Title: Quantum Information in the 21st Century

Date: Jun 22, 2015 02:50 PM

URL: http://pirsa.org/15060046

Abstract:

Convergence!

June 22, 1975

Quantum Hardware

Schoelkopf

Martinis

Yacoby

Two-level ions in a Paul trap, coupled to “phonons.”

Superconducting circuits with Josephson junctions.

Electron spin (or charge) in quantum dots.

Cold neutral atoms in optical lattices.

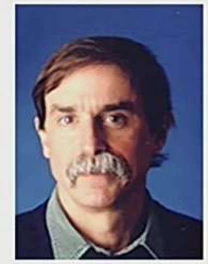
Two-level atoms in a high-finesse microcavity, strongly coupled to cavity modes of the electromagnetic field.

Linear optics with efficient single-photon sources and detectors.

Nuclear spins in semiconductors, and in liquid state NMR.

Nitrogen vacancy centers in diamond.

Anyons in topological matter , quantum wires, etc.

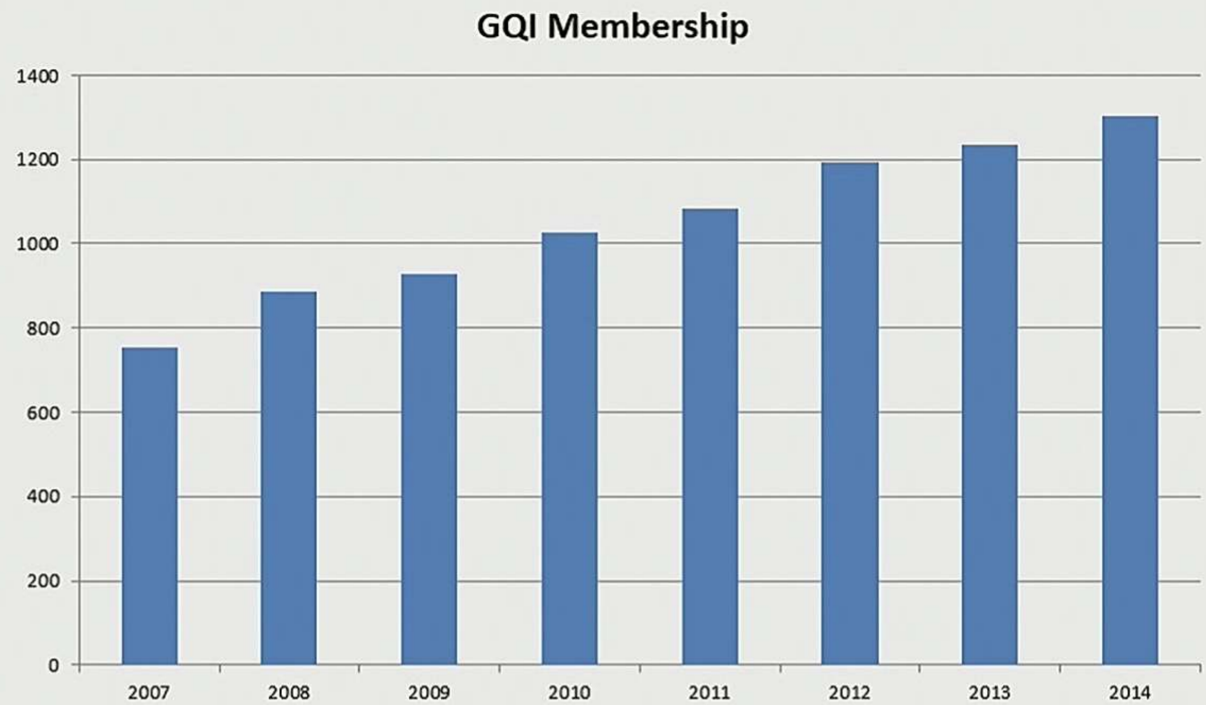


Wineland

Blatt

Marcus

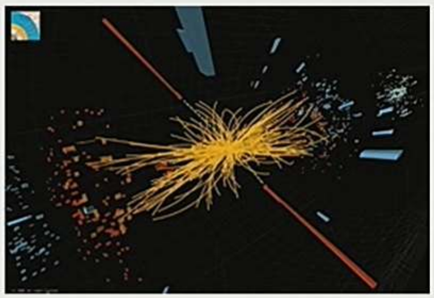
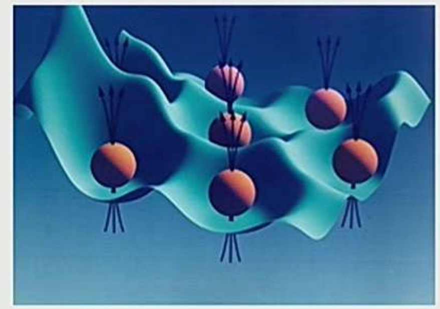
APS Topical Group on Quantum Information

