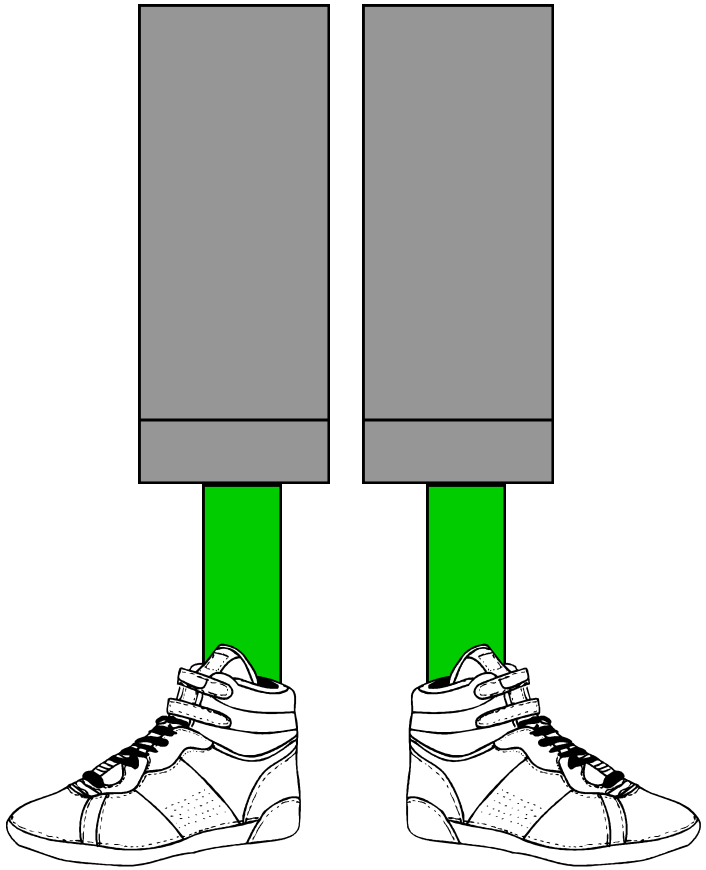
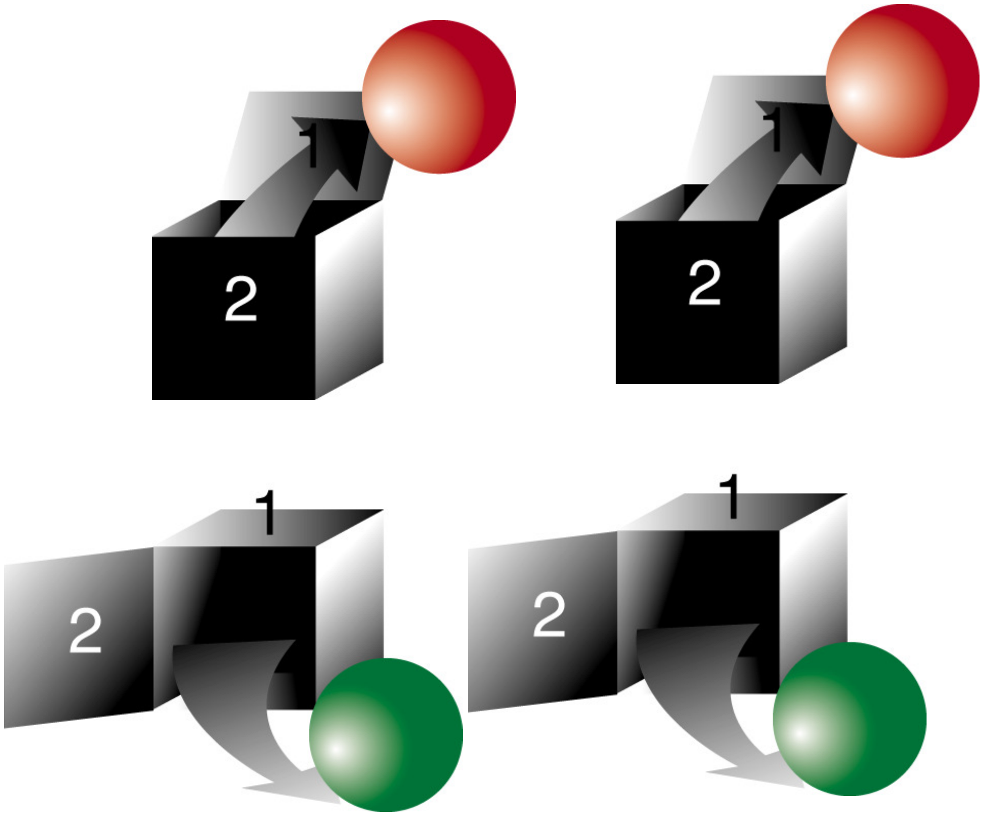


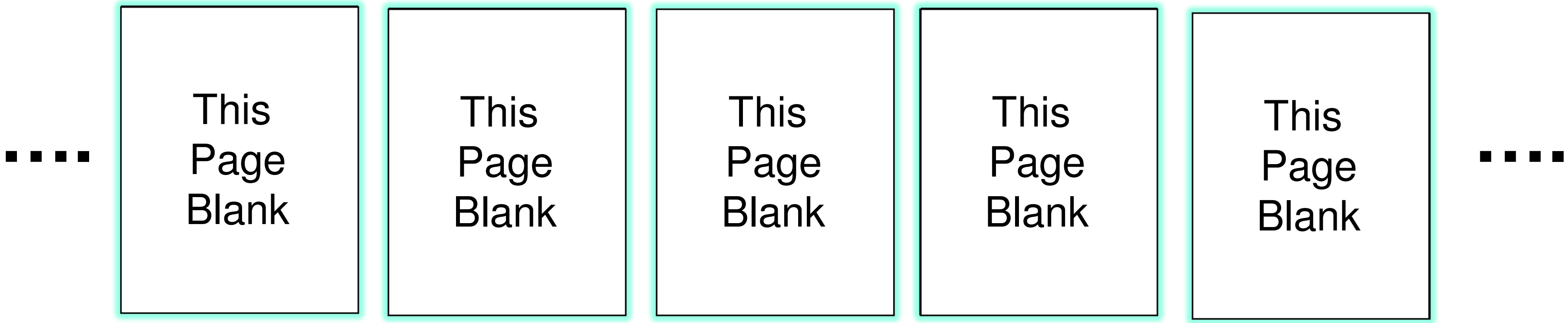
Classical Correlations



Quantum Correlations

Boxes are not like soxes!

Quantum entanglement



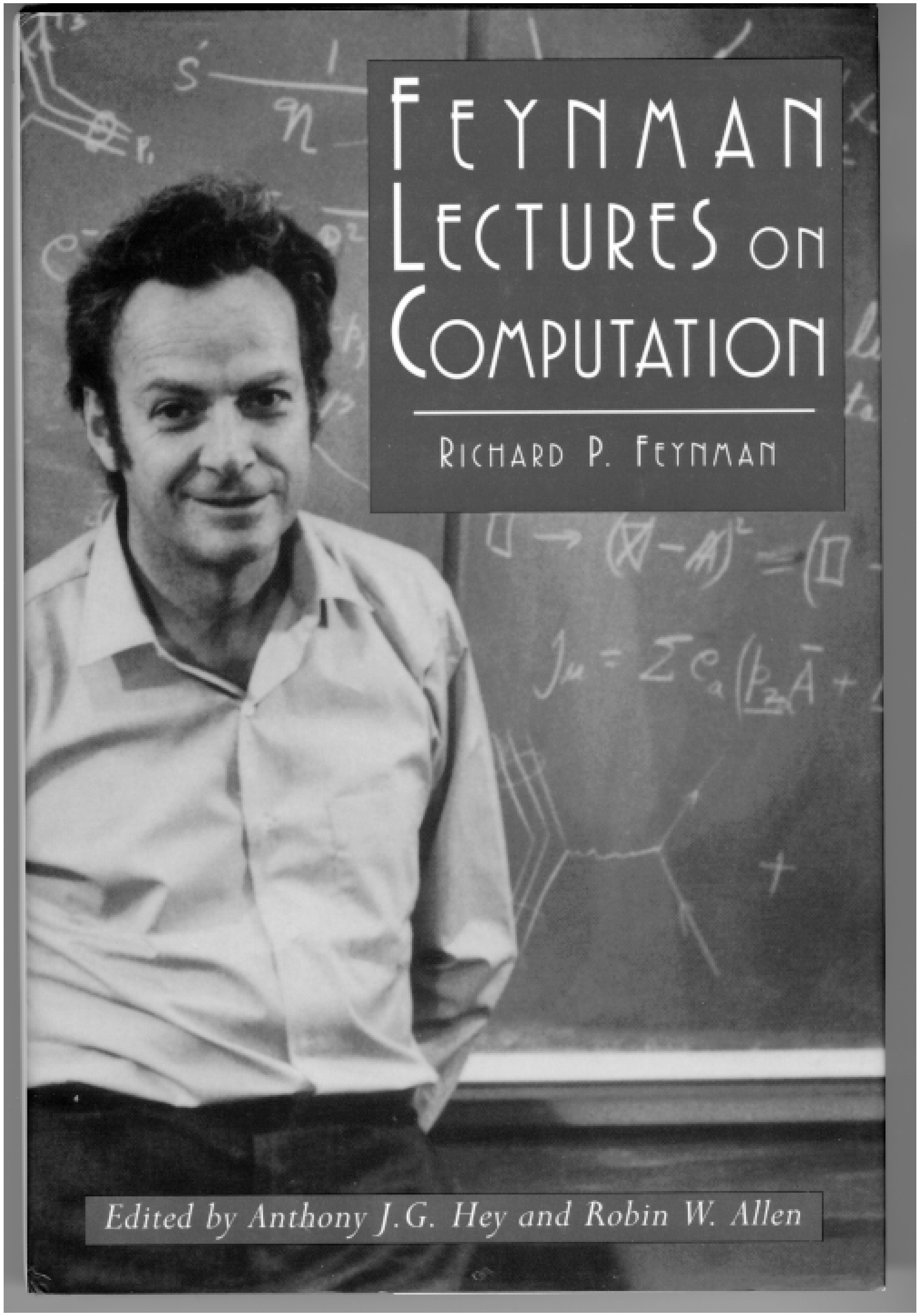
Nearly all the information in a typical entangled “quantum book” is encoded in the correlations among the “pages”.

You can't access the information if you read the book one page at a time.

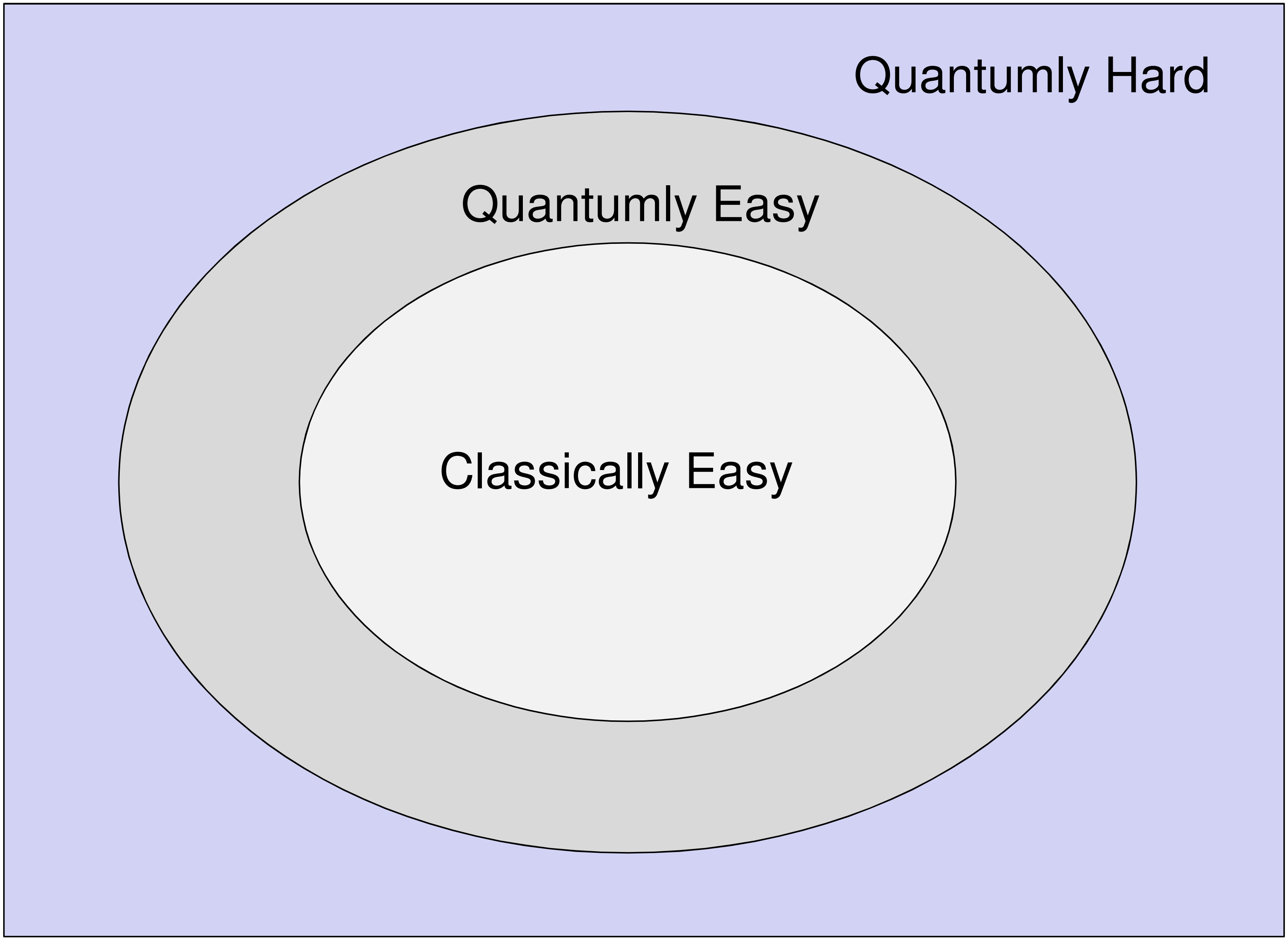
To describe 300 qubits, we would need more numbers than the number of atoms in the visible universe!

We can't even hope to *describe* the state of a few hundred qubits in terms of classical bits.

Might a computer that operates on qubits rather than bits (a *quantum computer*) be able to perform tasks that are beyond the capability of any conceivable classical computer?



Problems

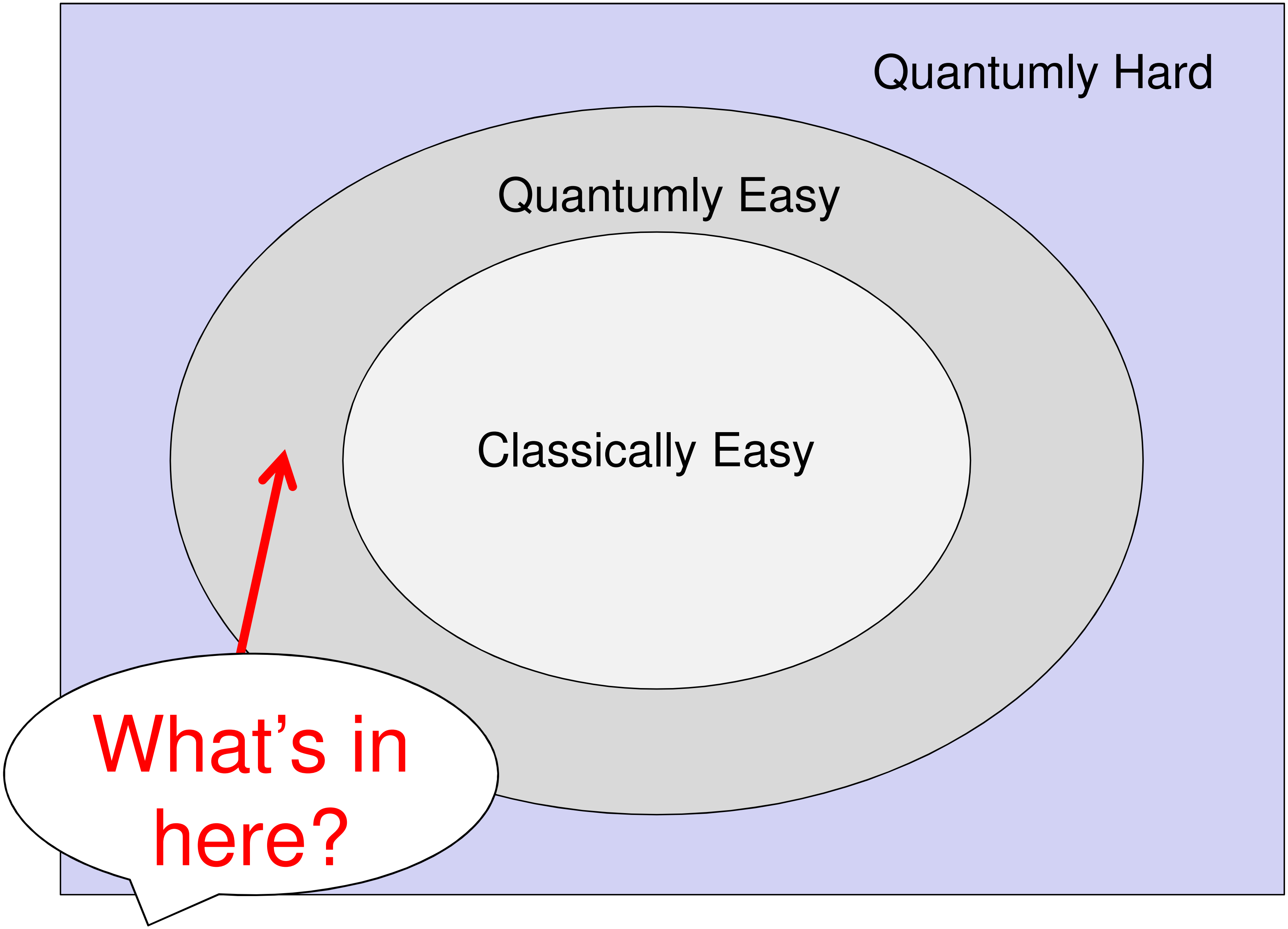


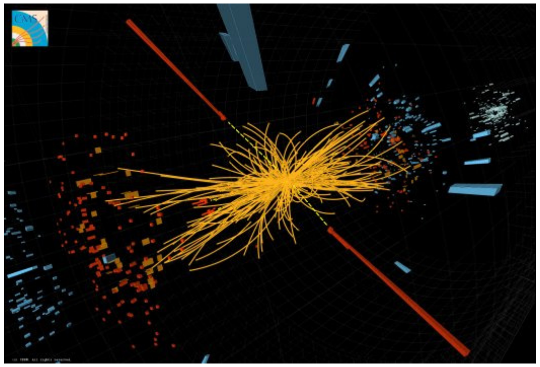
Quantumly Hard

Quantumly Easy

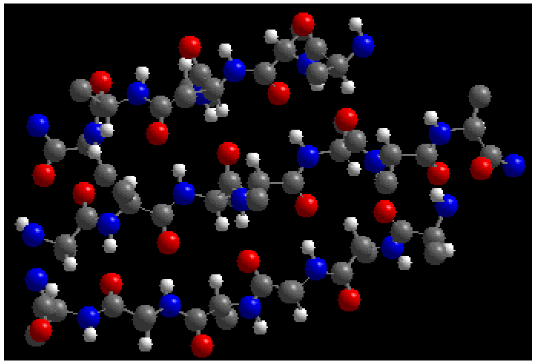
Classically Easy

Problems

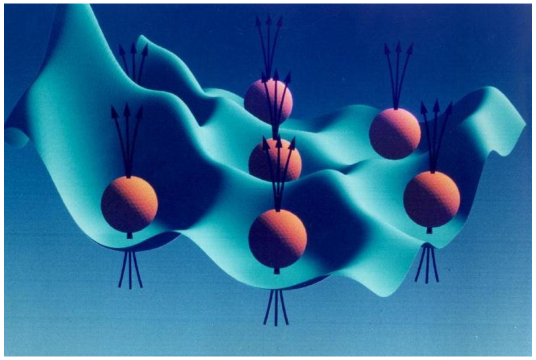

Quantumly Hard
Quantumly Easy
Classically Easy
What's in here?



