Title: Quantum error-correction and quantum gravity

Speakers: Beni Yoshida

Series: Colloquium

Date: April 05, 2023 - 2:00 PM

URL: https://pirsa.org/23040082

Abstract: In this colloquium, I will review how the notion of quantum error-correction has transformed our understanding of quantum gravity in the past decade.

Zoom link: https://pitp.zoom.us/j/94349082665?pwd=OFdJdkpHU1NEcmlNeW5pWlg4WmNBZz09

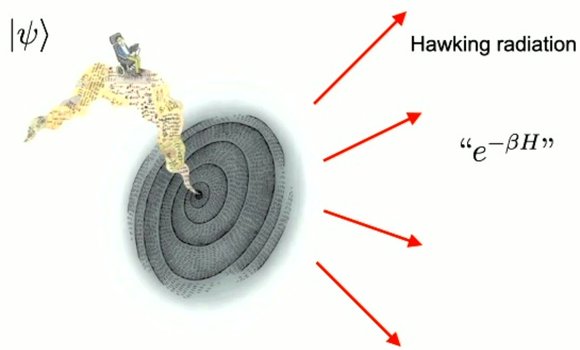
Quantum error-correction in quantum gravity

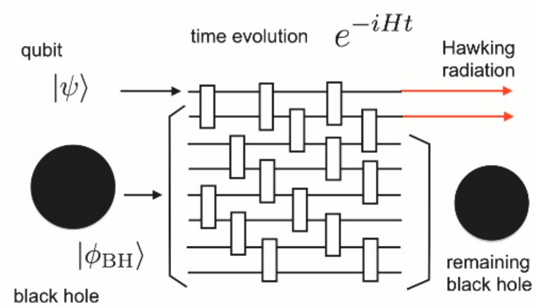
Beni Yoshida (Perimeter Institute)

Quantum Information in Gravity

✤ Quantum mechanics and general relativity are in serious conflicts, e.g. information loss puzzle, firewall puzzle, etc…

✤ These are questions of quantum information theory.

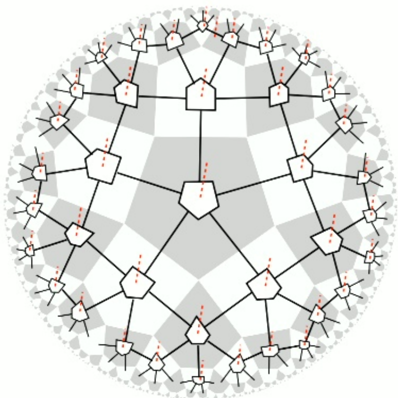


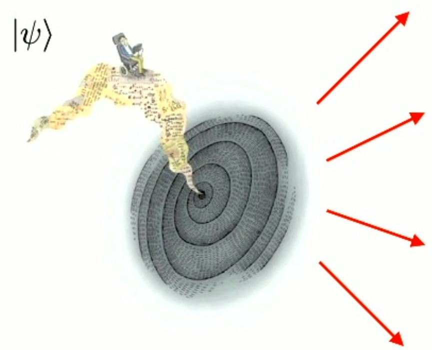


Quantum Error-Correction in Gravity ?

✤ Stores quantum information non-locally into many-body degrees of freedom. Local measurements/errors cannot destroy/reveal the hidden information.

✤ Quantum gravity seems to hide quantum information, like a quantum error-correcting code.





Overview

✤ Bulk-boundary mapping in the AdS/CFT correspondence, and beyond

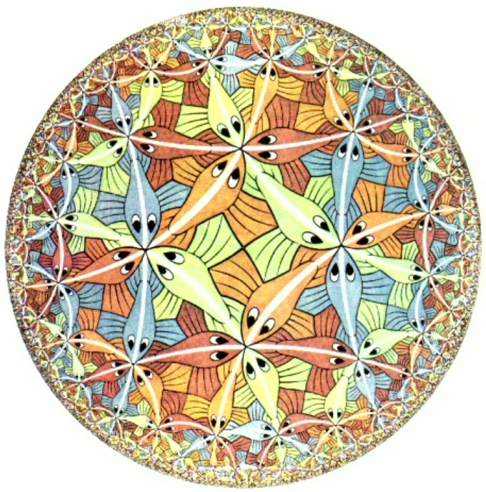
- Holographic quantum error-correcting code (Harlow-Pastawski-Preskill-BY 2015)
- Holographic scattering (May-Sorce-BY 2022)