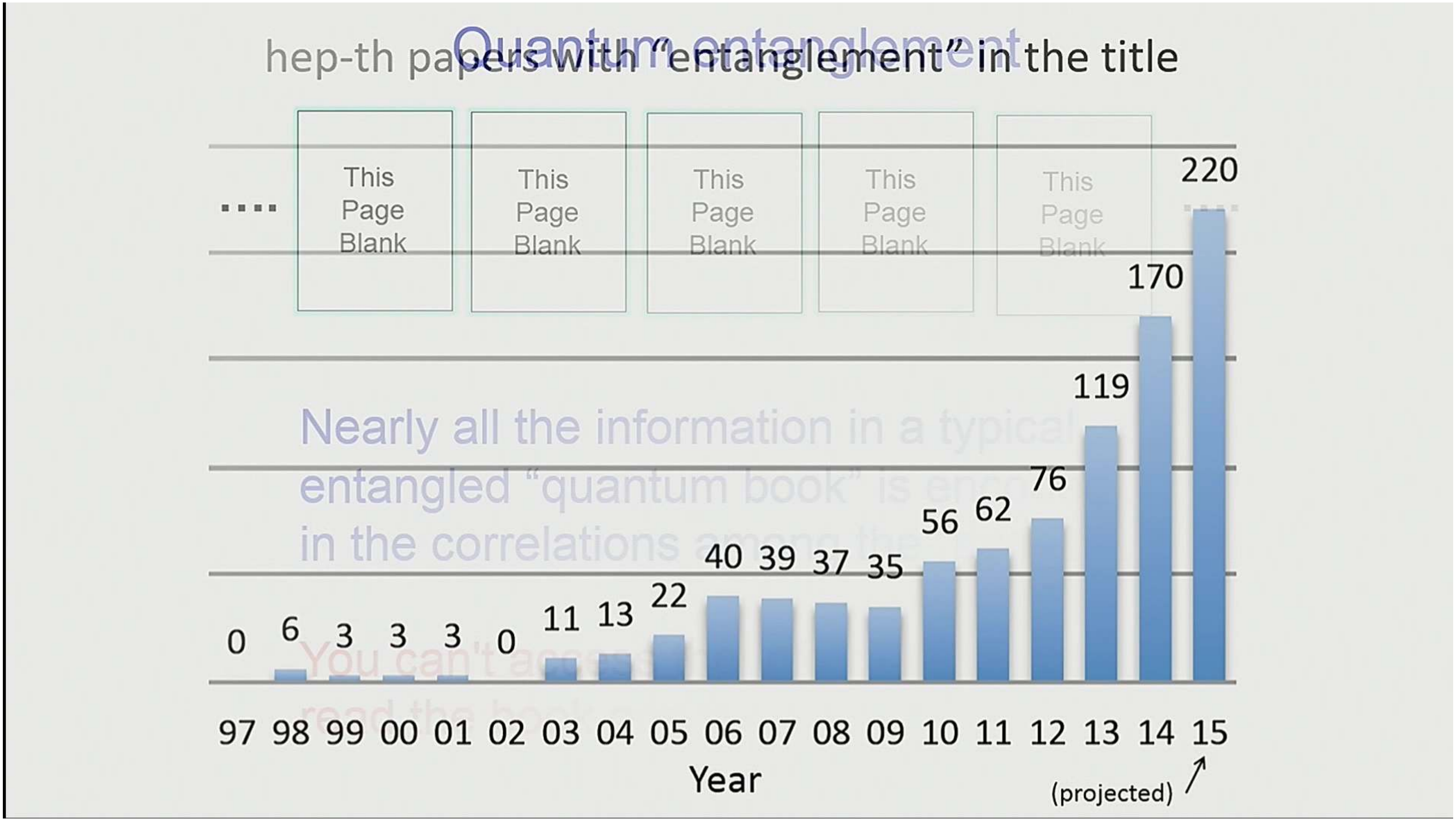


http://www.aps.org/membership/units/statistics.cfm

(Founded 2005. Membership is 57% students.)

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		Emergent geometry


hep-th papers with “entanglement” in the title
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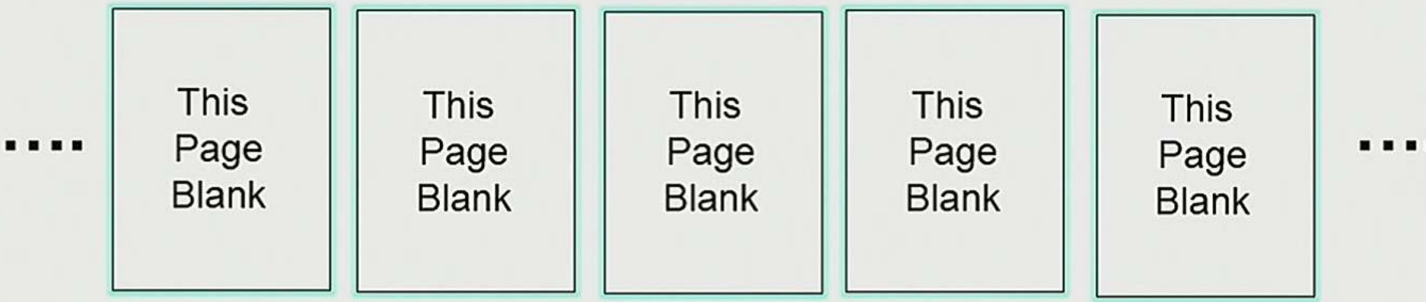
0 6 3 3 3 0 11 13 22 40 39 37 35 56 62 76 119 170 220
97 98 99 00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15
Year
(projected)

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!