particle collision



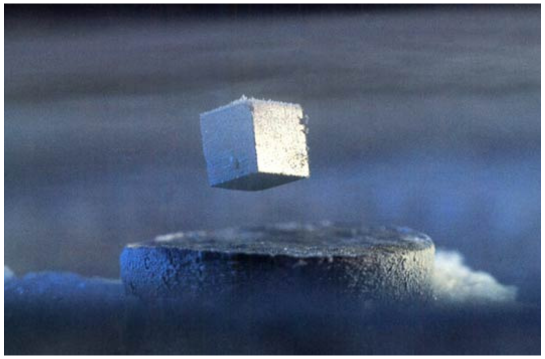
molecular chemistry



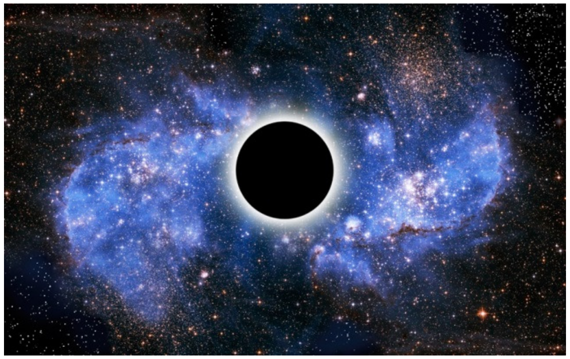
entangled electrons

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

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



superconductor

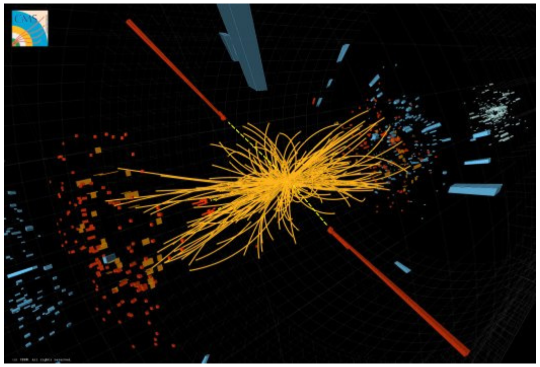


black hole

early universe

Frontiers of Physics

short distance



Higgs boson

Neutrino masses

Supersymmetry

Quantum gravity

String theory

long distance

Large scale structure

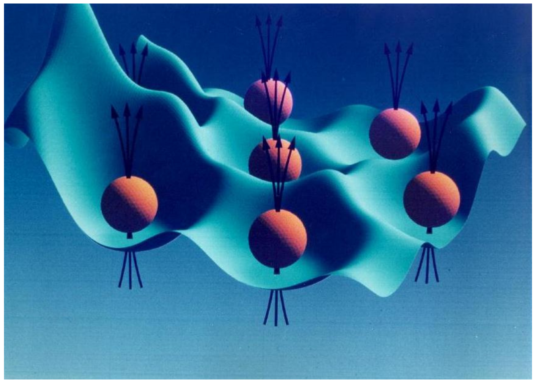
Cosmic microwave background

Dark matter

Dark energy

Gravitational waves

complexity



“More is different”

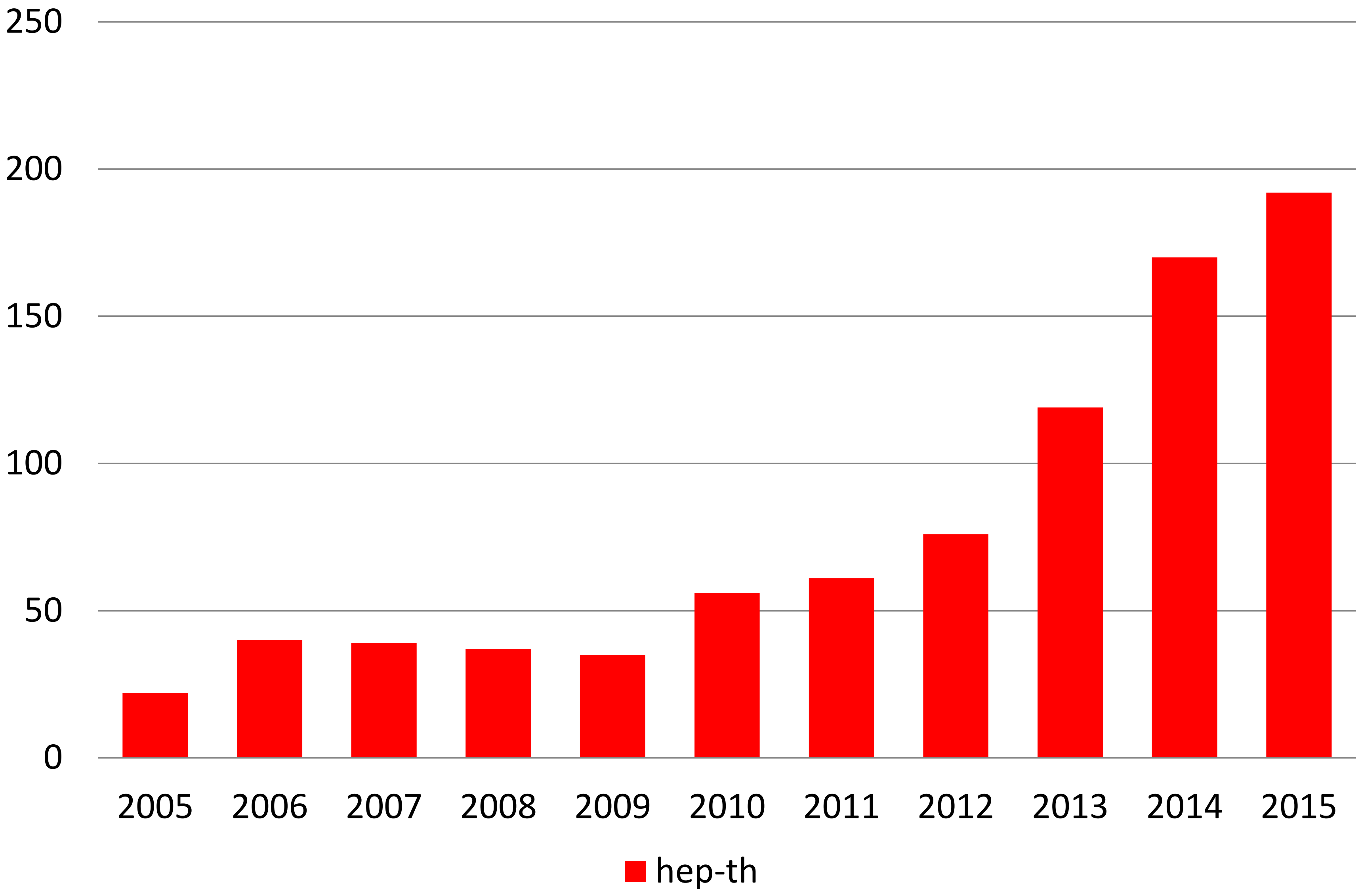
Many-body entanglement

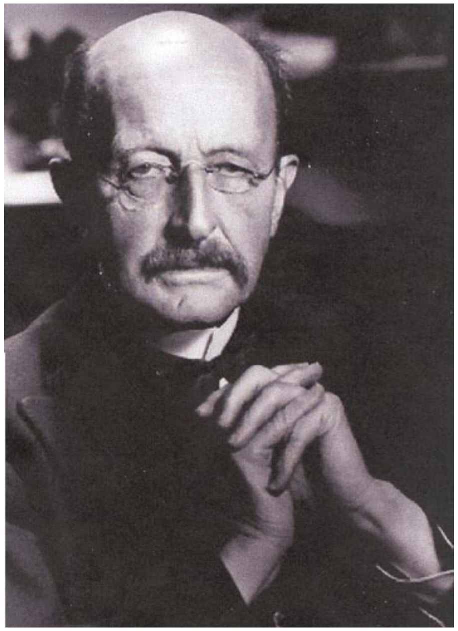
Phases of quantum matter

Quantum computing

Quantum spacetime

hep-th papers with “entanglement” in the title





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

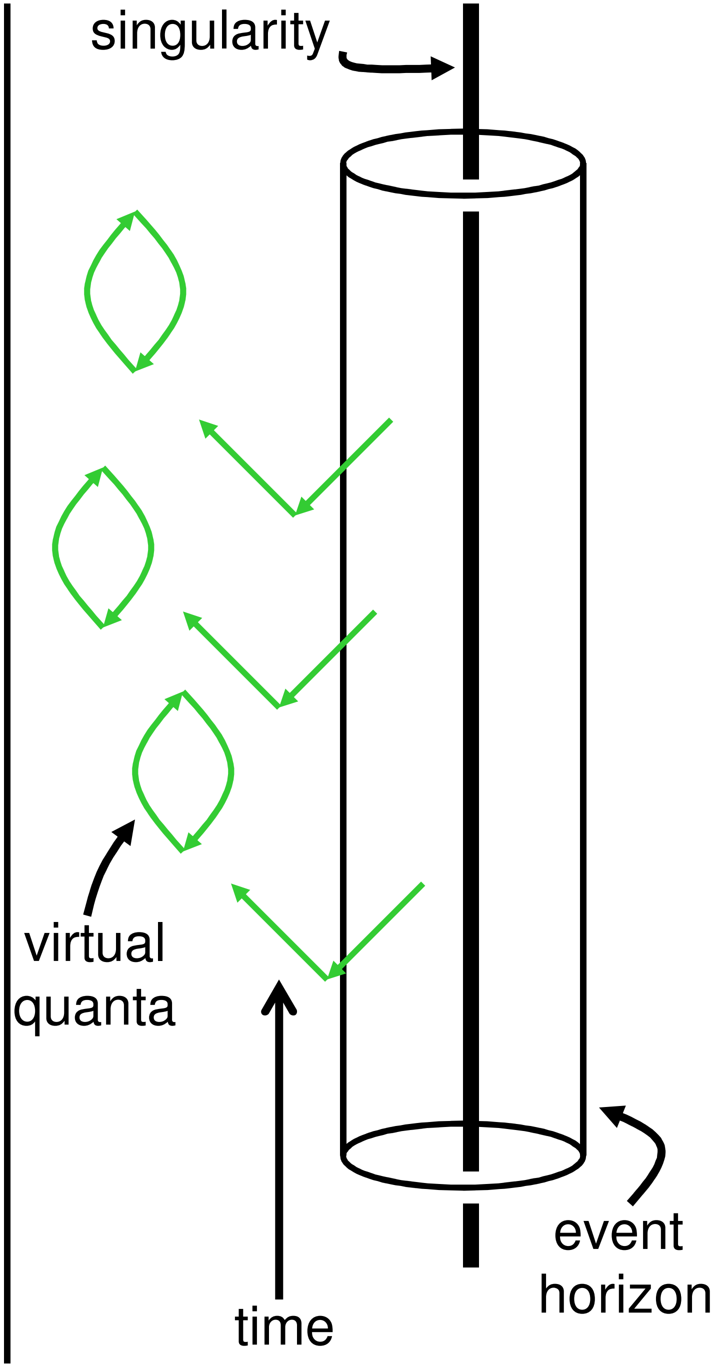
Classically, nothing can escape from a black hole, but quantumly, black holes *radiate*.

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.

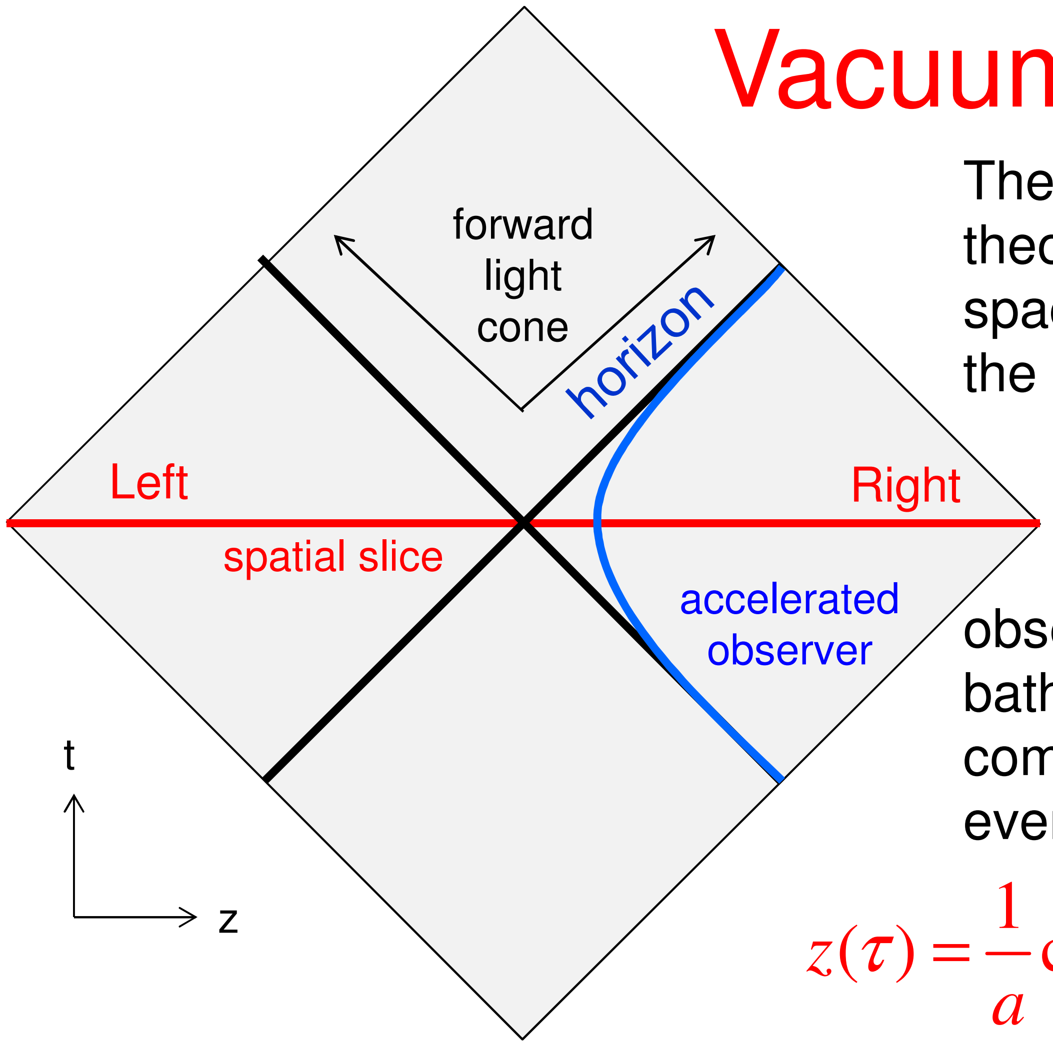
To an observer far away, the black hole seems to be a source of featureless thermal radiation with wavelength comparable to the black hole radius:

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

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



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):

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

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

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”:

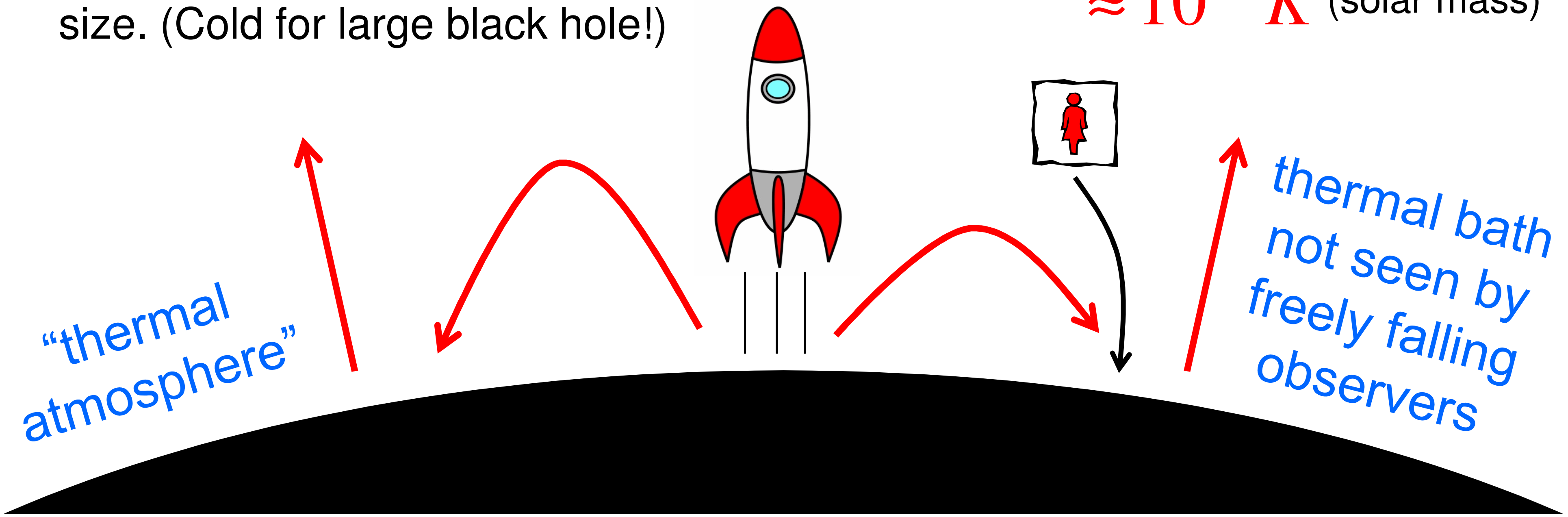
$$\kappa = \frac{c^2}{2R_{BH}}$$

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

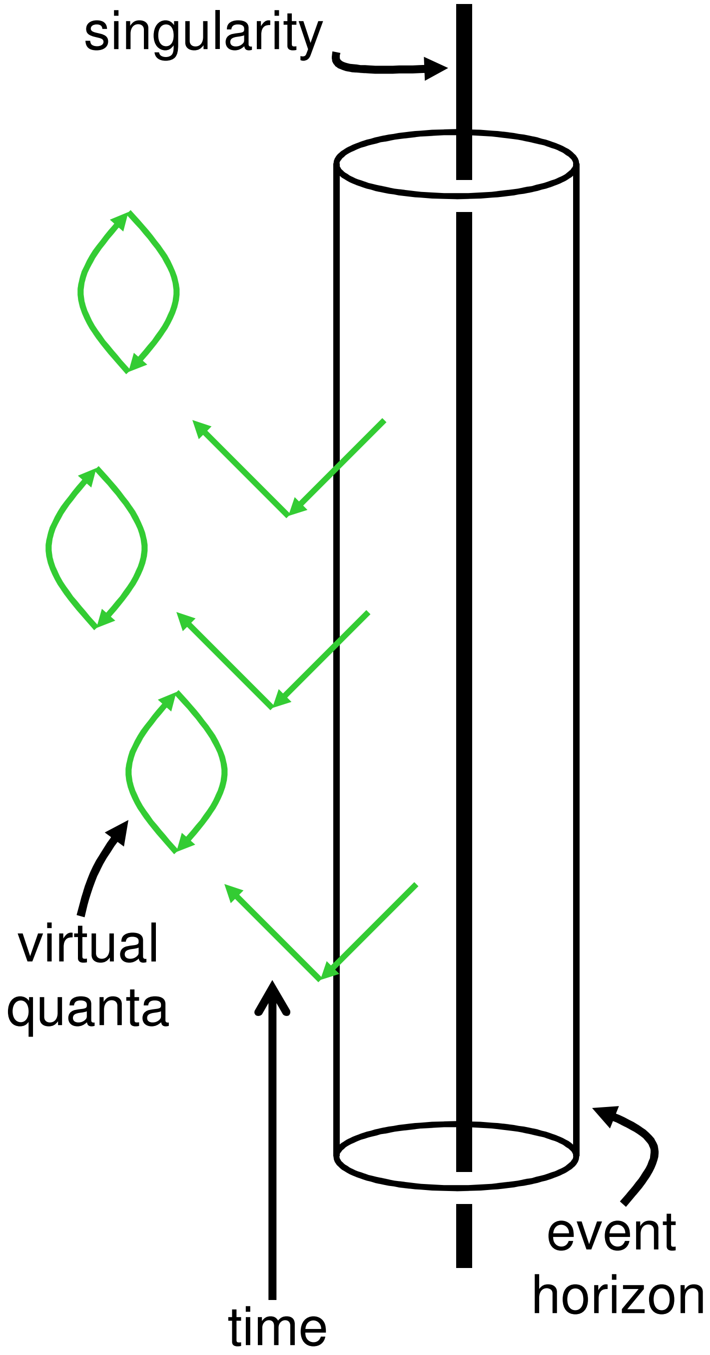
$$k_B T_{\text{black hole}} = \hbar c / 4\pi R_{\text{black hole}}$$

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

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

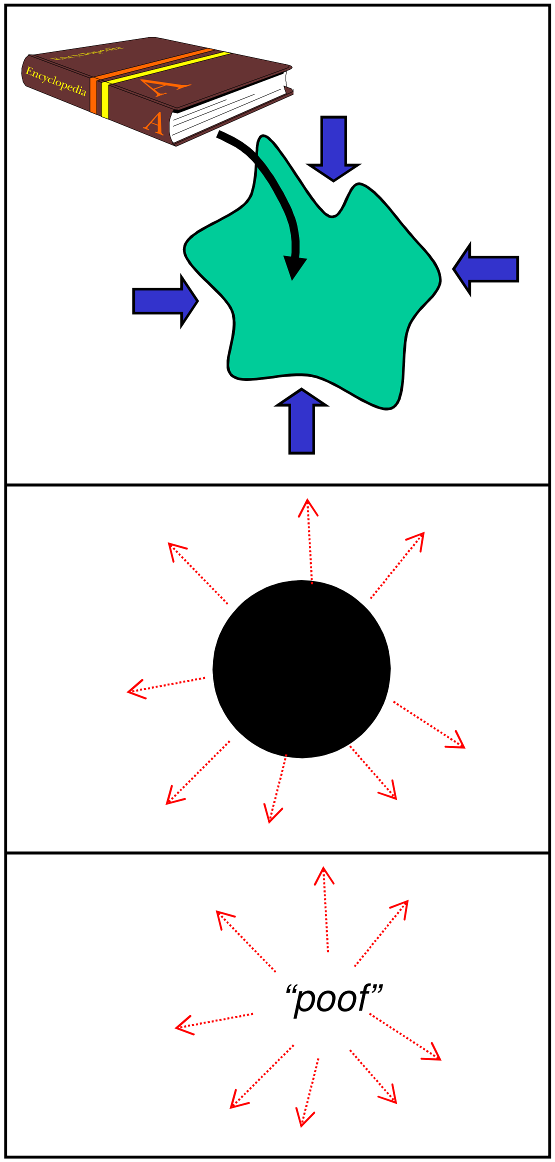
where
$$L_{\text{Planck}} = \left(\hbar G / c^3\right)^{1/2} = 10^{-33}\,\text{cm}$$

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).



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?

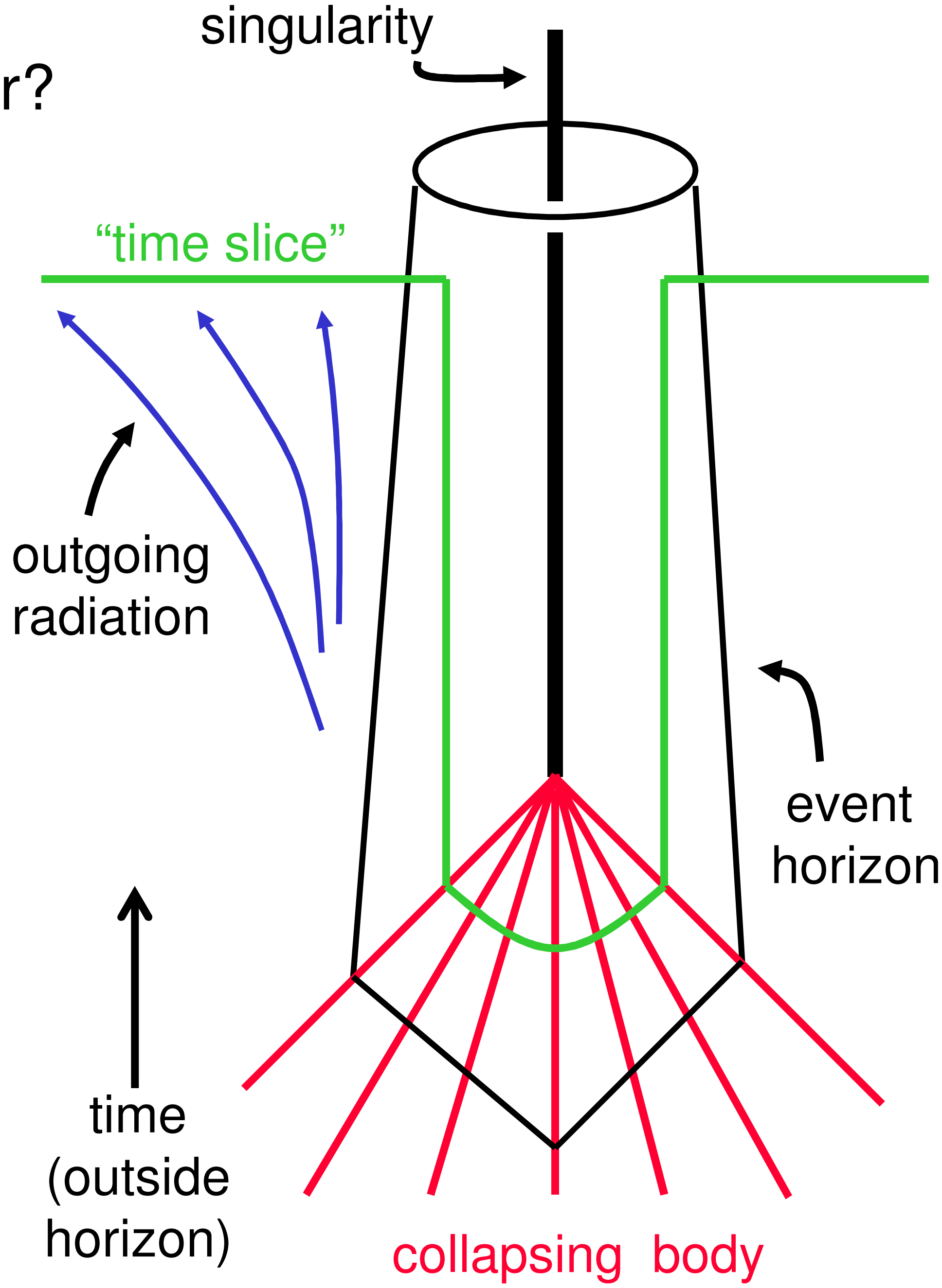
Information Puzzle:

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.

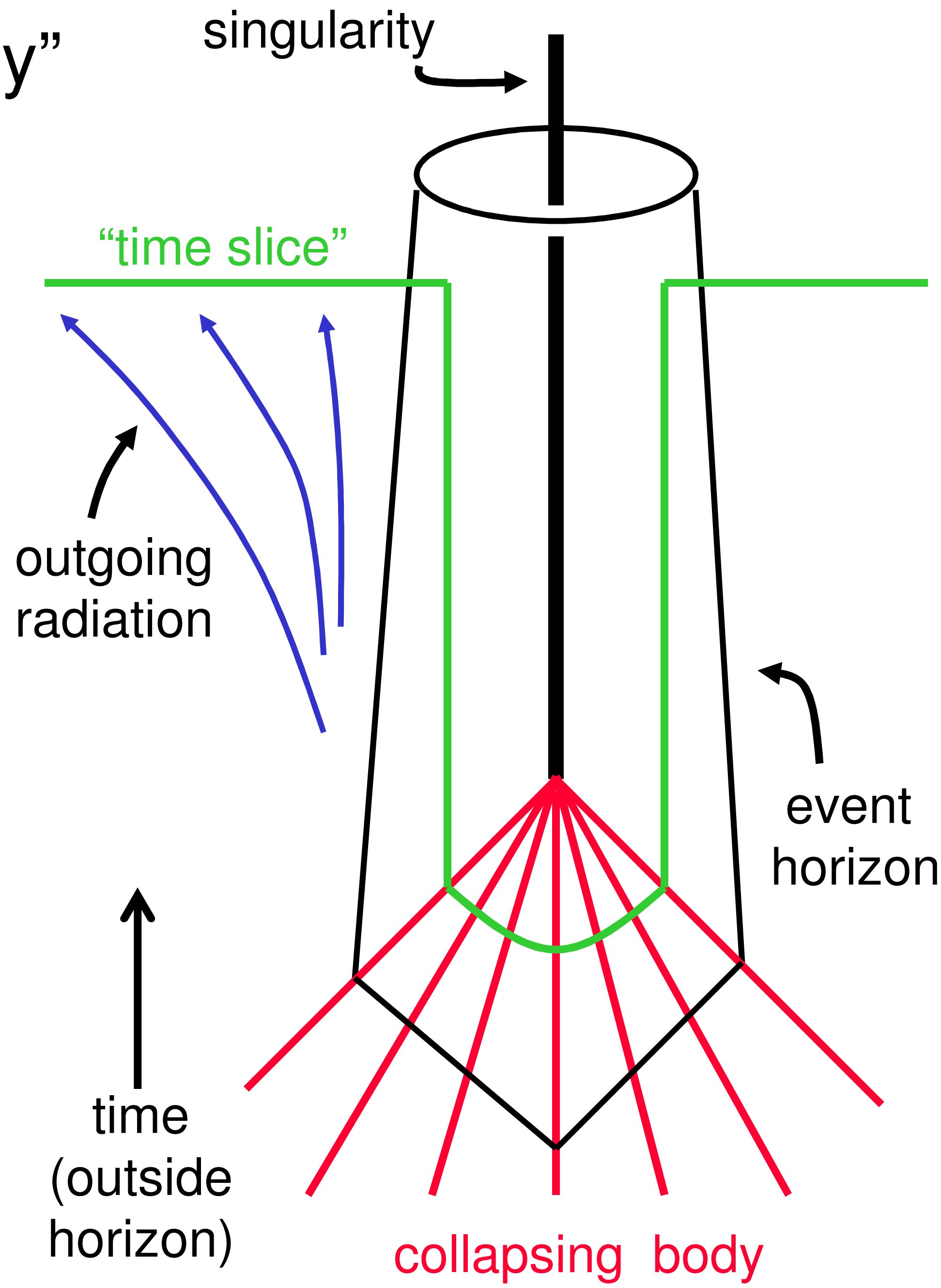


“Black hole complementarity”

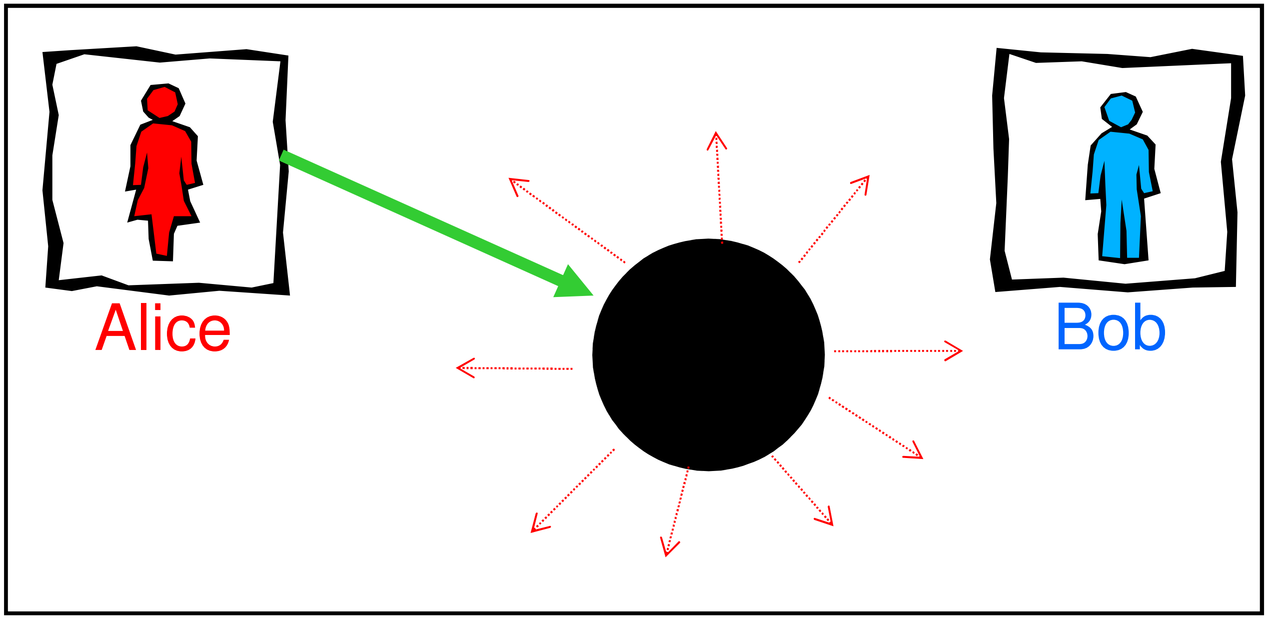
The inside and the outside are not two separate systems.

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

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



Black holes as mirrors



An old black hole scrambles information and reveals it quickly.

$$\Delta t_s = O\left(r_s \log r_s\right)$$

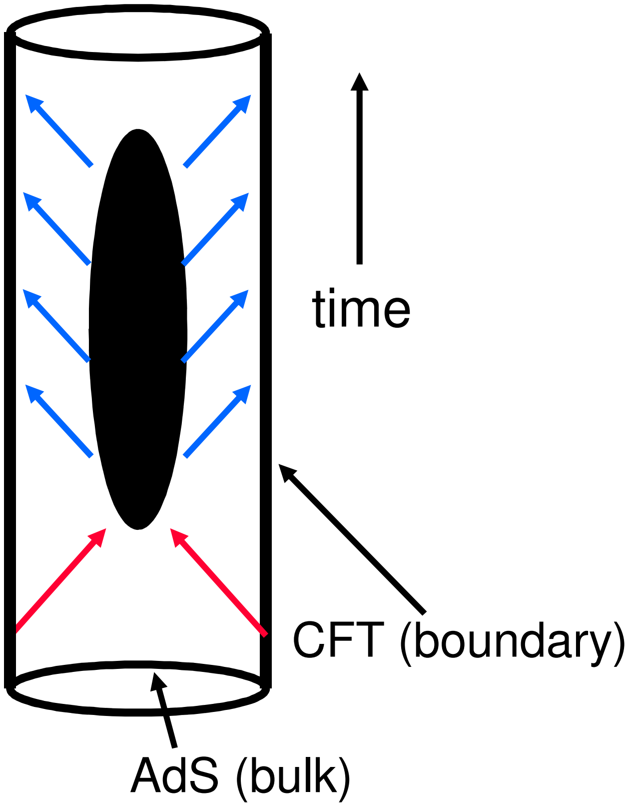
~ 1 millisecond for a solar mass black hole

But not quite quickly enough for Alice to verify that the quantum information is in two places at once (both inside and outside the black hole). [Hayden-Preskill 2007, Sekino-Susskind 2008].