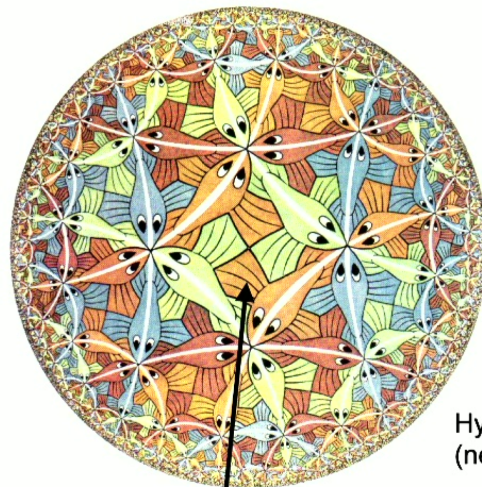
✤ Quantum information scrambling and black holes

- Information recovery from black hole (Hosur-Qi-Roberts-BY 2015, BY-Kitaev 2017)
- Firewall puzzle and black hole interior (BY 2019)

AdS/CFT correspondence

✤ Quantum gravity in bulk = CFT on boundary ?





Hyperbolic space (negatively curved)

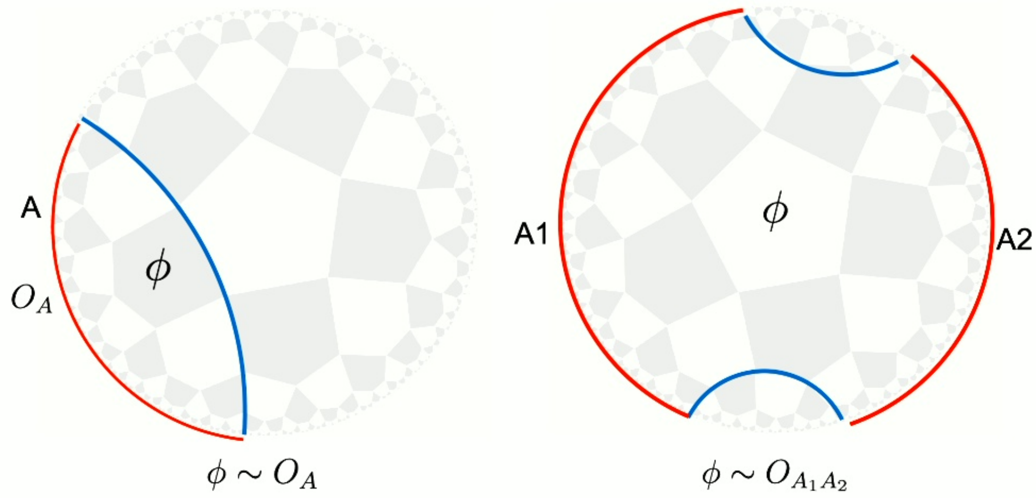
Boundary D-dimensional conformal field theory (without gravity)

Bulk (D+1)-dimensional theory with gravity on AdS space

Bulk operator vs boundary operator

✤ Entanglement wedge reconstruction

A bulk operator ϕ can be represented by some integral of local boundary operators supported on A if ϕ is contained inside the entanglement wedge of A.

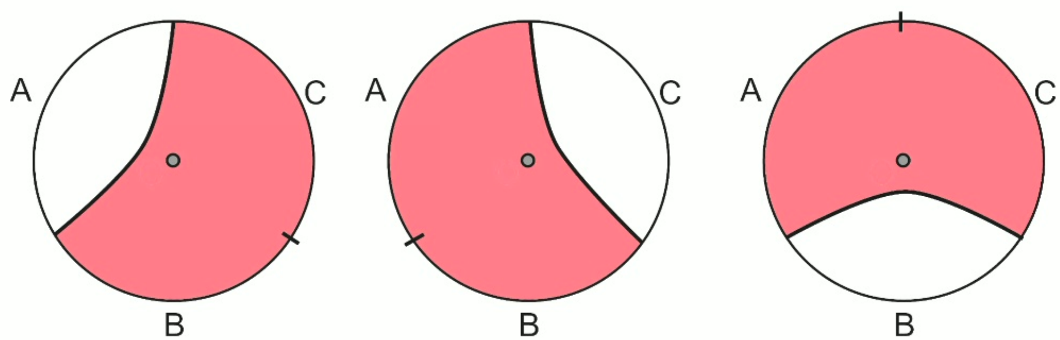


- "Proven" by using a generalized RT formula (Jefferis et al)
- No explicit recipe is known for more than one intervals

Bulk locality puzzle

✤ The reconstruction recipe leads to a paradox

- All the bulk operators must correspond to identity operators on the boundary ?