Finding Prime Factors

1807082088687
4048059516561
6440590556627
8102516769401
3491701270214
5005666254024
4048387341127
5908123033717
8188796656318
2013214880557

=

3968599945959
7454290161126
1628837860675
7644911281006
4832555157243

×

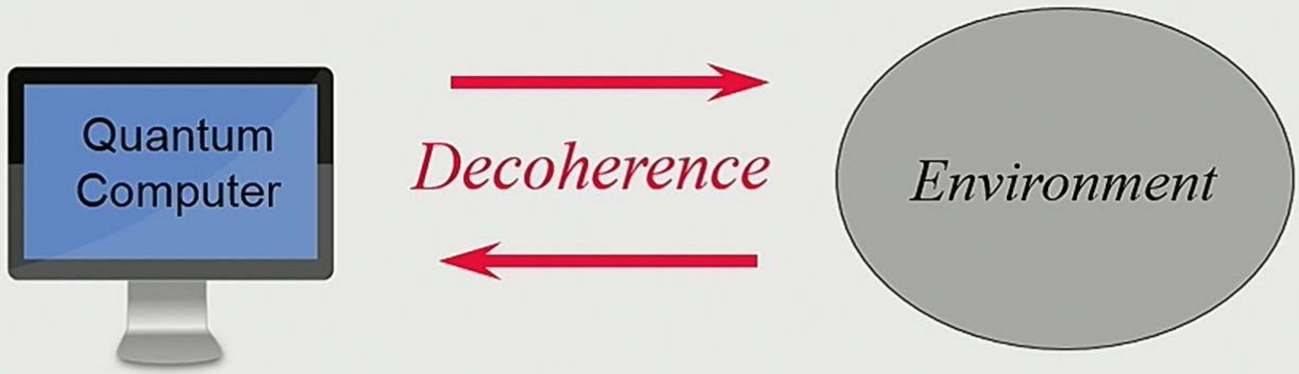
4553449864673
5972188403686
8972744088643
5630126320506
9600999044599

The boundary between "hard" and "easy" seems to be different in a quantum world than in a classical world.

Shor

RSA
SECURITY™

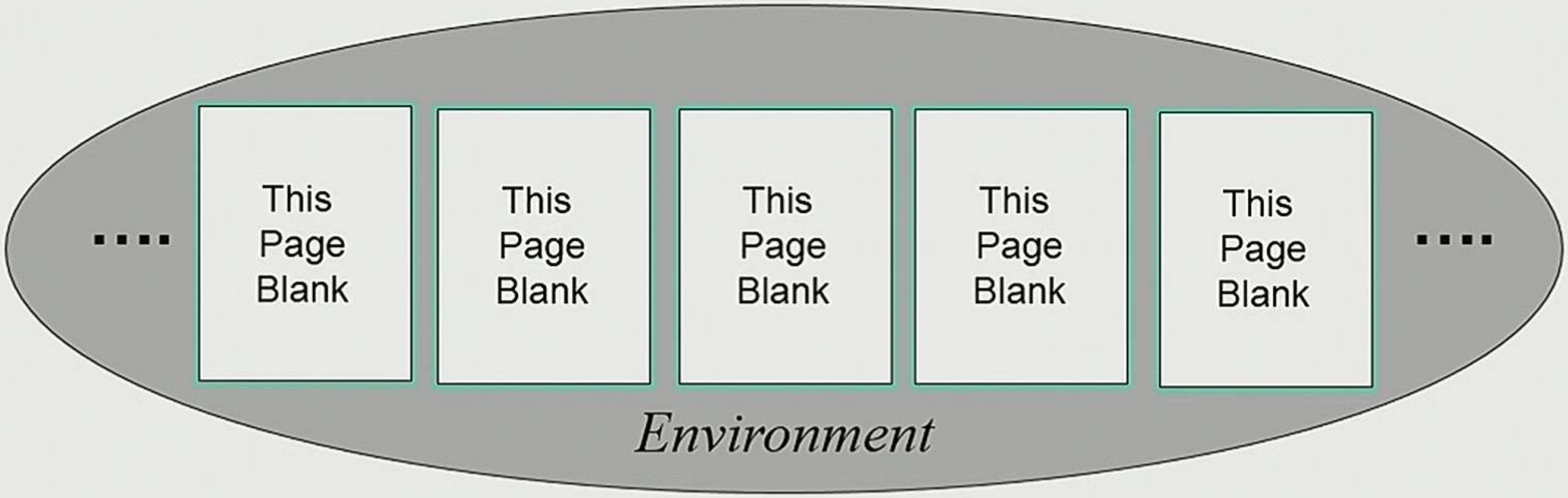
Ron Rivest Adi Shamir Len Adleman



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.

Some recently reported error rates

Ion trap – one-qubit gates:

$\sim 2 \times 10^{-5}$ [NIST]

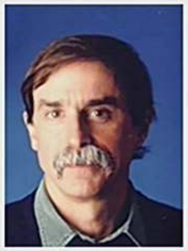
Ion trap – two-qubit gates:

$\sim 5 \times 10^{-3}$ [Innsbruck]

Superconducting circuits – two-qubit gates

$\sim 6 \times 10^{-3}$ [UCSB]

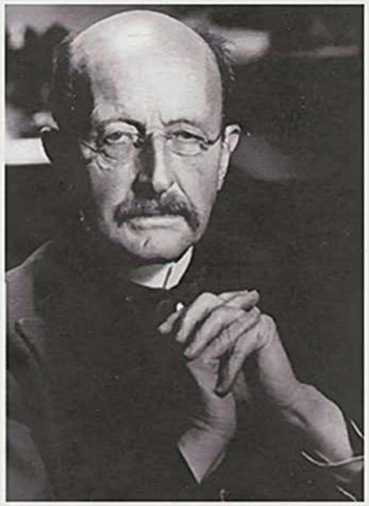
Quantum error correction becomes effective when gate error rates are low enough, and the overhead cost of error correction improves as hardware becomes more reliable.