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*).

A concrete realization of the “holographic principle” (*’t Hooft, Susskind*).



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!

Black hole complementarity challenged

Three reasonable beliefs, not all true!

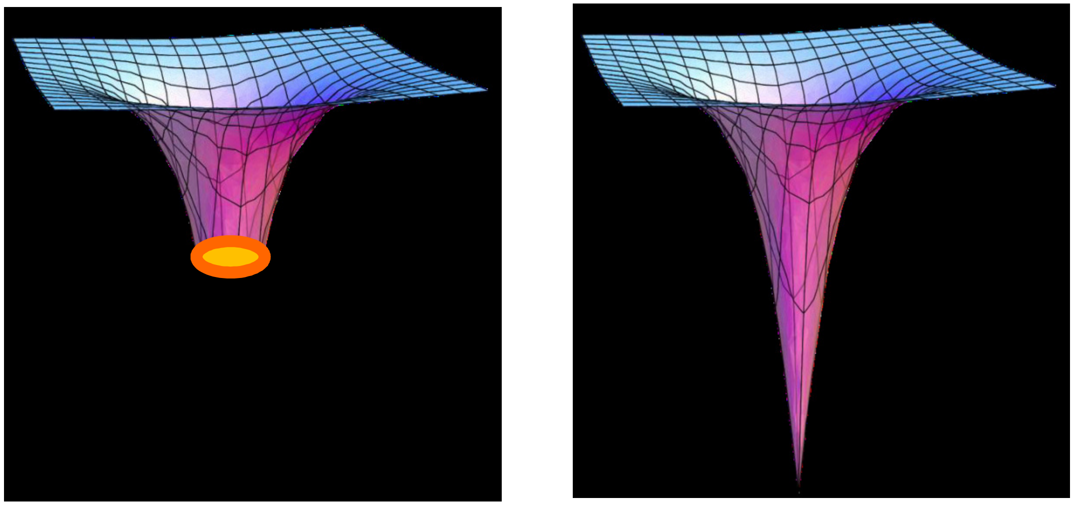
[Almheiri, Marolf, Polchinski, Sully (AMPS) 2012]

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

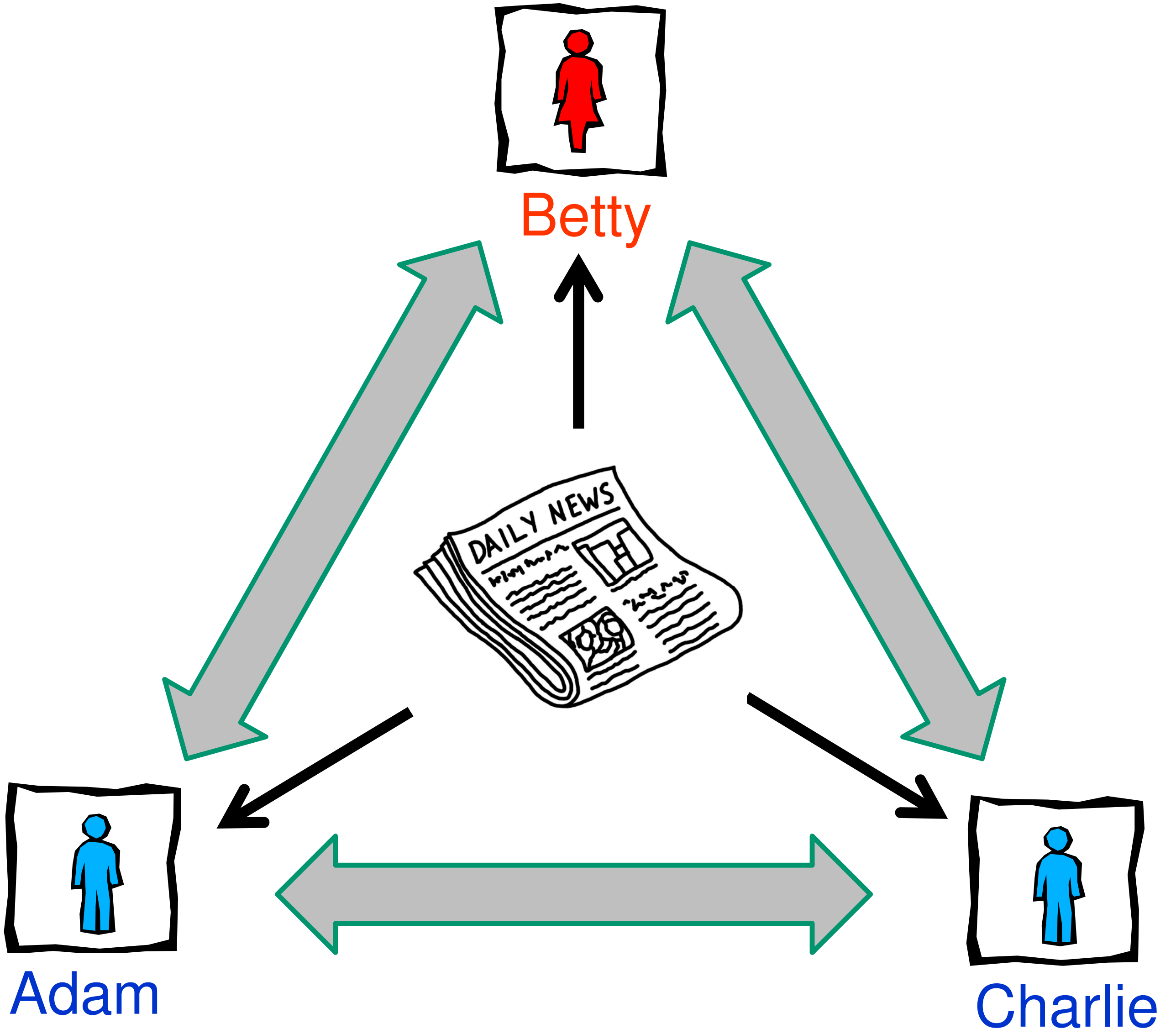
(2) An observer who falls through the black hole horizon sees nothing unusual (at least for a while).

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

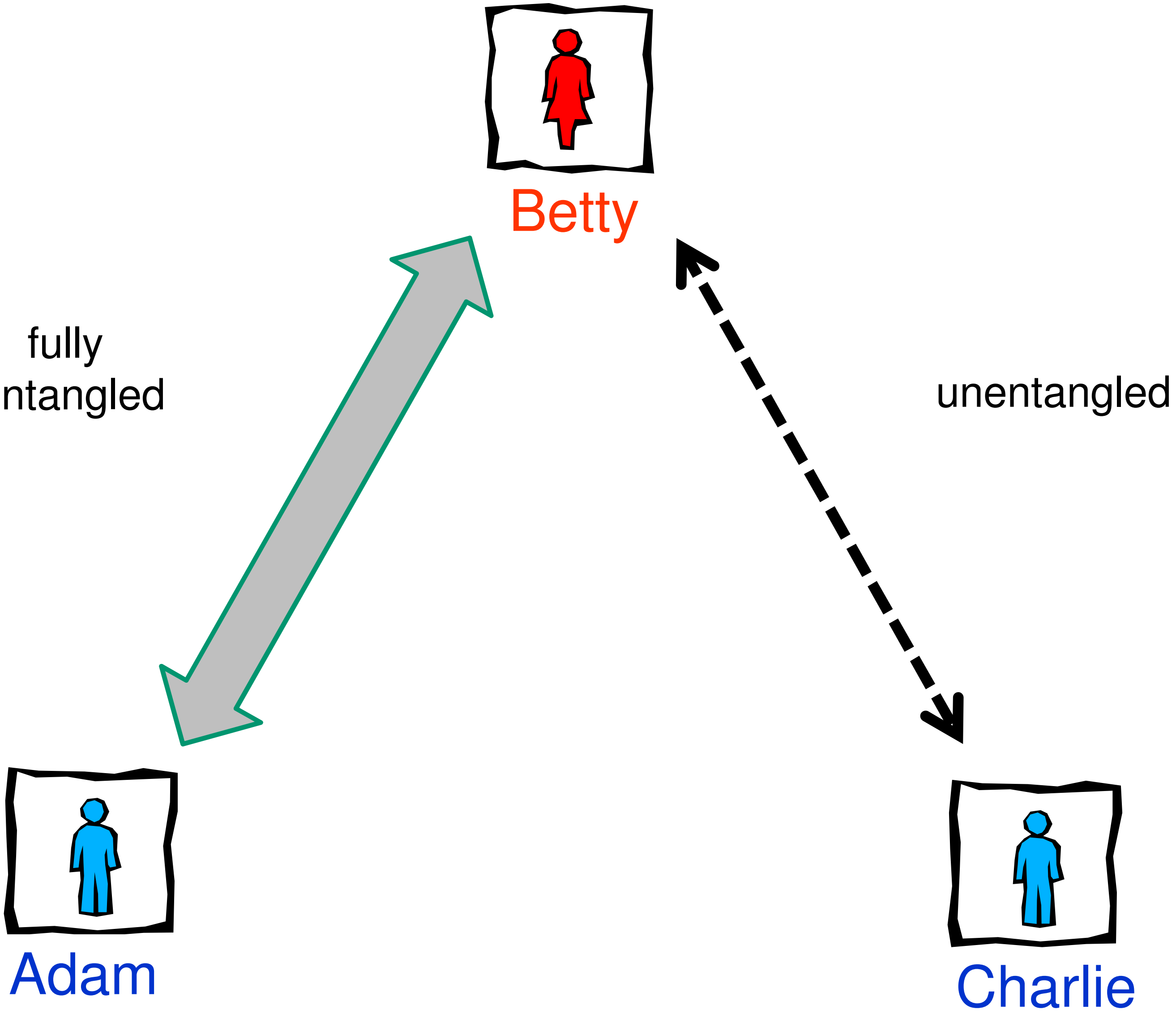
"Conservative" resolution:
A "firewall" at the horizon,
rather than (2).



Classical correlations are polyamorous



Quantum correlations are *monogamous*



Betty

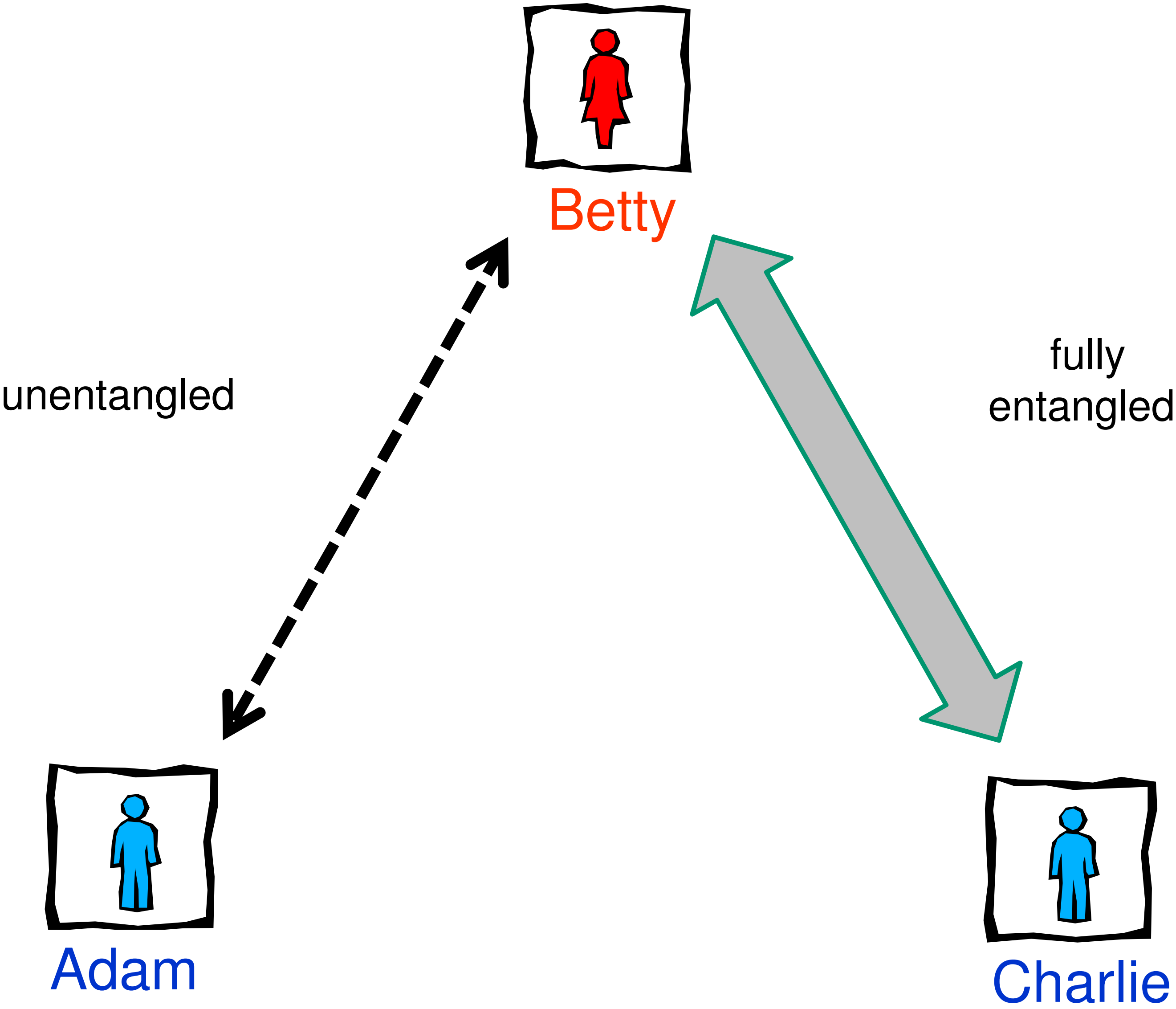
fully
entangled

unentangled

Adam

Charlie

Quantum correlations are *monogamous*



Betty

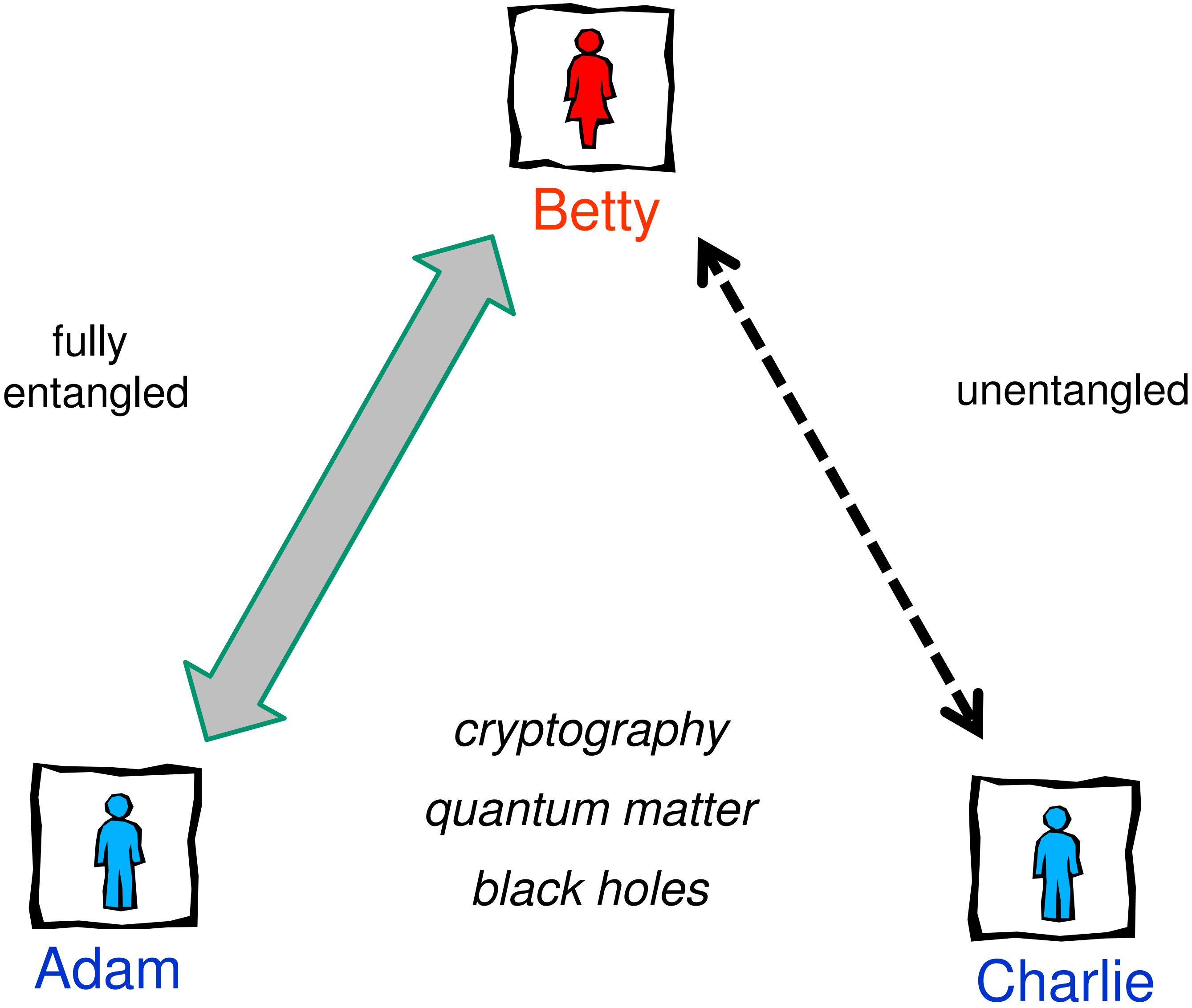
unentangled

fully
entangled

Adam

Charlie

Monogamy is *frustrating*!