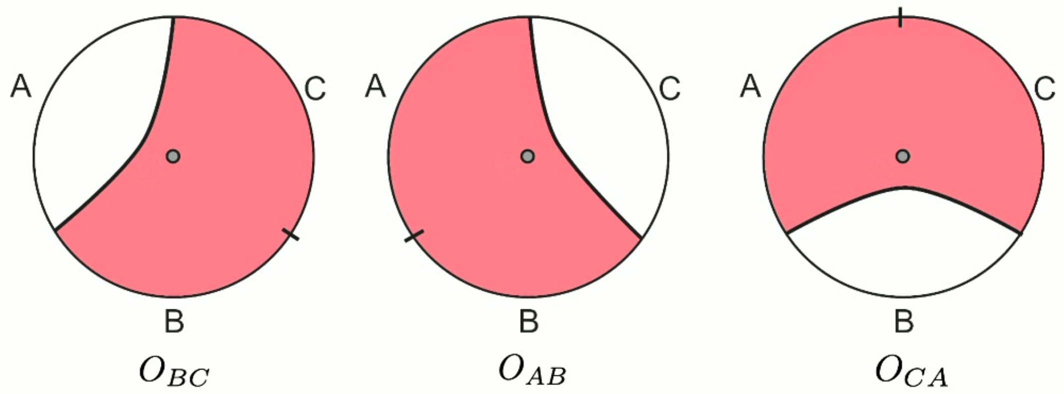


If so, the AdS/CFT seems very boring …

(Almheiri-Dong-Harlow)

Quantum error-correction in AdS/CFT ?

✤ The AdS/CFT correspondence can be viewed as a quantum error-correcting code.



They are different operators, but act in the same manner in a low energy subspace.

cf. Quantum secret-sharing code

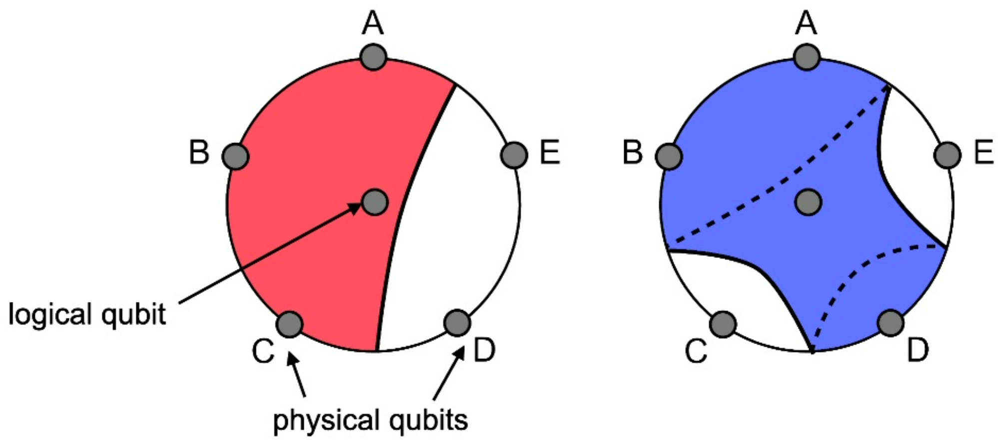
A simple toy model ?

1 bulk qubit

5 boundary qubits

in total, just 6 qubits

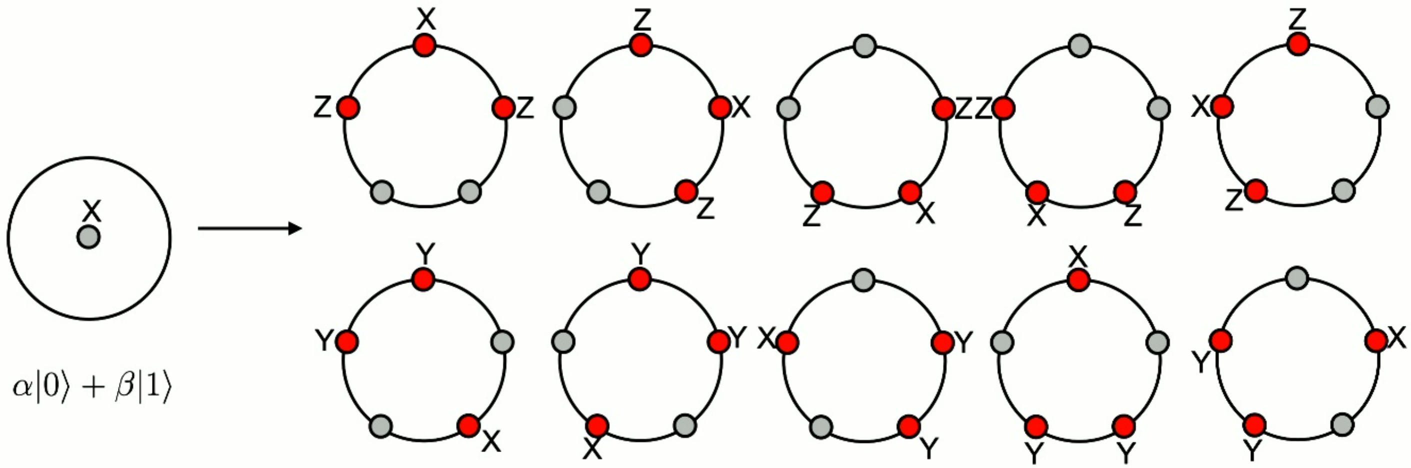
A bulk operator must have representations on any region with three qubits.