Wineland

Blatt

Martinis



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….

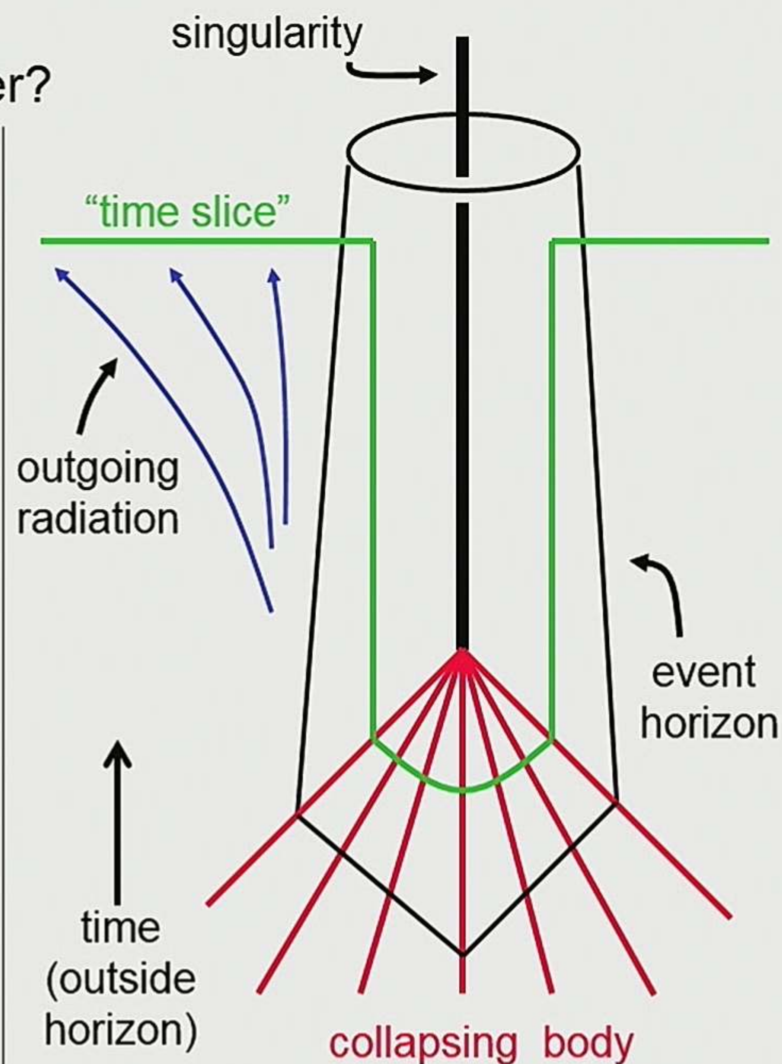
Planck 1900	Hawking 1975
"*The ultraviolet catastrophe*"	"*The information loss puzzle*"
In thermal equilibrium at nonzero temperature, the elelctromagnetic field carries an infinite energy per unit volume …	The radiation emitted by an evaporating black hole is featureless, revealing nothing about how the black hole formed …
The end of classical physics!	The end of quantum physics? (Or of relativistic causality?)

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 challenged

Three reasonable beliefs, not all true!

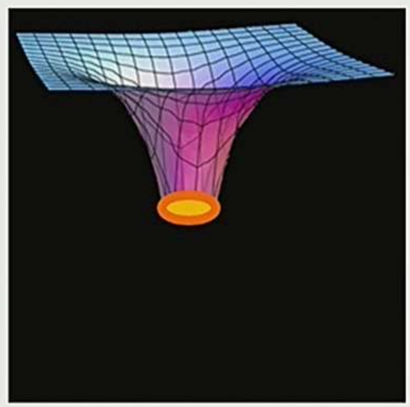
[*Almheiri, Marolf, Polchinski, Sully (AMPS) 2012*]

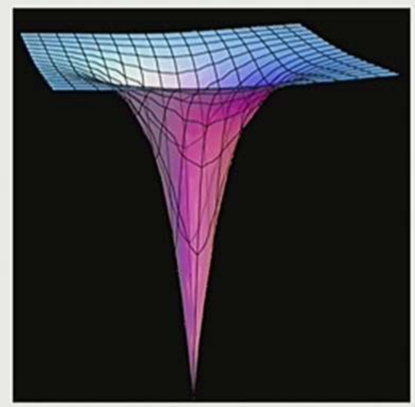
(1) The black hole “scrambles” information, but does not destroy it.

(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).