Betty

fully
entangled

unentangled

Adam

Charlie

cryptography

quantum matter

black holes

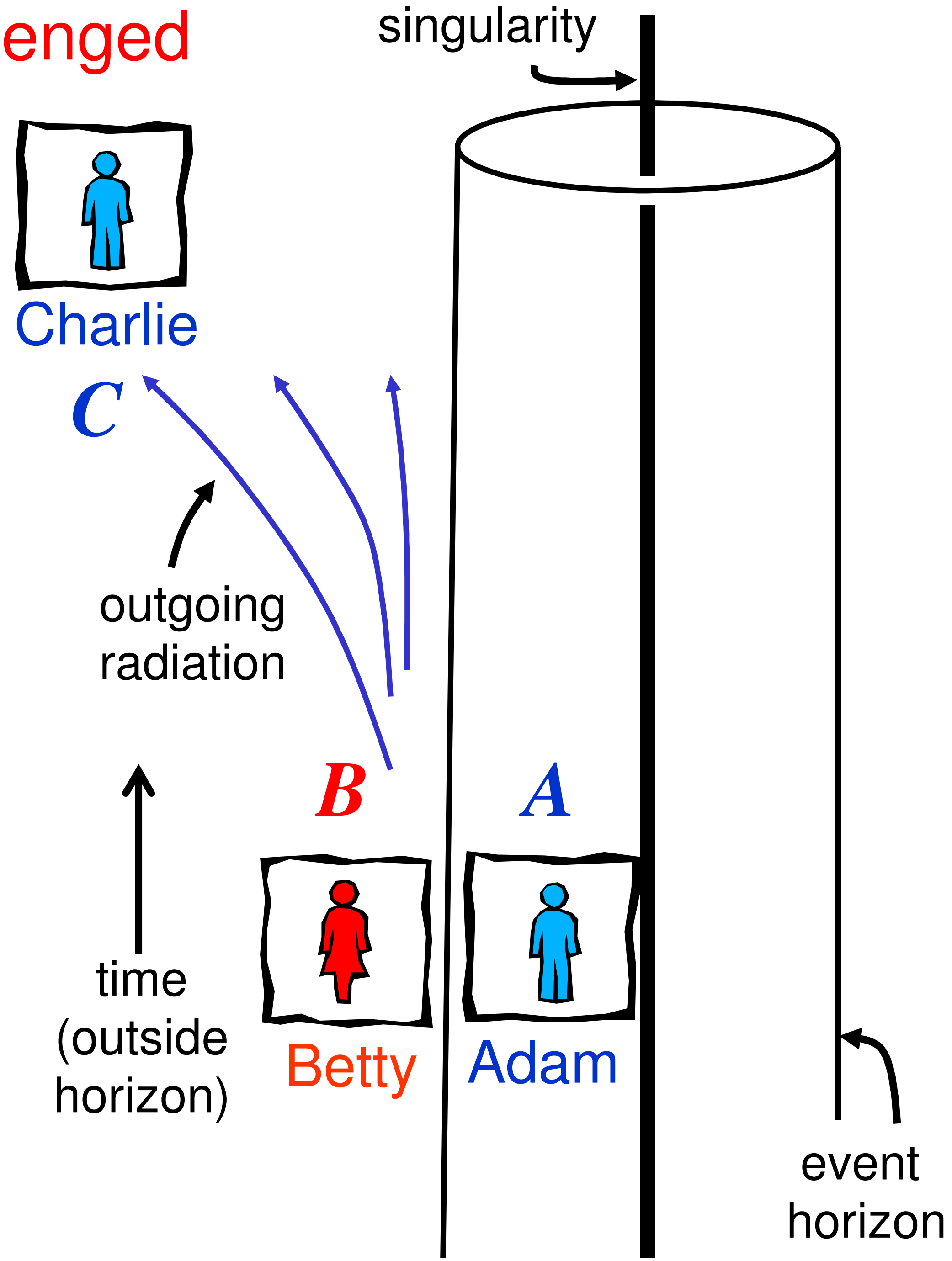
Complementarity Challenged

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

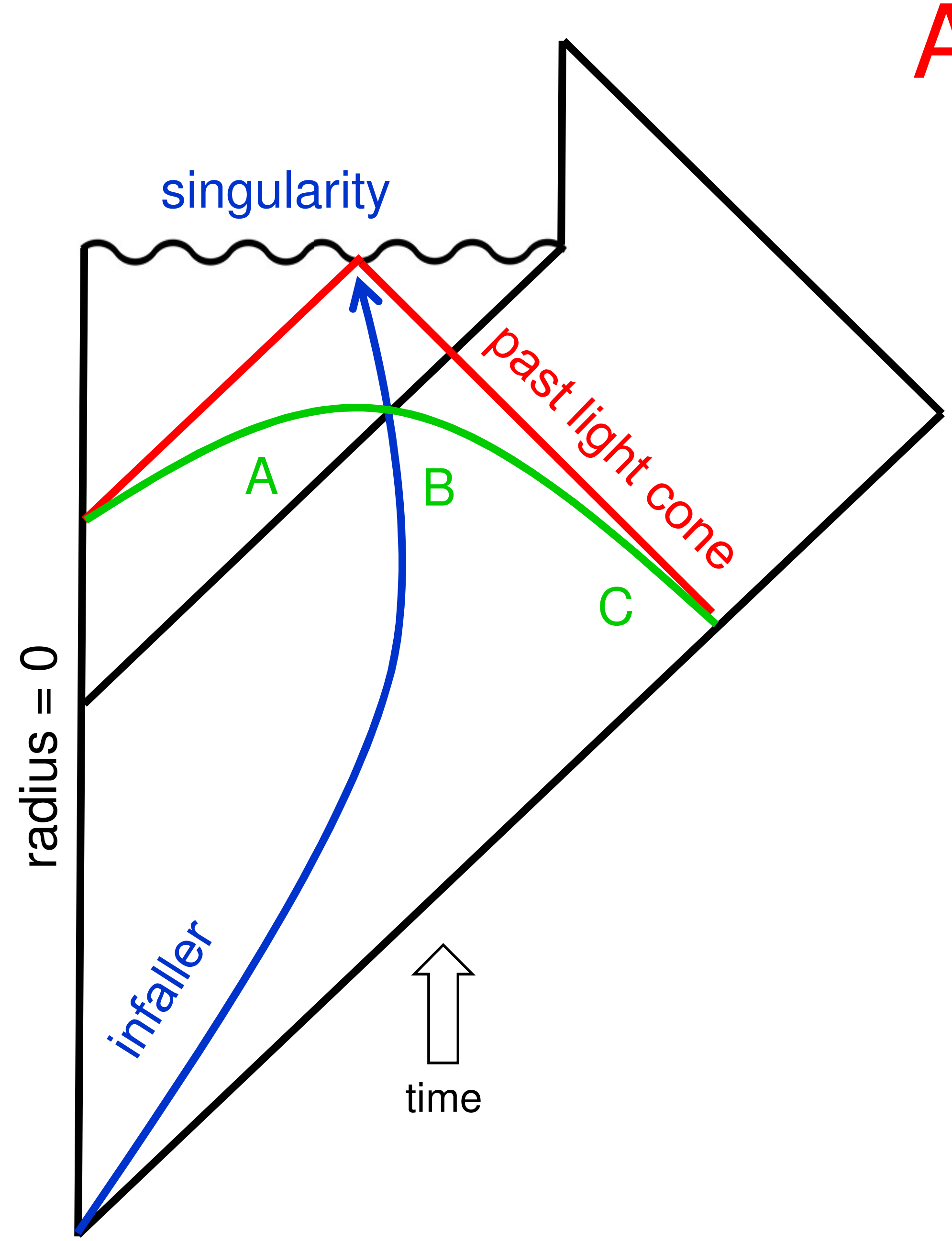
(2) If freely falling observer sees vacuum at the horizon, then the recently emitted radiation (B) is highly entangled with modes behind the horizon (A).

(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?

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.

Bulk/boundary duality: an *exact* correspondence

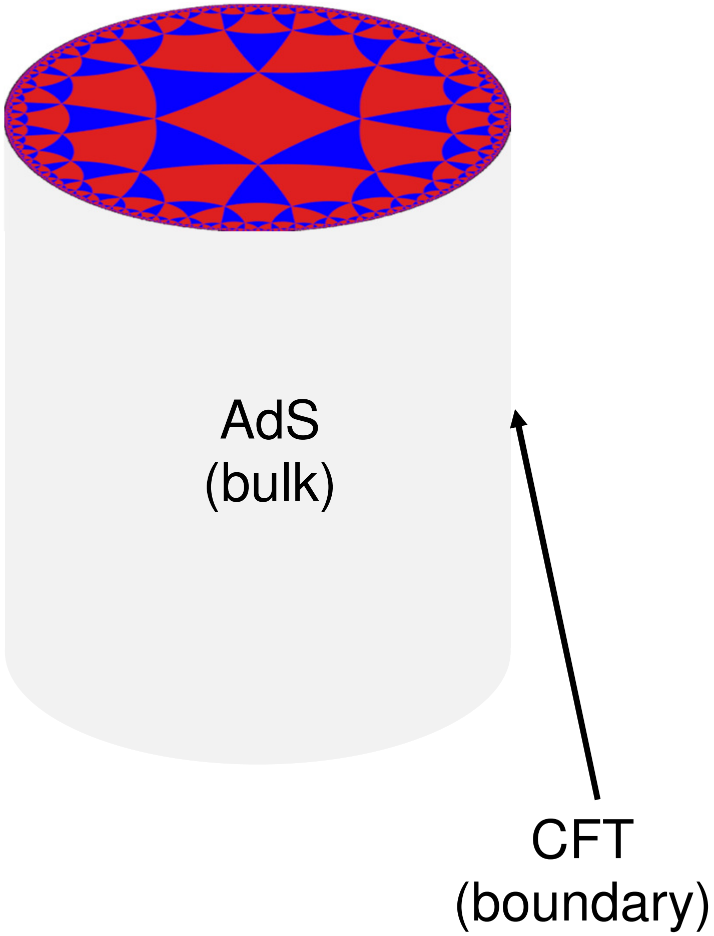
-- Weakly-coupled gravity in the bulk ↔ strongly-coupled conformal field theory on boundary.

-- Complex dictionary maps bulk operators to boundary operators.

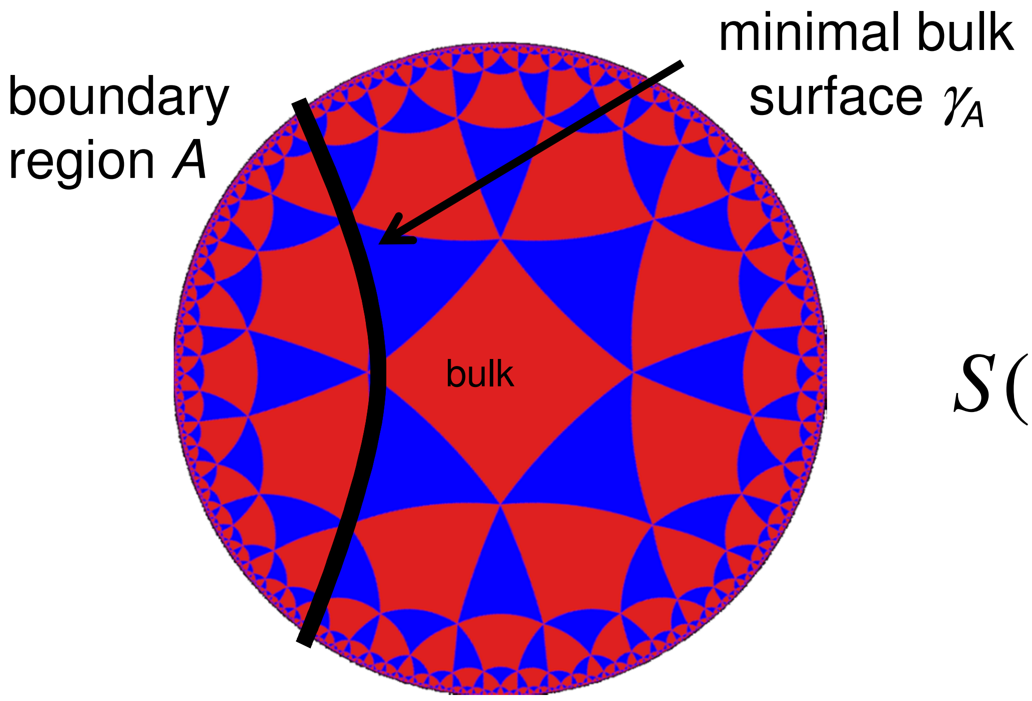
-- Emergent radial dimension can be regarded as an RG scale.

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

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



Holographic entanglement entropy



boundary region *A*

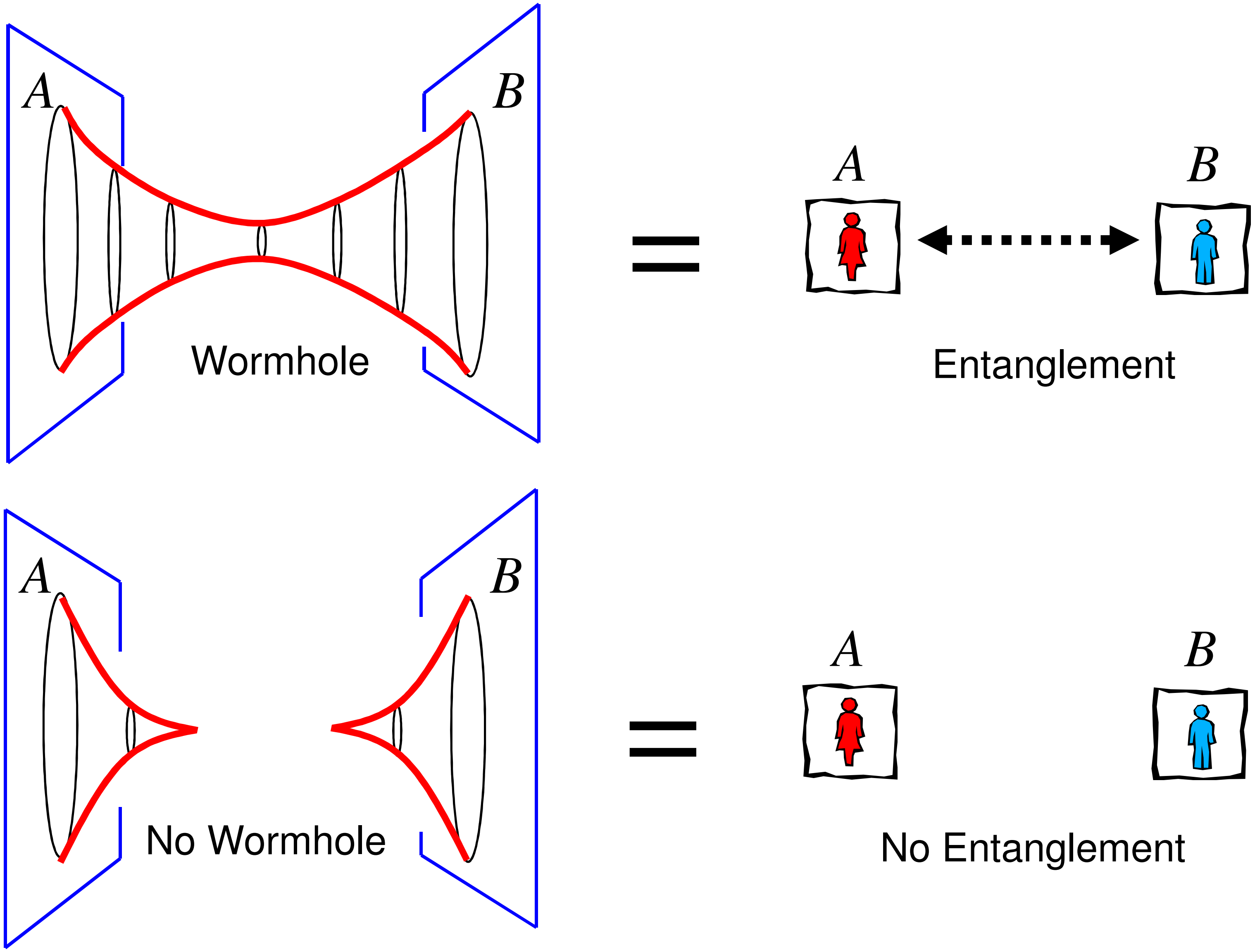
minimal bulk surface γ_A

bulk

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

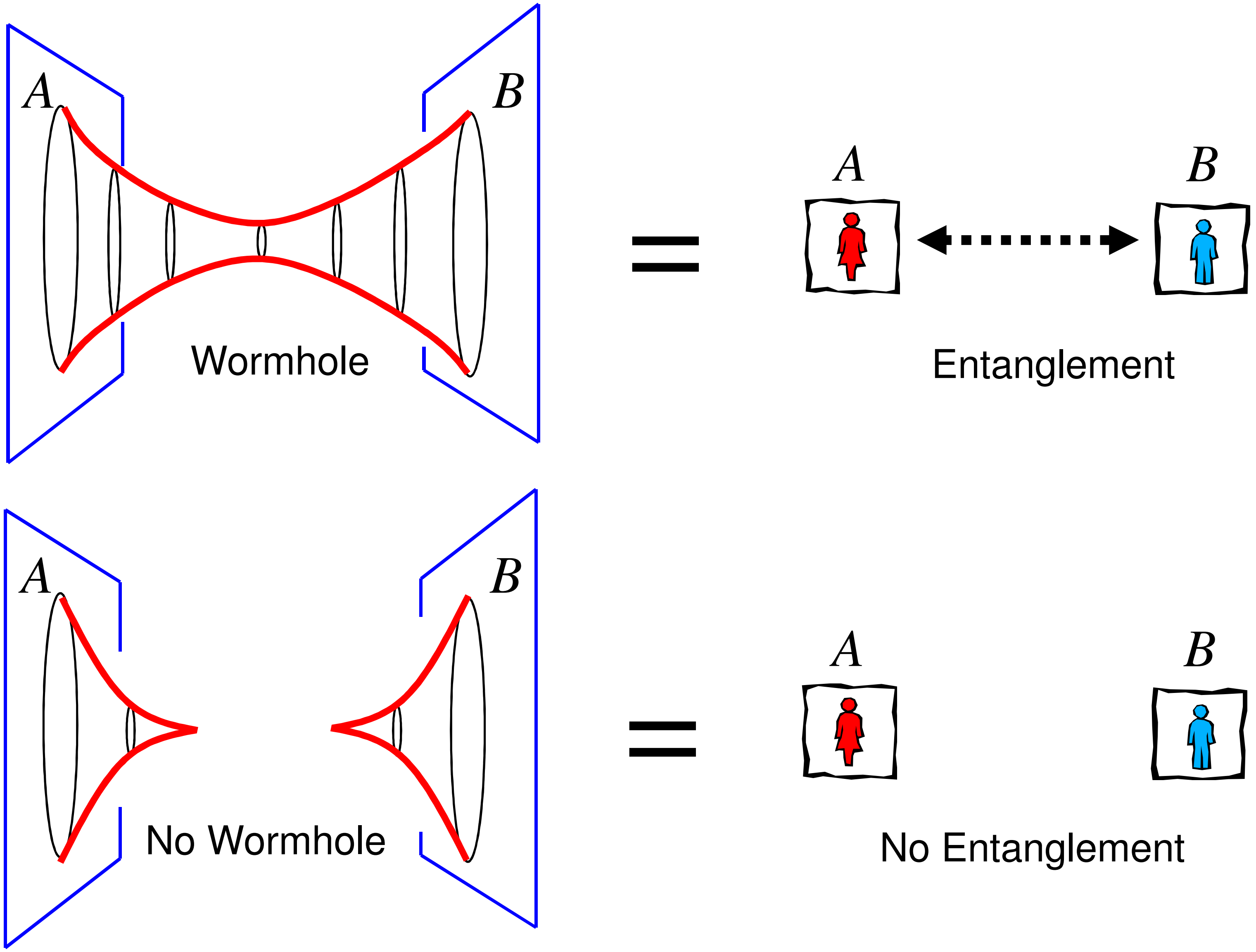
To compute entropy of region *A* in the boundary field theory, find minimal area of the bulk surface γ_A with the same boundary (*Ryu-Takayanagi).*