Entanglement wedge reconstruction !

Five-qubit code

✤ Pauli X operator in the input (bulk) corresponds to following 3-body operators.

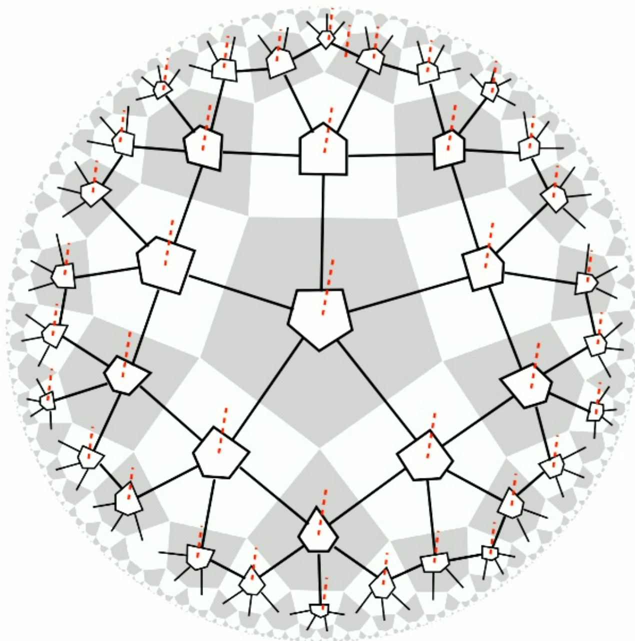


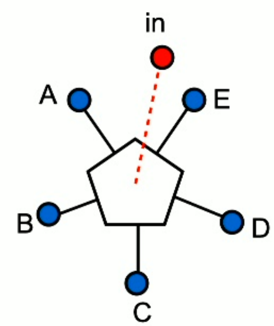
$\alpha|0\rangle + \beta|1\rangle$

$\alpha|c_0\rangle + \beta|c_1\rangle$

Holographic quantum error-correcting code

✤ A tiling of the five qubit code via tensor network technique





five-qubit code

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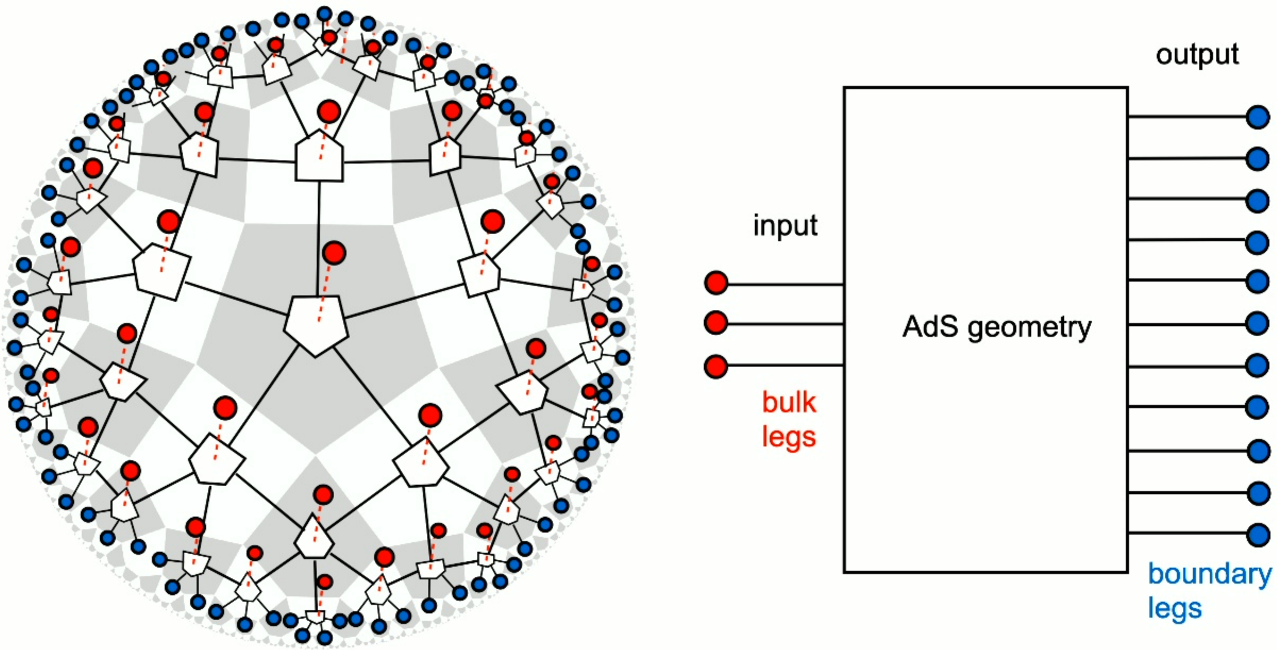