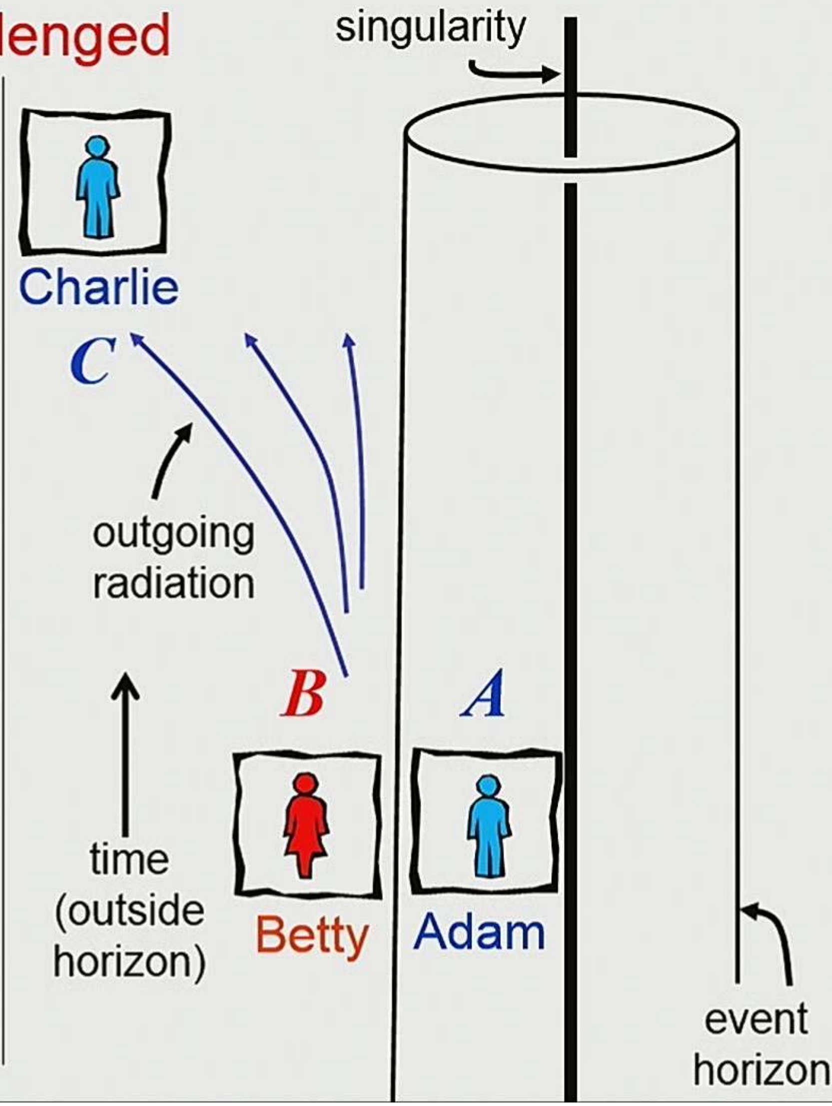
Complementarity Challenged

(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!



What's inside a black hole?

A. An unlimited amount of stuff.

B. Nothing at all.

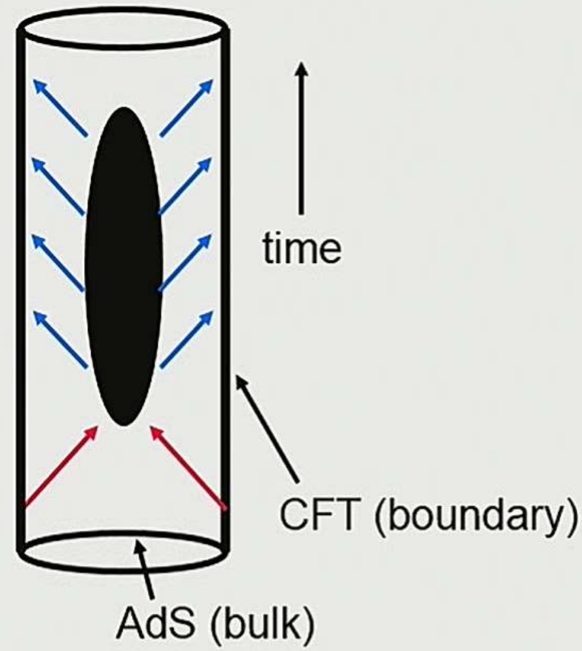
C. A huge but finite amount of stuff, which is also outside the black hole.

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*).