Building spacetime from quantum entanglement

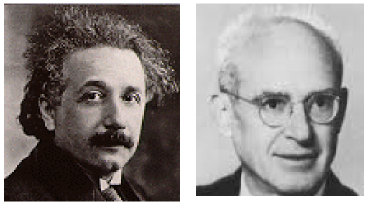


[Maldacena 2003, Van Raamsdonk 2010, Maldacena-Susskind 2013]

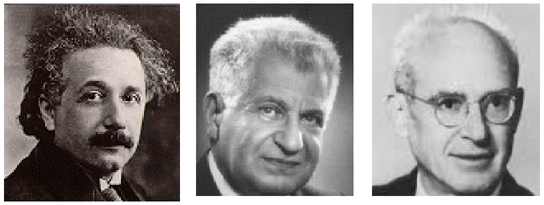
ER = EPR

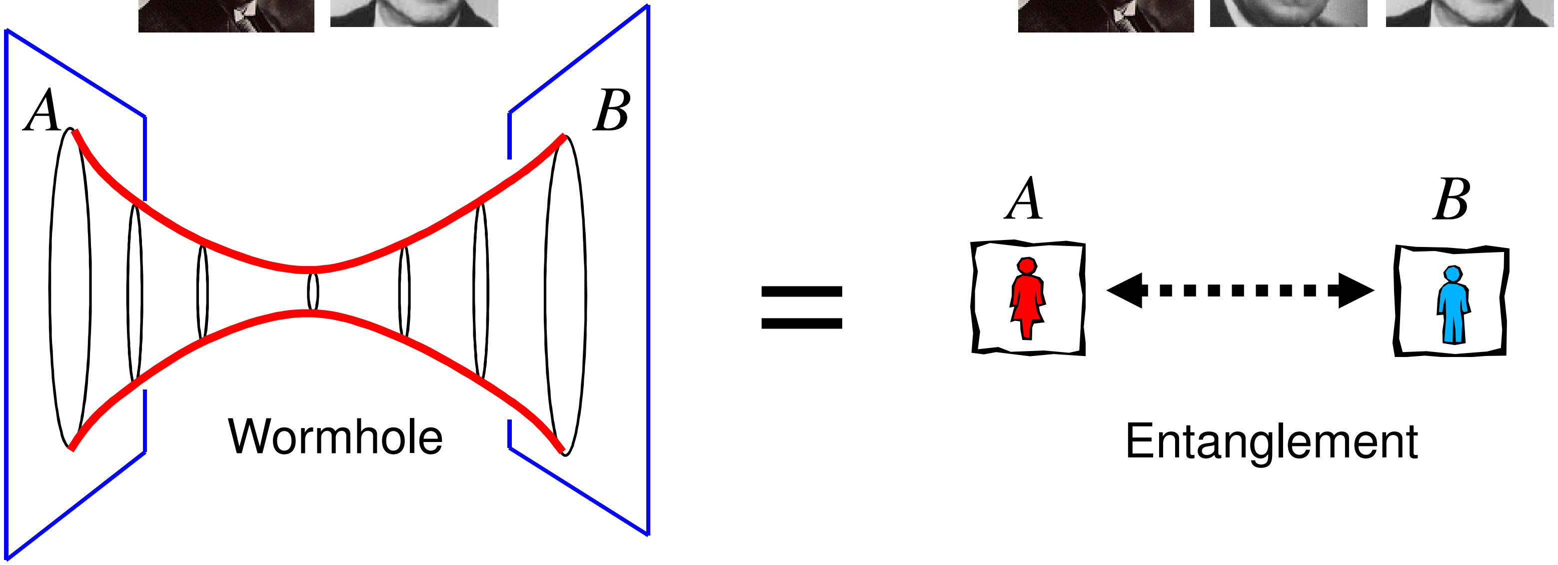


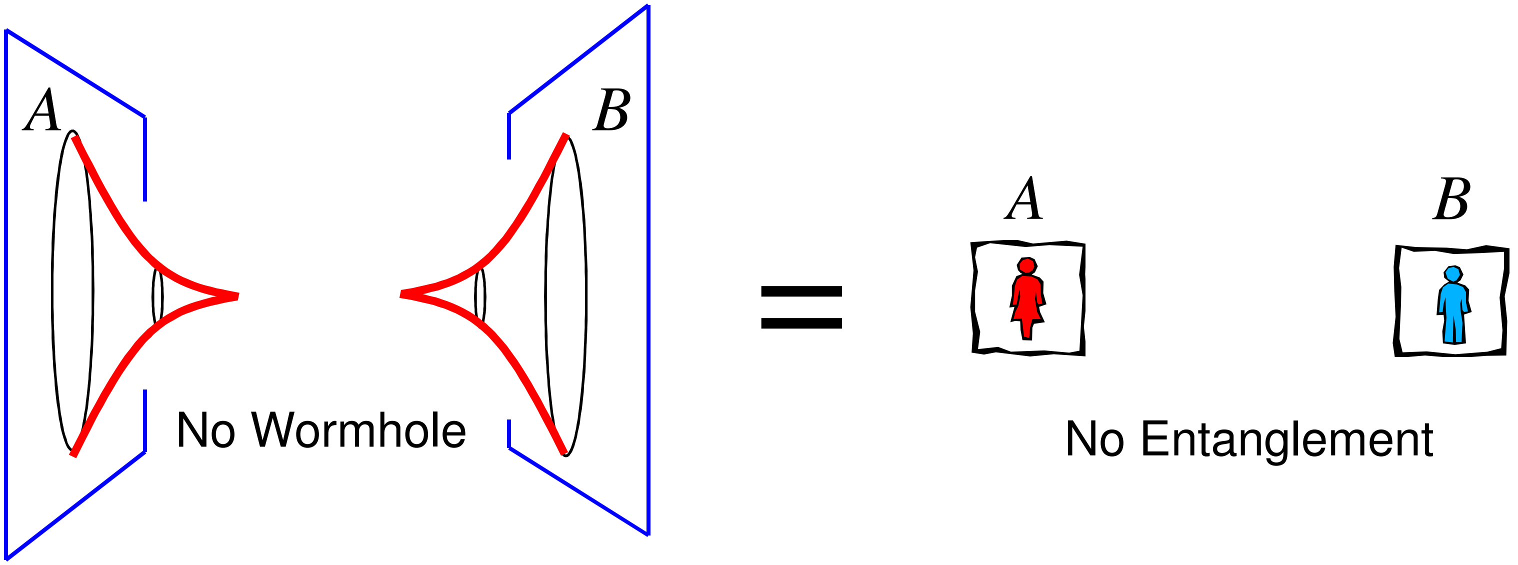
[Maldacena 2003, Van Raamsdonk 2010, Maldacena-Susskind 2013]



ER = EPR

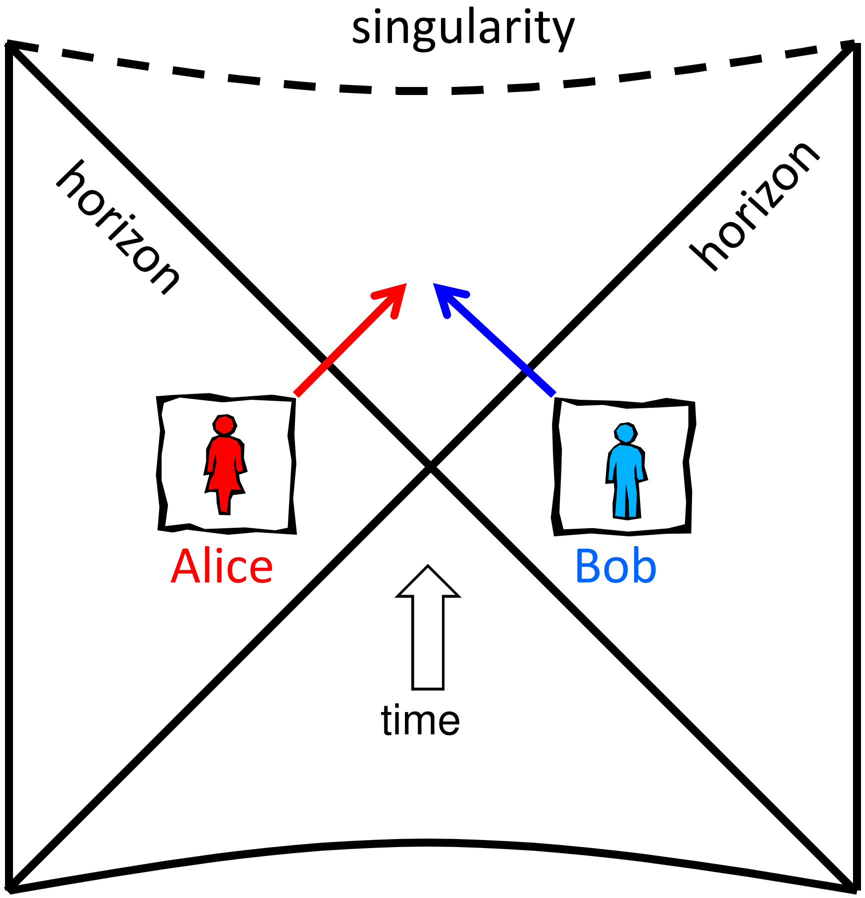






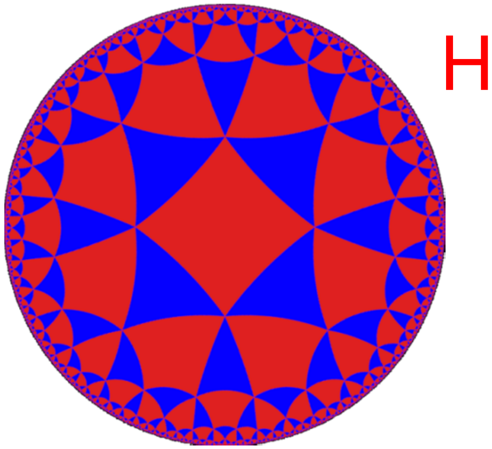
[Maldacena 2003, Van Raamsdonk 2010, Maldacena-Susskind 2013]

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.

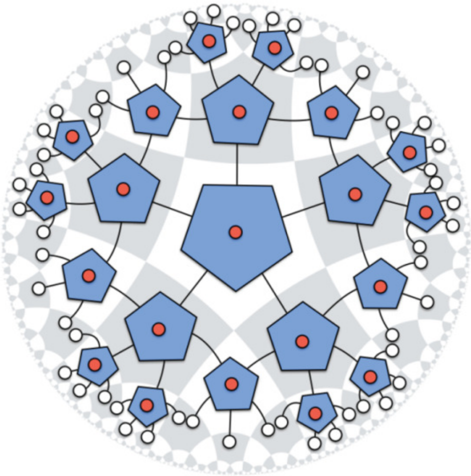
Two amazing ideas:



Holographic correspondence

Quantum error correction

Are they closely related?



-- 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?

Pastawski

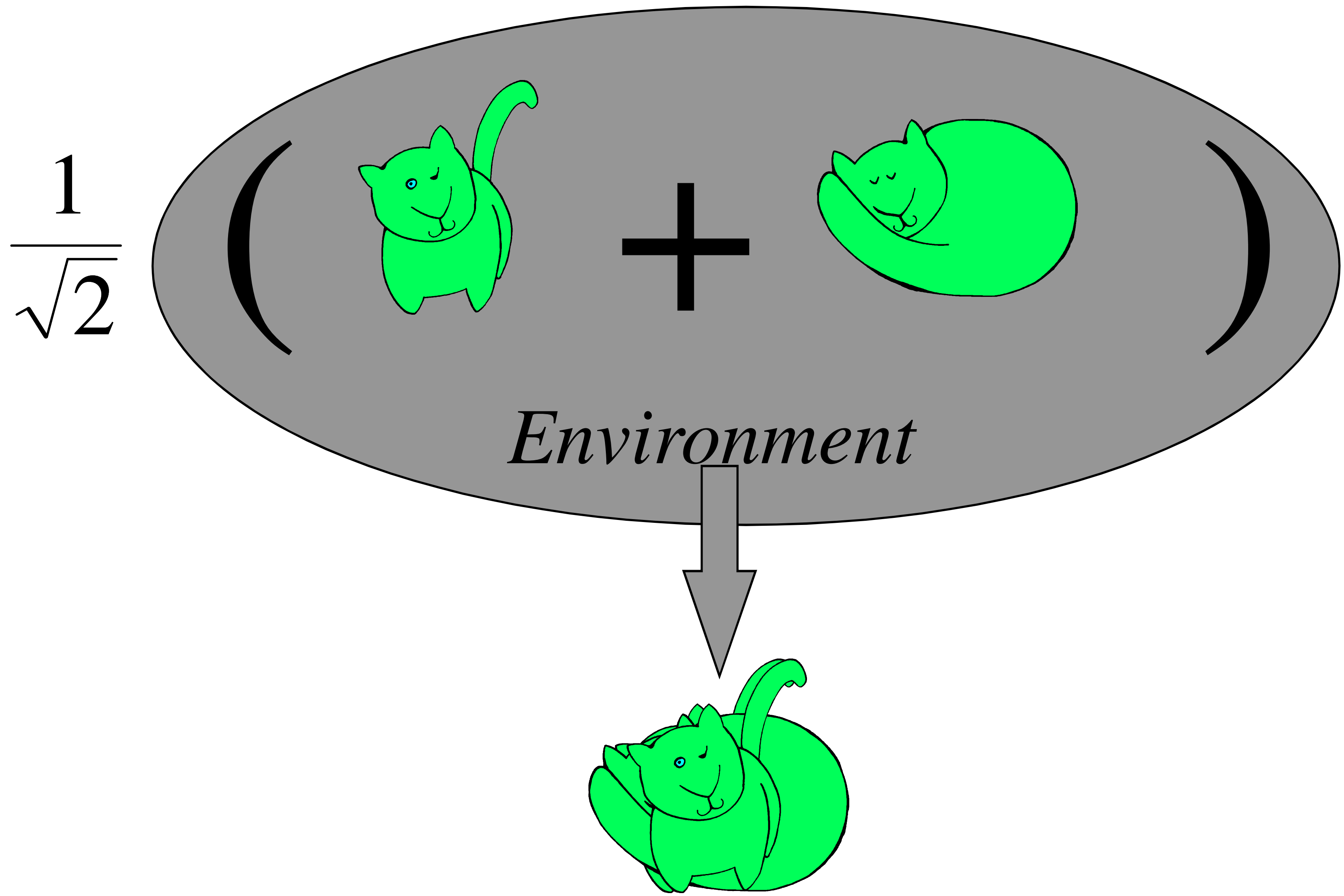
Yoshida

Harlow

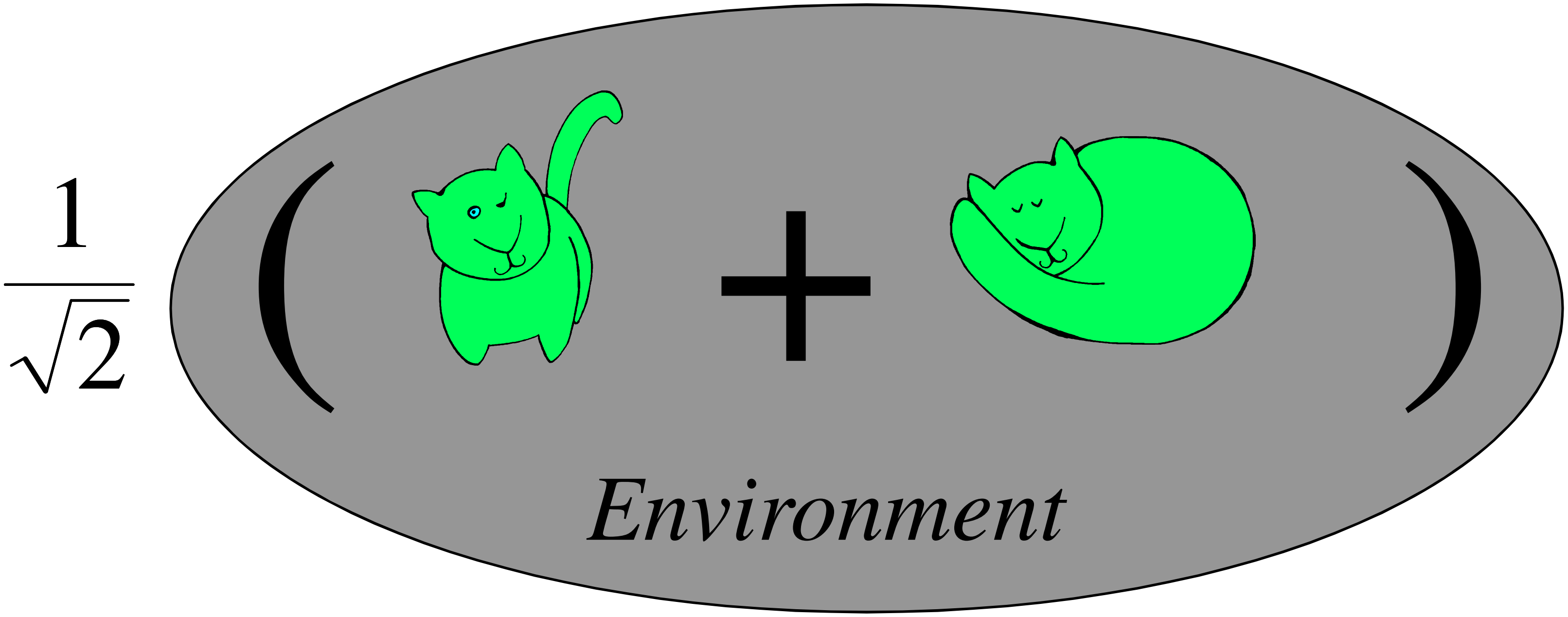
Holographic Quantum Error-Correcting Codes, Journal of High Energy Physics 6, 149 (2015).