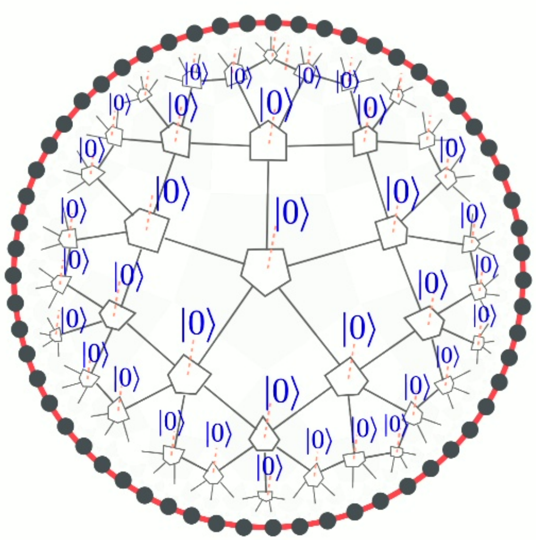


* Tensor network and AdS/CFT : Vidal07, Swingle12, Qi13, Czech et al15 …

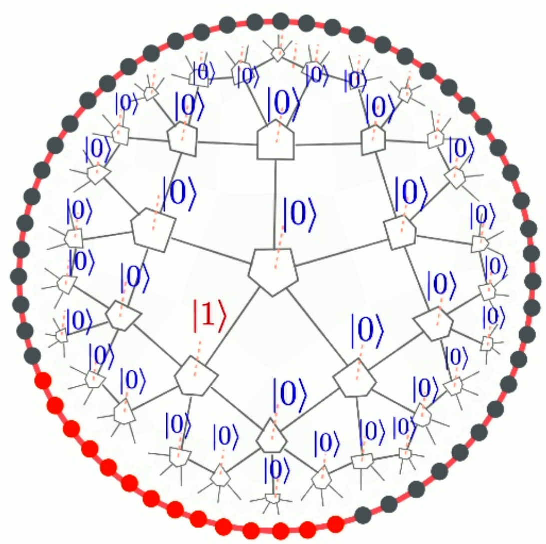
Physical interpretation

✤ Qubits on the bulk represent matter fields, coupled to the geometry (via tensors).

✤ Perturbations around a fixed geometry.



Vacuum



Excited state

Holographic quantum error-correcting code

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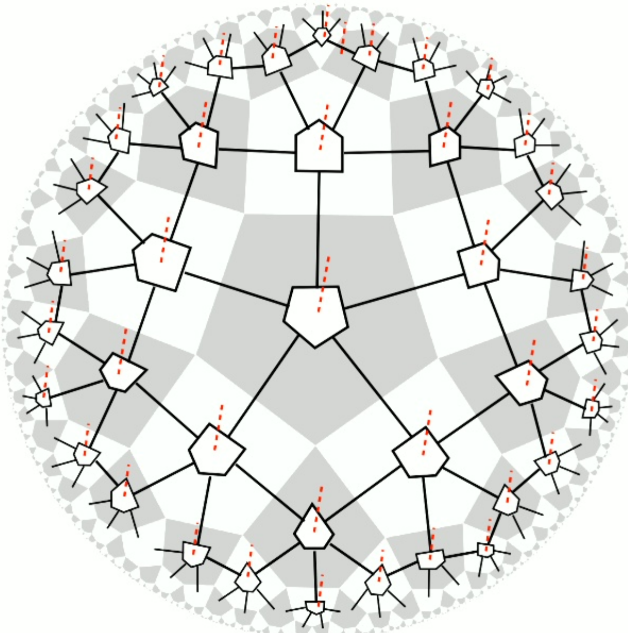