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

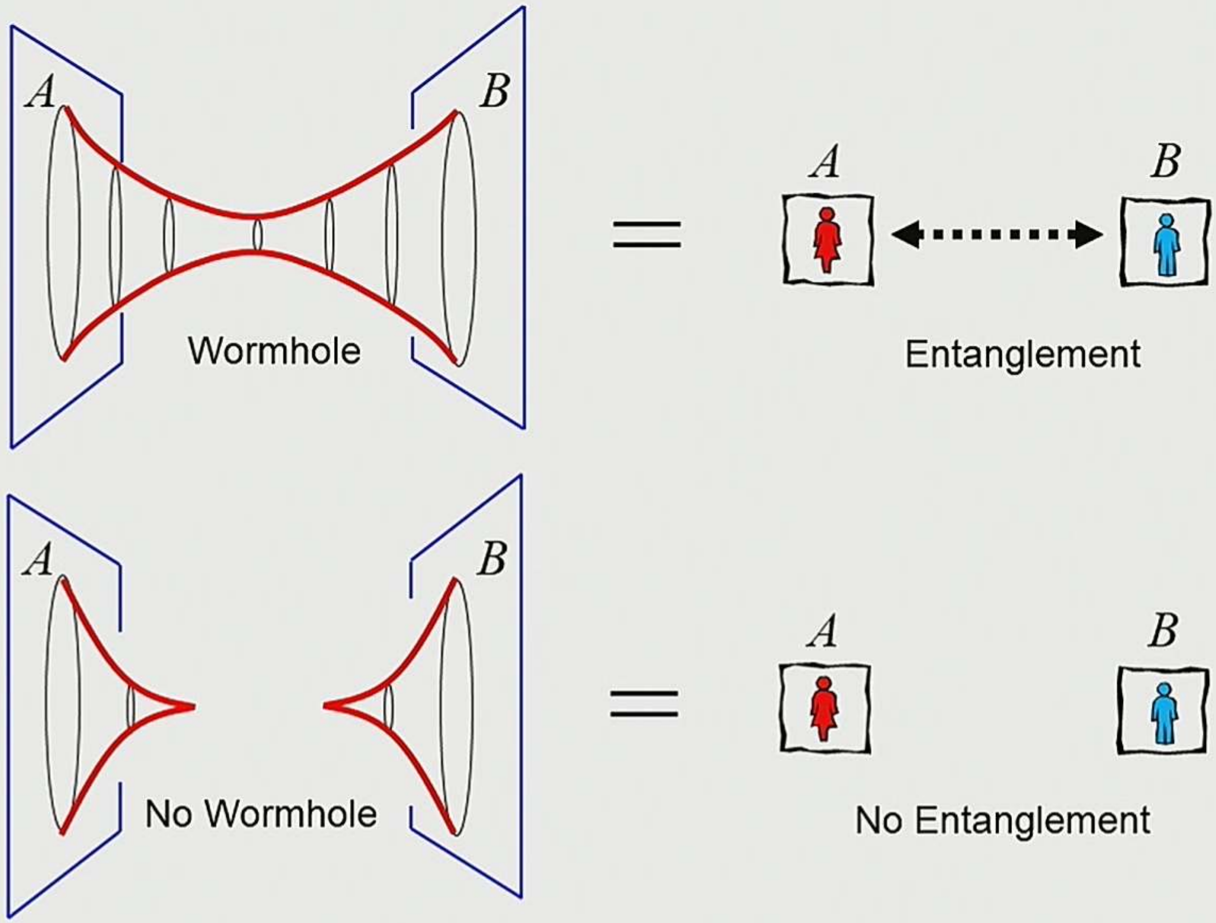


So at least in the one case where we think we understand how quantum gravity works, a black hole seems not to destroy information!

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

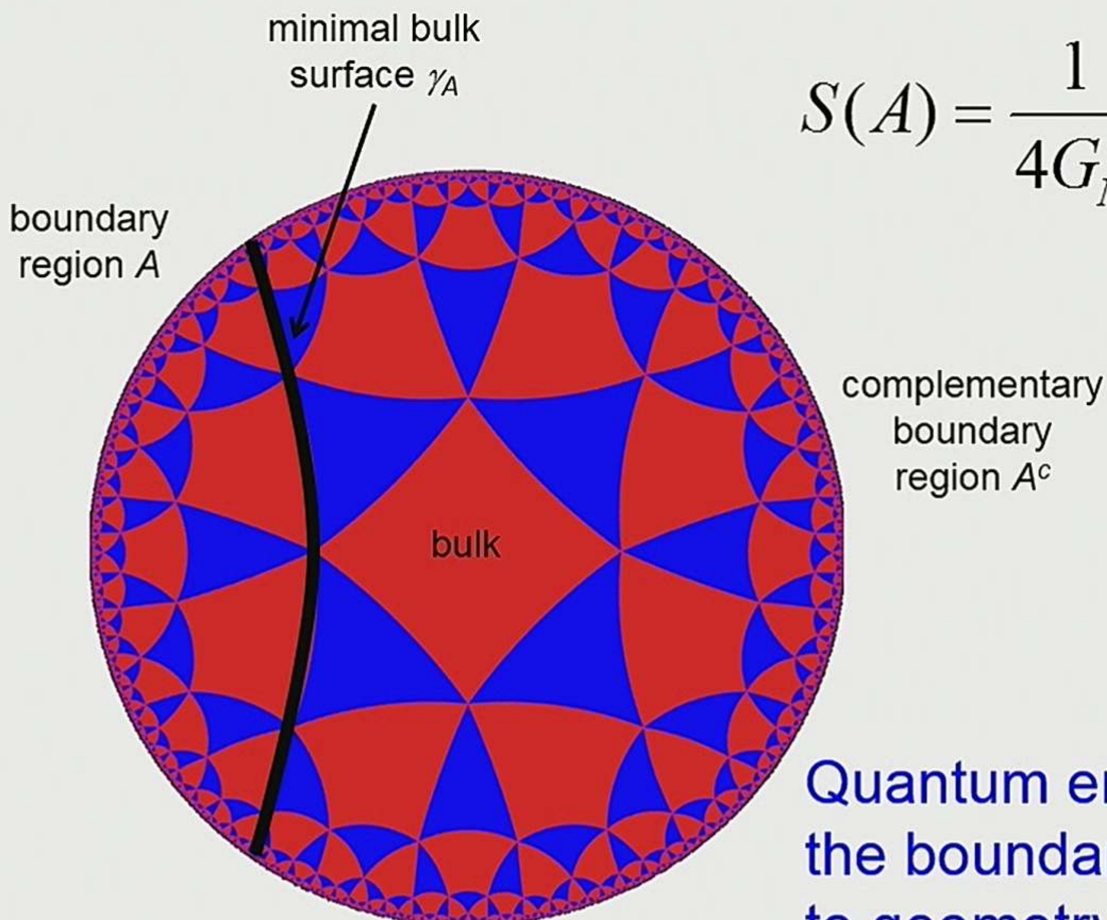
Indeed, it is not clear whether or how the boundary theory describes the experience of observers who cross into the black hole interior, or even if there is an interior!