Building on Almheiri, Dong, Harlow (2014).

Decoherence



Decoherence



Decoherence explains why quantum phenomena, though observable in the microscopic systems studied in the physics lab, are not manifest in the macroscopic physical systems that we encounter in our ordinary experience.

Quantum Computer

Decoherence

Environment

ERROR!

How can we protect a quantum computer from decoherence and other sources of error?

Quantum Computer

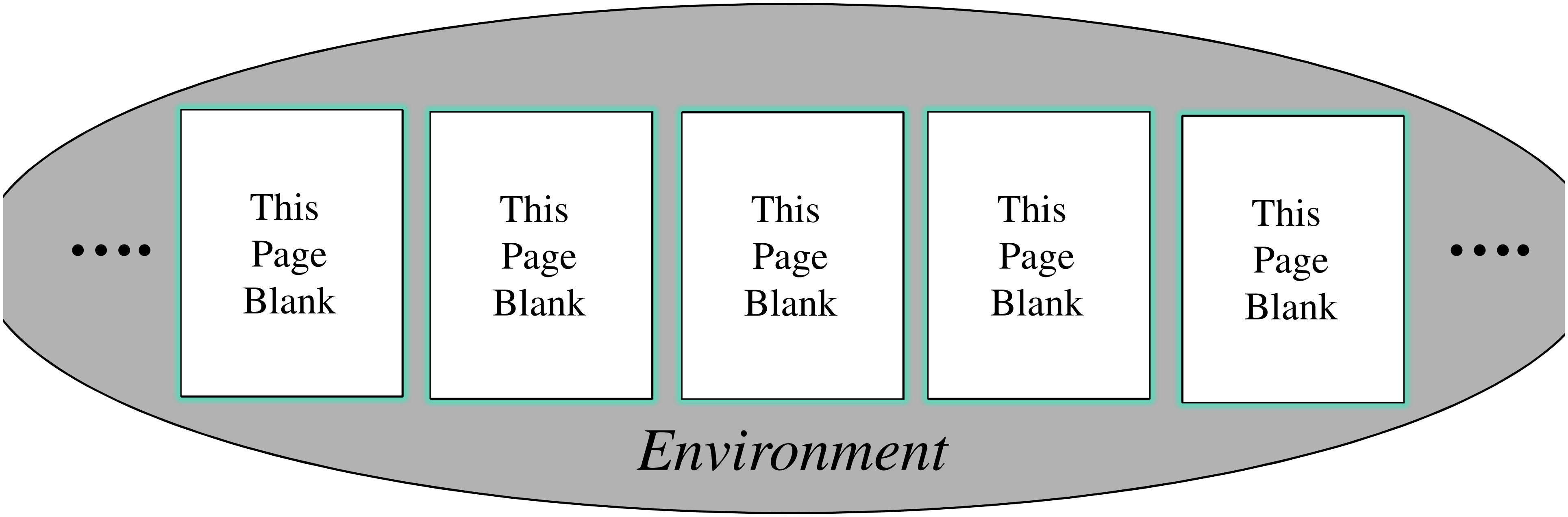
Decoherence

Environment

ERROR!

To resist decoherence, we must prevent the environment from “learning” about the state of the quantum computer during the computation.

Quantum error correction



The protected “logical” quantum information is encoded in a highly entangled state of many physical qubits.

The environment can't access this information if it interacts locally with the protected system.

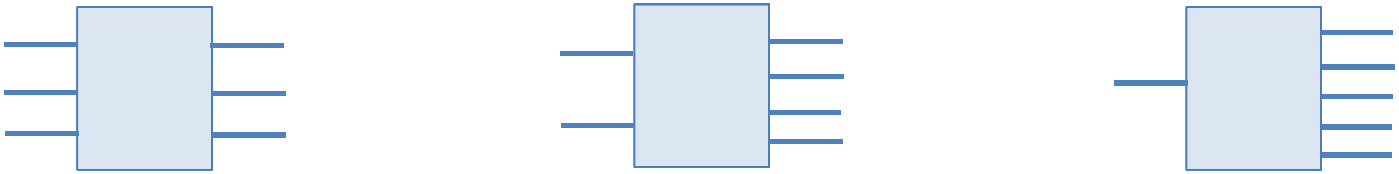
Perfect tensors

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

$$\boxed{|\psi\rangle = \sum_{a_1,a_2,\ldots,a_{2n}} T_{a_1a_2\ldots a_{2n}} |a_1a_2\ldots a_{2n}\rangle}$$

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

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



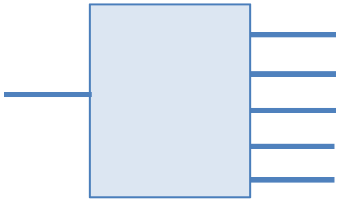
$$\sum_{a_1,\ldots a_6} T_{a_1\ldots a_6} |a_4a_5a_6\rangle\langle a_1a_2a_3| \qquad \sum_{a_1,\ldots a_6} T_{a_1\ldots a_6} |a_3a_4a_5a_6\rangle\langle a_1a_2| \qquad \sum_{a_1,\ldots a_6} T_{a_1\ldots a_6} |a_2a_3a_4a_5a_6\rangle\langle a_1|$$

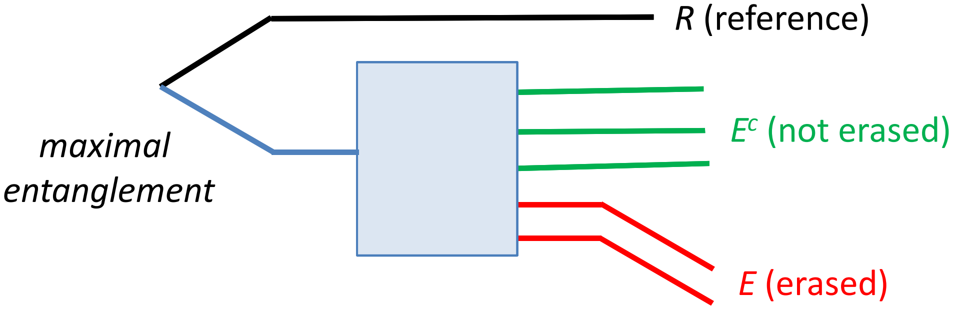
These are the isometric encoding maps (up to normalization) of quantum error-correcting codes. The 2→4 map encodes two qubits in a block of 4, and corrects 1 erasure. The 1→5 map encodes one qubit in a block of 5, and corrects 2 erasures.

Erasure correction

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

$$\sum_{a_1,\ldots a_6} T_{a_1\ldots a_6} \,|\, a_2a_3a_4a_5a_6\rangle\langle a_1 \,|$$





R (reference)

maximal entanglement

EE^c (not erased)

E (erased)

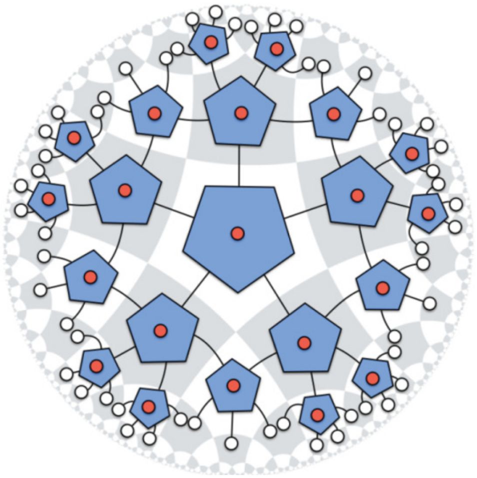
We say qubits are erased if they are removed from the code block. But we know *which* qubits were erased and may use that information in recovering from the error.

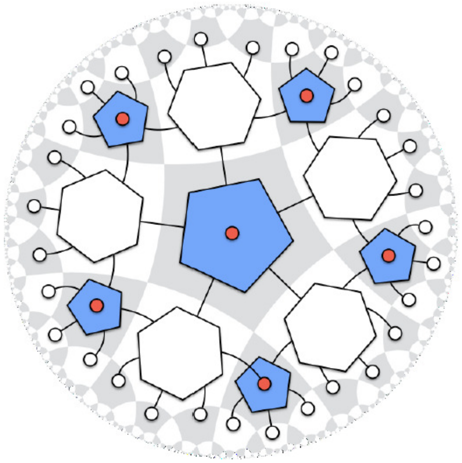
Consider maximally entangling a *reference qubit R* with the encoded qubit. Suppose two physical qubits (the subsystem *E*) are removed, while their complement E^c is retained.

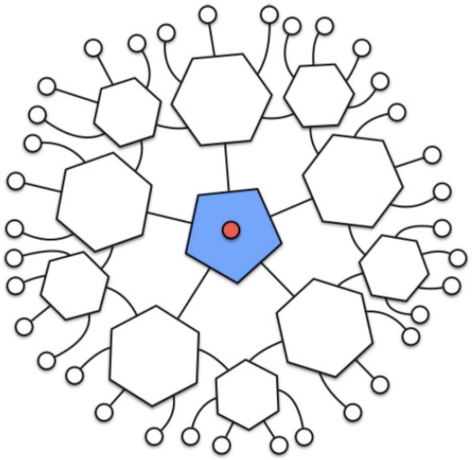
Because the tensor *T* is perfect, *RE* is maximally entangled with E^c, hence *R* is maximally entangled with a subsystem of E^c. Thus the logical qubit can be decoded by applying a unitary decoding map to E^c alone; *E* is not needed.

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

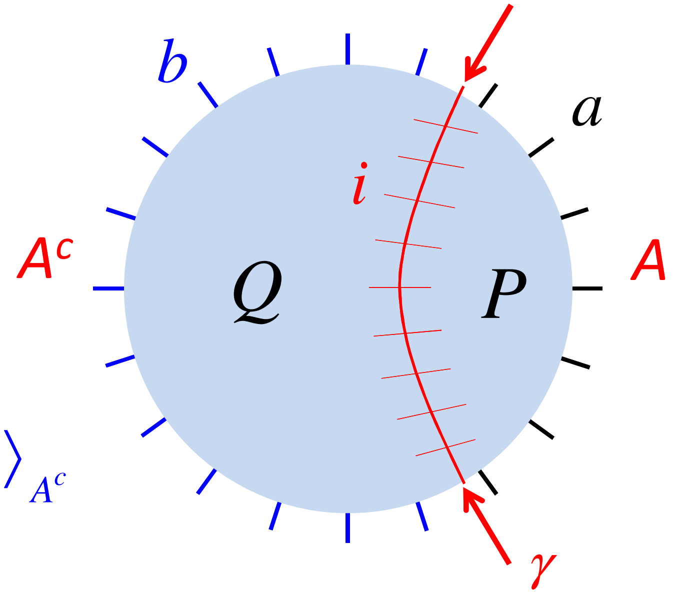

one encoded qubit

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.

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*).

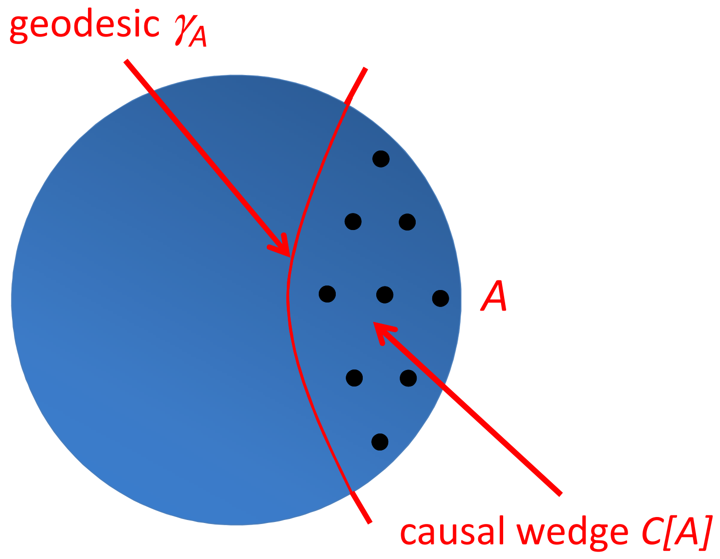
If each internal index takes v values, there are $v^{|\gamma|}$ terms in the sum over i. and the vectors $\{\,|\,P\,\rangle_i\,\}$, $\{\,|\,Q\,\rangle_i\,\}$ are orthonormal. Therefore

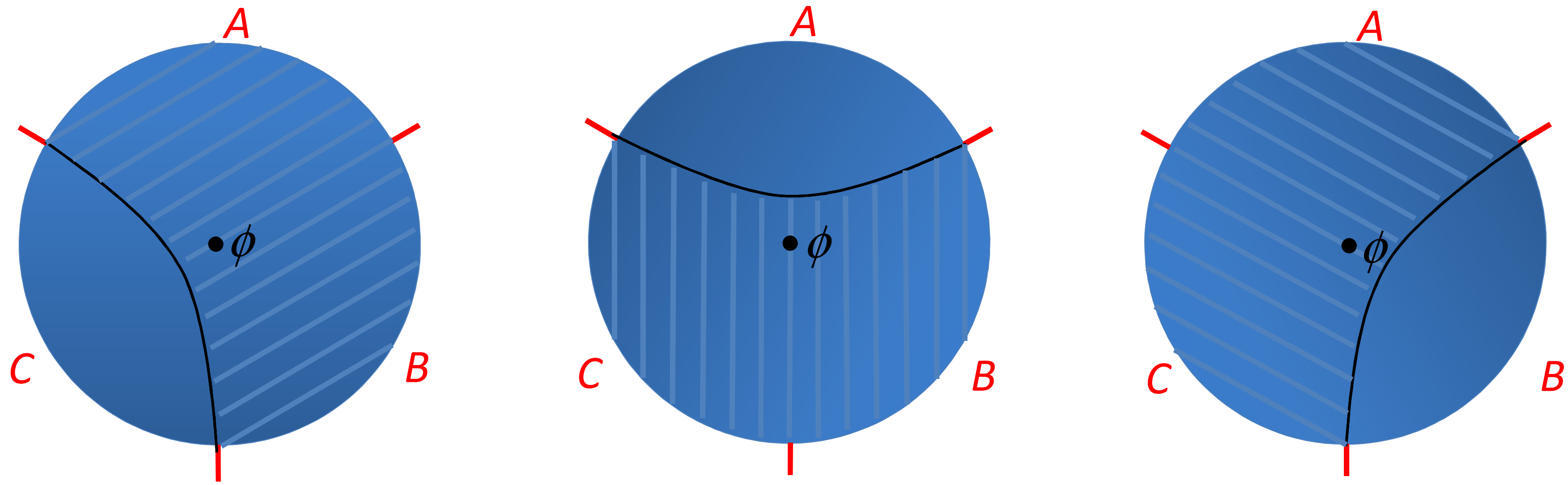
$$S(A) = |\,\gamma_A\,|\log v$$

Protection against erasure

For a connected region *A* on the boundary there is a corresponding *geodesic* γ_A and *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.