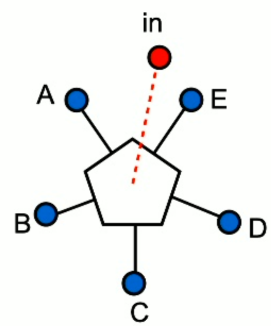

five-qubit code

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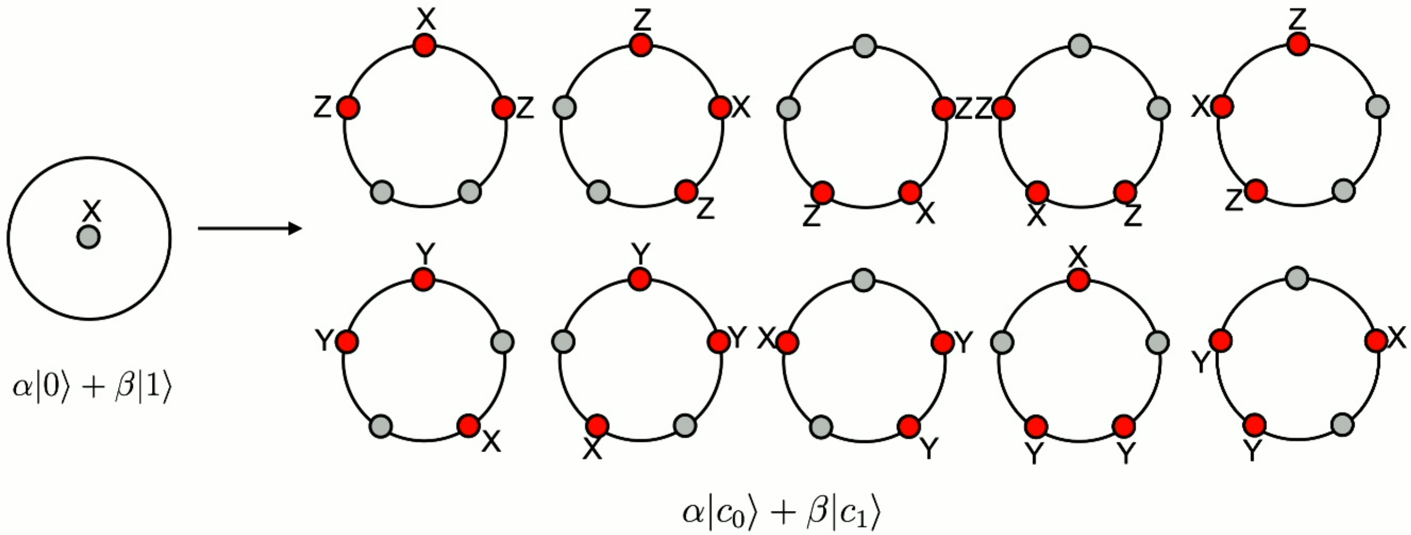

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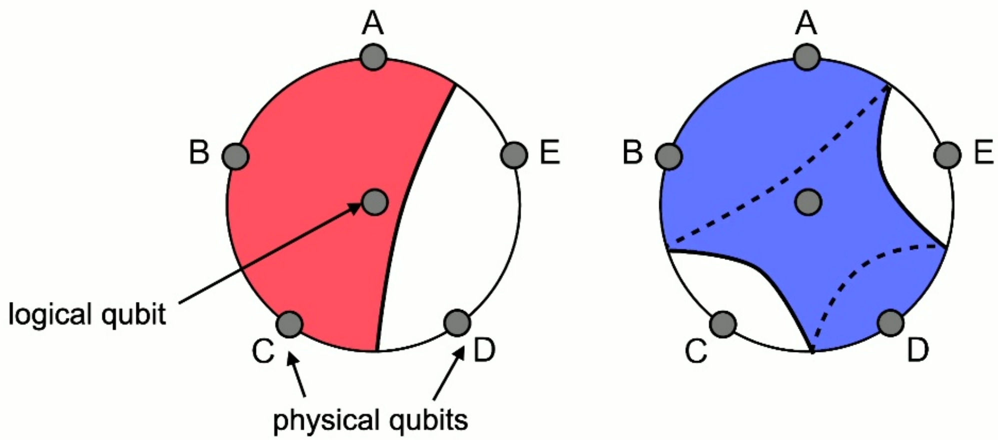