Building spacetime from quantum entanglement



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

Holographic entanglement entropy

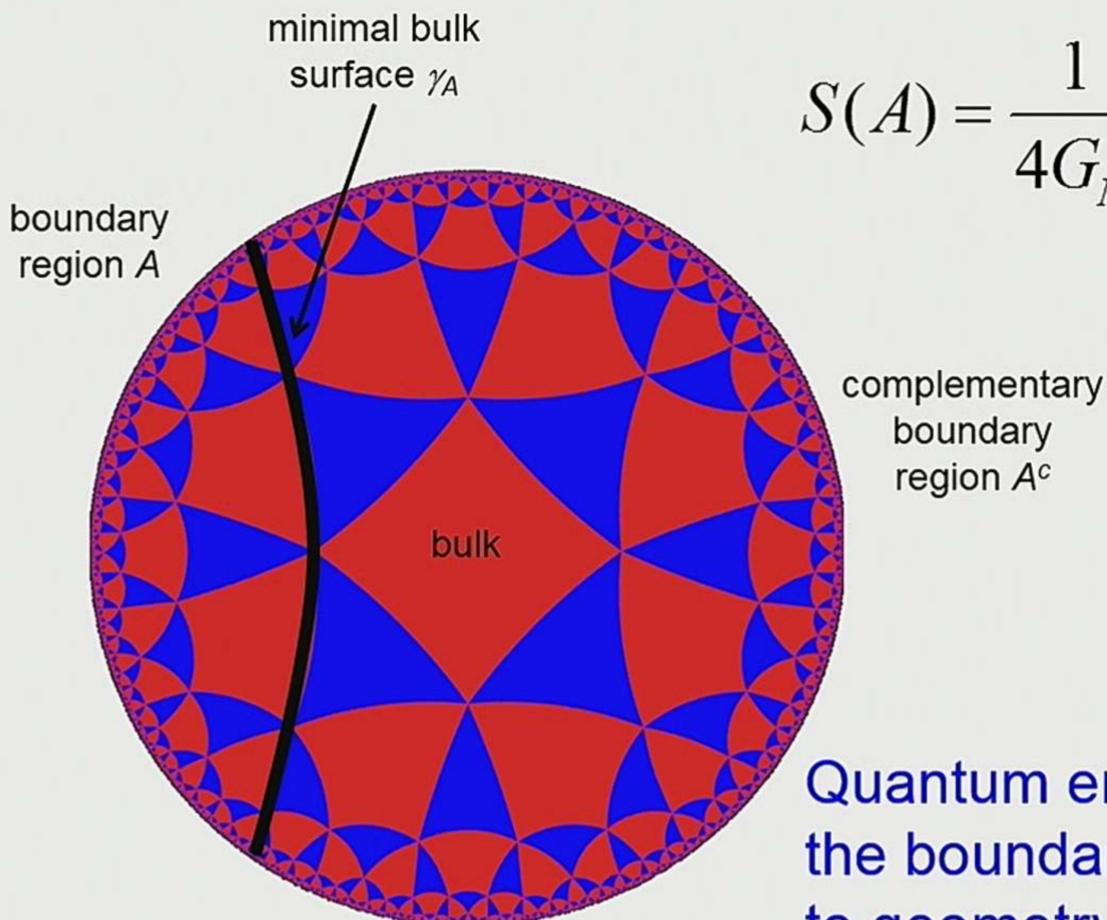


$$S(A) = \frac{1}{4G_N}\mathrm{Area}(\gamma_A) + \cdots$$

(*Ryu-Takayanagi*).

Quantum entanglement on the boundary corresponds to geometry in the bulk.

Holographic entanglement entropy



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

(*Ryu-Takayanagi*).

Quantum entanglement on the boundary corresponds to geometry in the bulk.

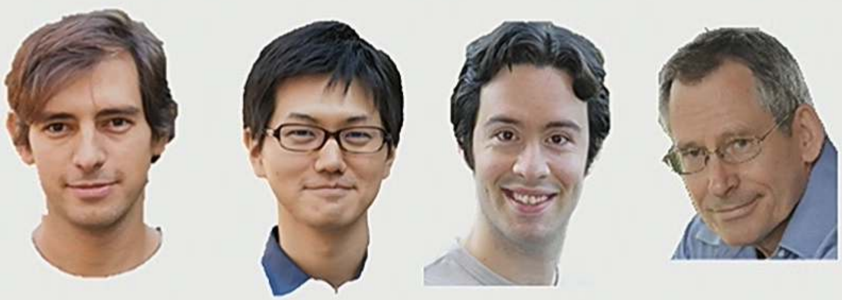
Two amazing ideas:

Holographic correspondence

Quantum error correction

Are they closely related?