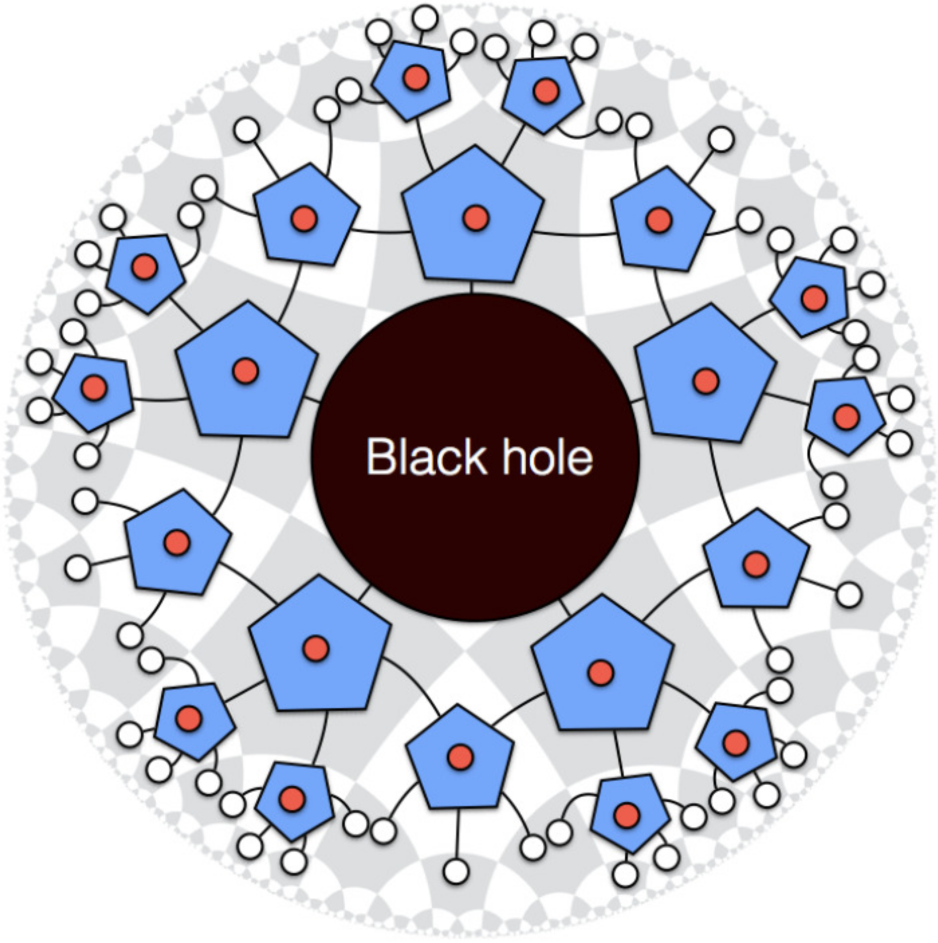
Holographic black holes

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

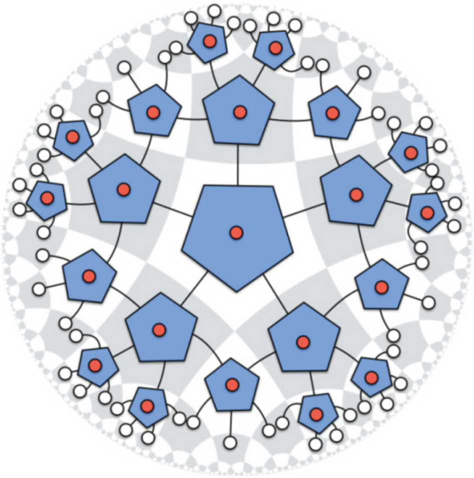
-- Bulk local operators acting outside the black hole can be reconstructed on the boundary.

-- 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.

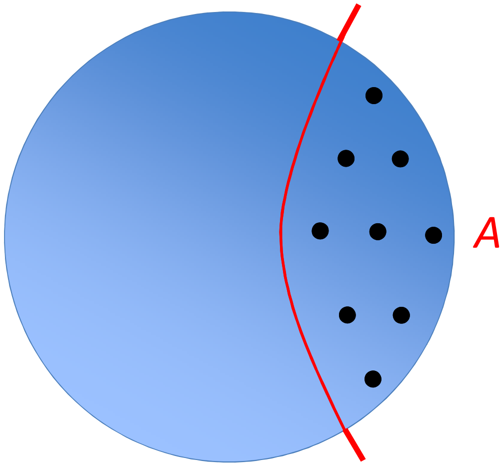


Holographic quantum codes



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

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



-- But … so far these models are not dynamical, and do not address bulk locality at sub-AdS distance scales.

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.

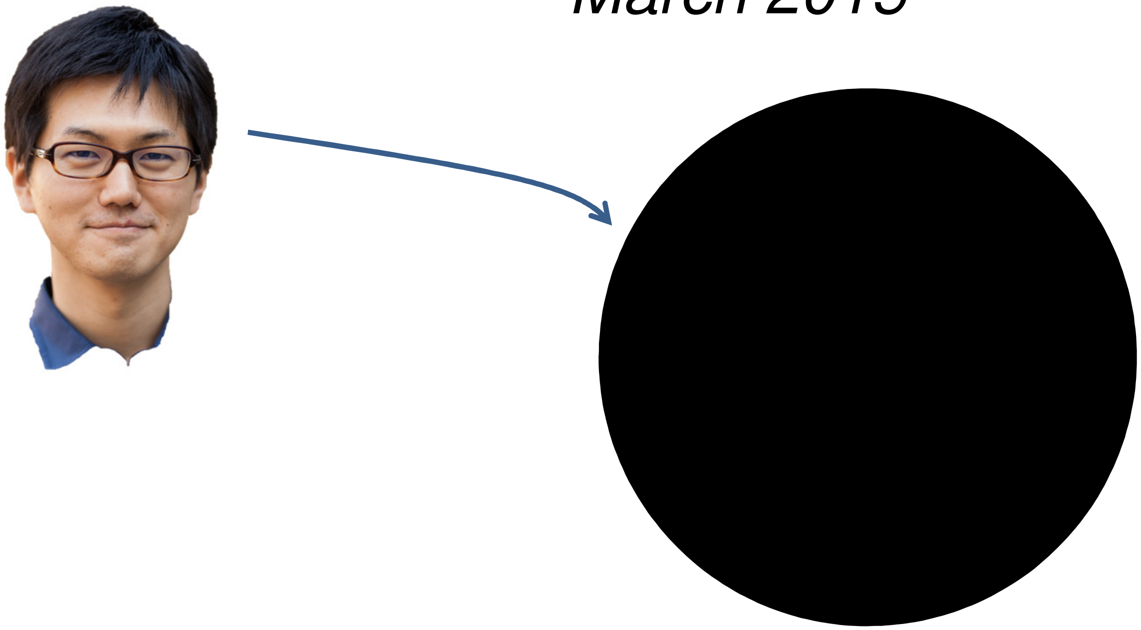
Witten: I hope so. I'm afraid it's hard to work on, so in fact I've worked with more familiar kinds of questions.

Kavli IPMU News
December 2014

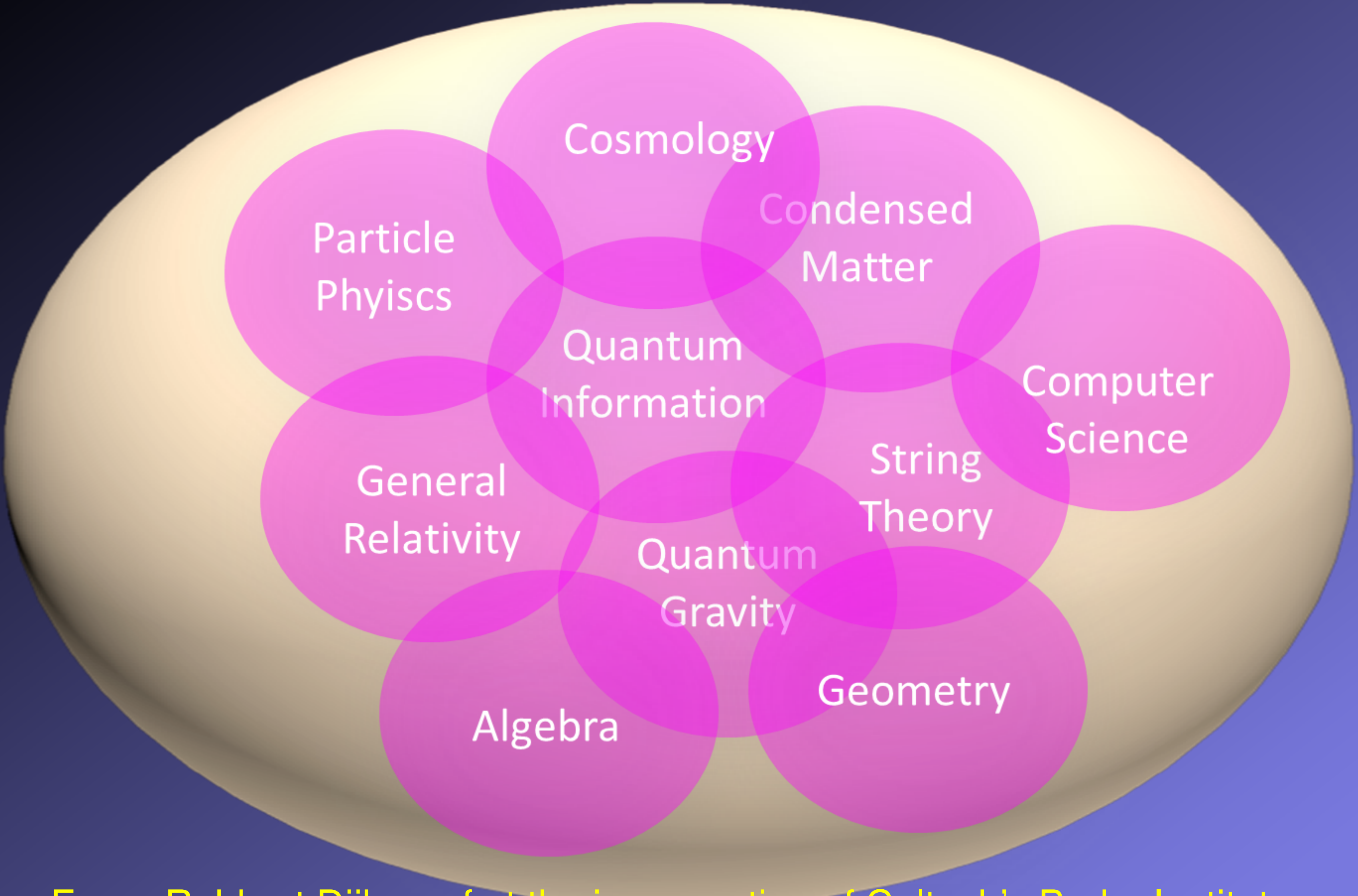
Notices of AMS
May 2015

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

Beni Yoshida
QuantumFrontiers.com
March 2015



Unity of Theoretical Physics



Cosmology

Particle Phyiscs

Condensed Matter

Quantum Information

Computer Science

String Theory

General Relativity

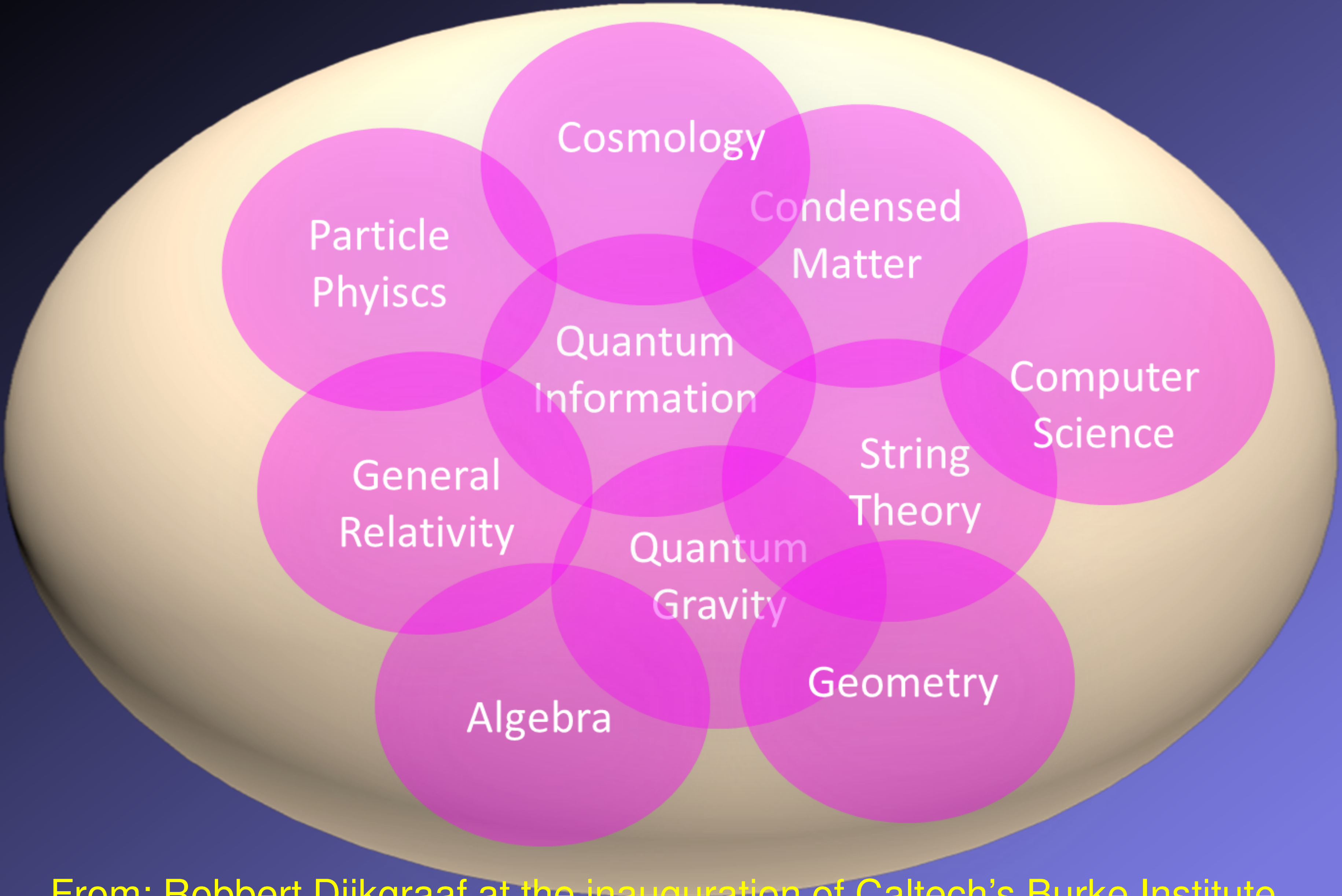
Quantum Gravity

Geometry

Algebra

From: Robbert Dijkgraaf at the inauguration of Caltech’s Burke Institute.

Unity of ~~Theoretical~~ Physics



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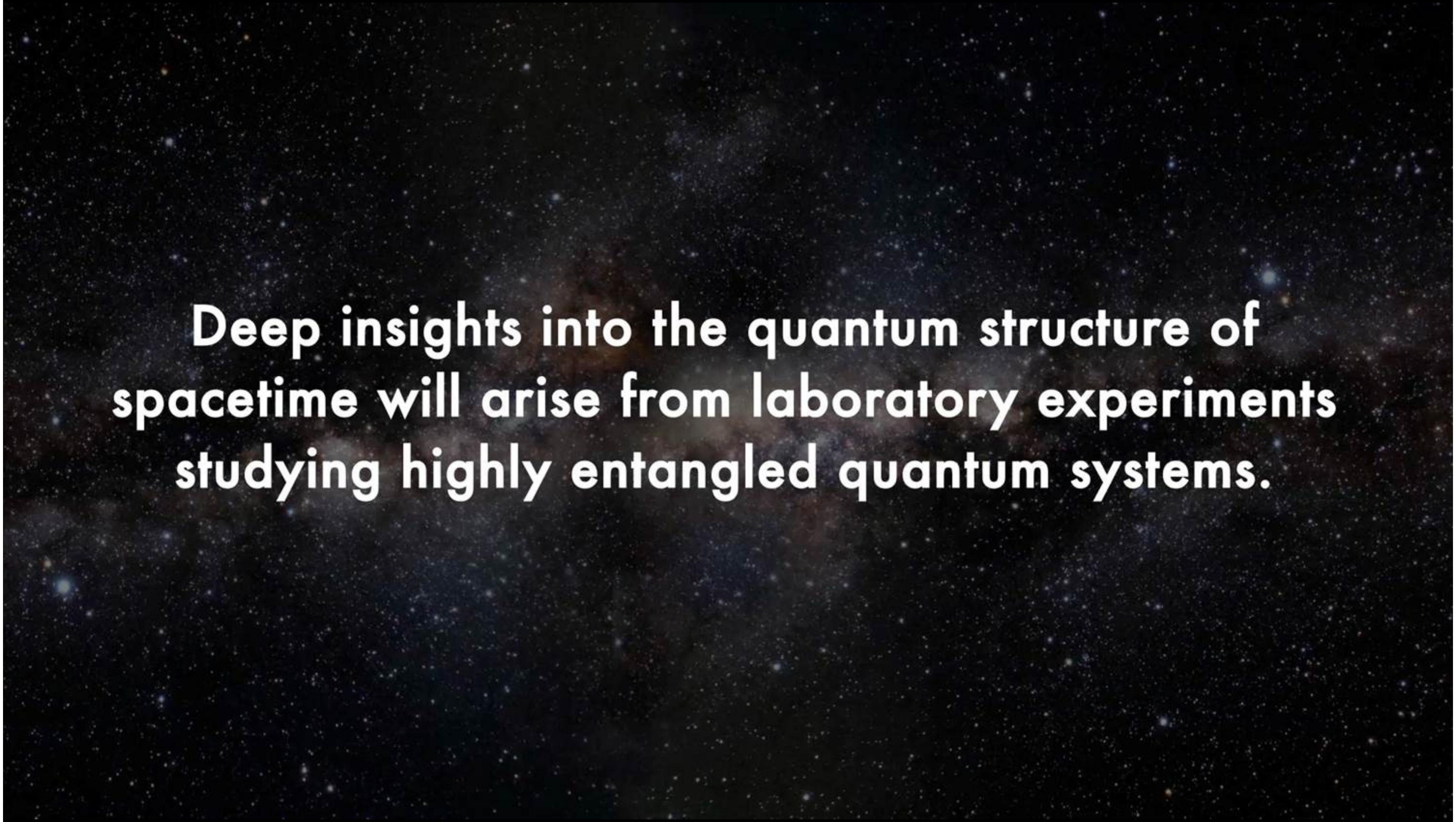

Deep insights into the quantum structure of spacetime will arise from laboratory experiments studying highly entangled quantum systems.

Firewalls: What now?

-- We’re confused because we don't have a complete theory. We thought we did, but AdS/CFT does not seem to be telling us about what is behind the horizon.

-- The system may be huge, the curvature small. Yet, if firewalls exist the quantum “corrections” are dramatic. The black hole has no inside!

-- A sharp paradox should always be welcomed; it’s resolution may lead to great advances! In this case, we hope for a deeper understanding of how spacetime emerges (or does not, in the case of the black hole interior).

-- We are trying simultaneously to determine both what the theory predicts and what the theory *is*, without guidance from experiment. Are we smart enough to figure it out? (I don’t see why not …)

-- The stakes are high, including implications for quantum cosmology.

-- Quantum informationists have much to contribute to the debate! Especially if quantum entanglement is really the foundation of spacetime geometry.