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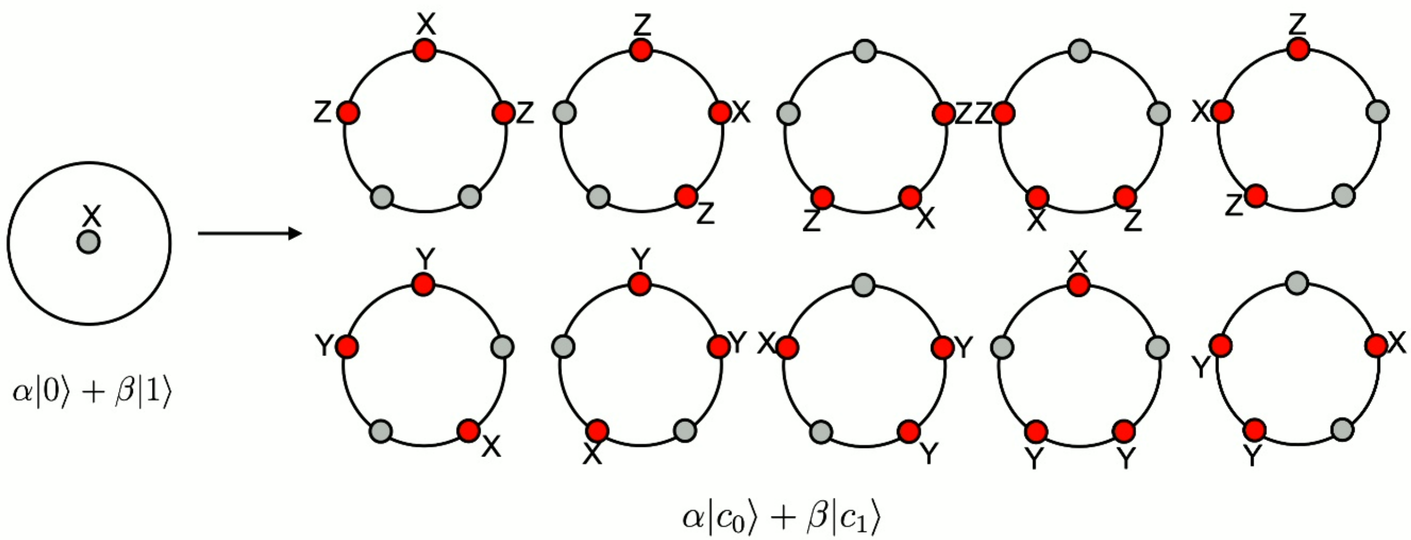
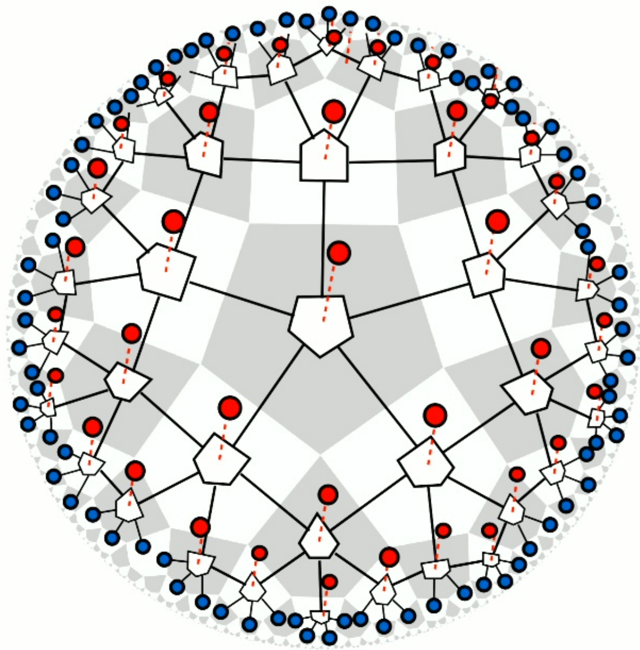
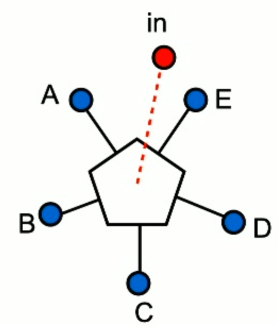


Holographic quantum error-correcting code

- A tiling of the five qubit code via tensor network technique





five-qubit code

* Tensor network and AdS/CFT : Vidal07, Swingle12, Qi13, Czech et al15 …

Aspects of holographic tensor networks

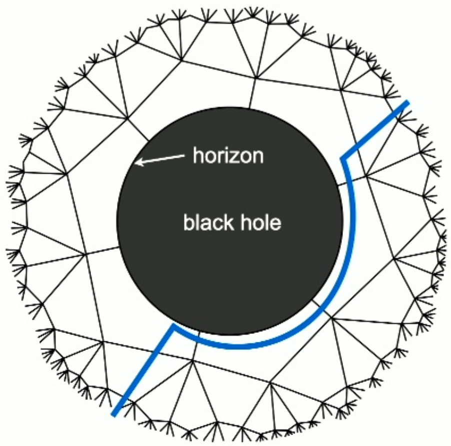
✤ Toy model becomes more "realistic" by using Haar random tensors.