Pastawski, Yoshida, Harlow, Preskill = HaPPY



arXiv:1503.06237

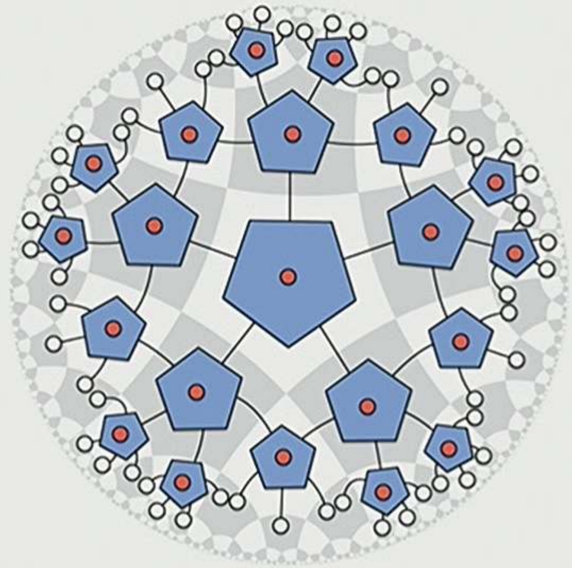
Building on
Almheiri, Dong, Harlow

Holographic Quantum Codes

Geometry emerges from entanglement.

Physical variables on boundary.
Encoded variables in the bulk.

Encoder is a *tensor network*.
Many small codes glued together.



Explicitly computable dictionary.
Computable boundary entanglement structure.

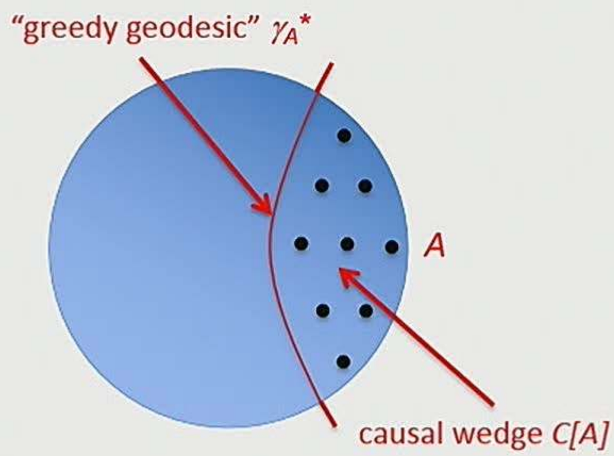
Local operators deep in the bulk mapped to highly nonlocal operators on the boundary, well protected against errors on the boundary.

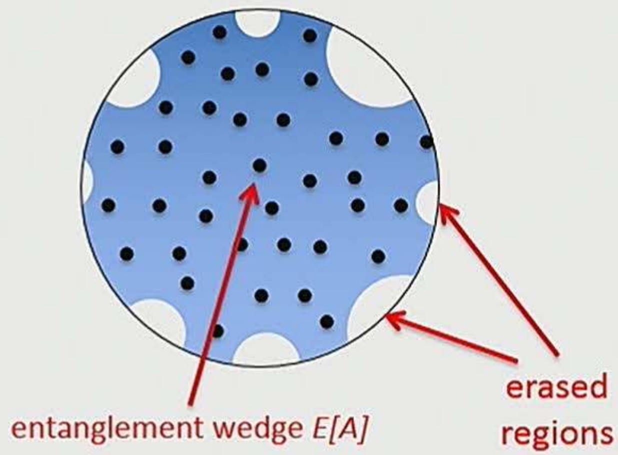
Properties of holographic codes

Ryu-Takayanagi relation between boundary entanglement and bulk geometry.

Bulk operators in the "causal wedge" of boundary region *A* can be reconstructed on *A*.

Reconstruction is highly ambiguous. (Bulk operator has many different physical realizations).

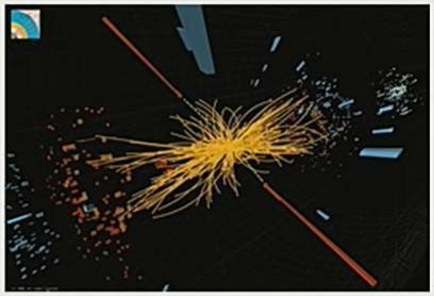




Operators deep in the bulk can be reconstructed on union of many small disjoint boundary regions. (Code provides good protection against erasure on the boundary.)

Frontiers of Physics

short distance

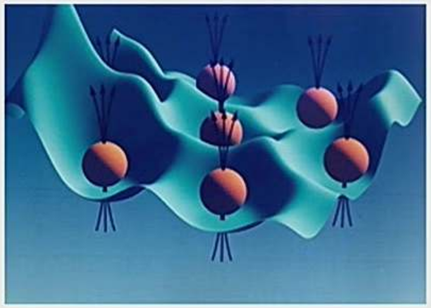


- Higgs boson
- Neutrino masses
- Supersymmetry
- Quantum gravity
- String theory

long distance

- Large scale structure
- Cosmic microwave background
- Dark matter
- Dark energy

complexity



- "More is different"
- Many-body entanglement
- Phases of quantum matter
- Quantum computing
- Emergent geometry

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.

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December 2014

Notices of AMS
May 2015