- Entanglement growth and operator growth in many-body physics.

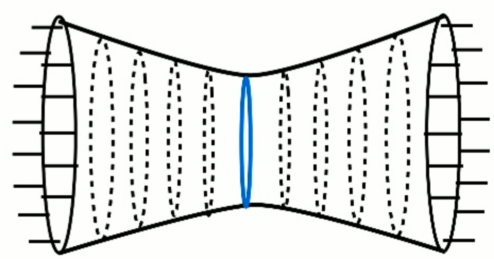
✤ Toy models of black holes.

- Complexity = Volume = Action? (number of tensors = complexity?)
- "Page curve" derivation

One-sided black hole



Two-sided black hole

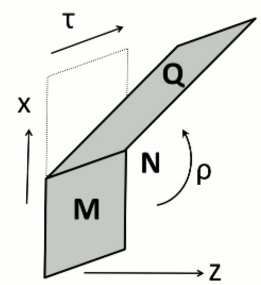


Einstein-Rosen bridge

Some of ongoing works

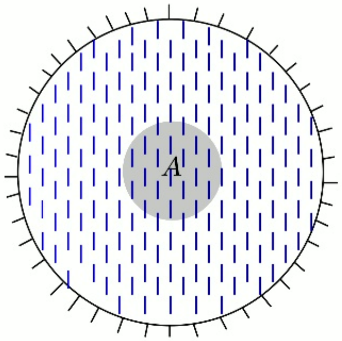
✤ Spacetime with End-of-World branes

- Projective measurements ? (Takayanagi et al)
- Causality violation ? (Omiya-Wei)



✤ de Sitter space

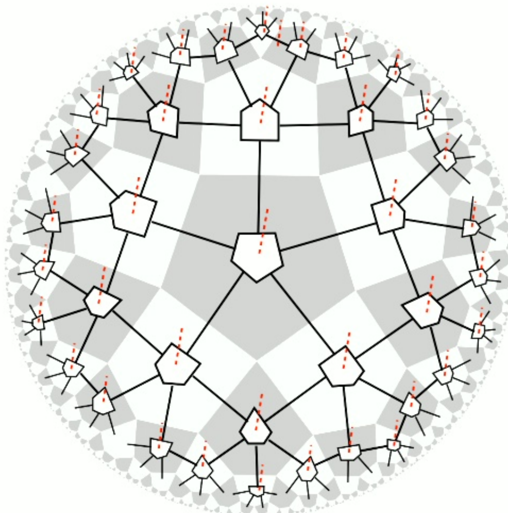
- Emergence of “dark force” (Verlinde)
- Puzzles about de Sitter horizon



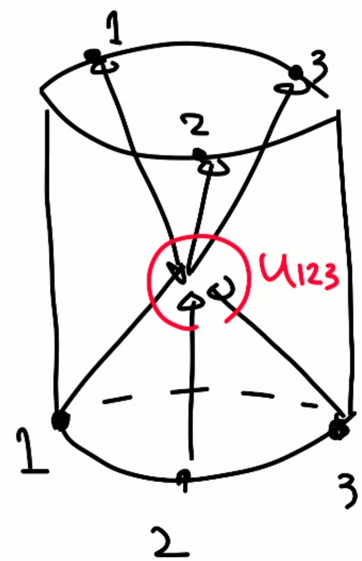
$S_A \propto \text{Volume}(A)$

Emergence of interaction

✤ Spacetime from entanglement



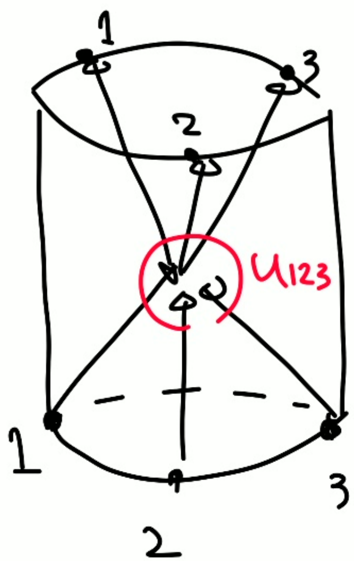
✤ Interaction from entanglement ?



[May 2019]

Holographic scattering

✤ How are interactions induced on the boundary quantum systems?

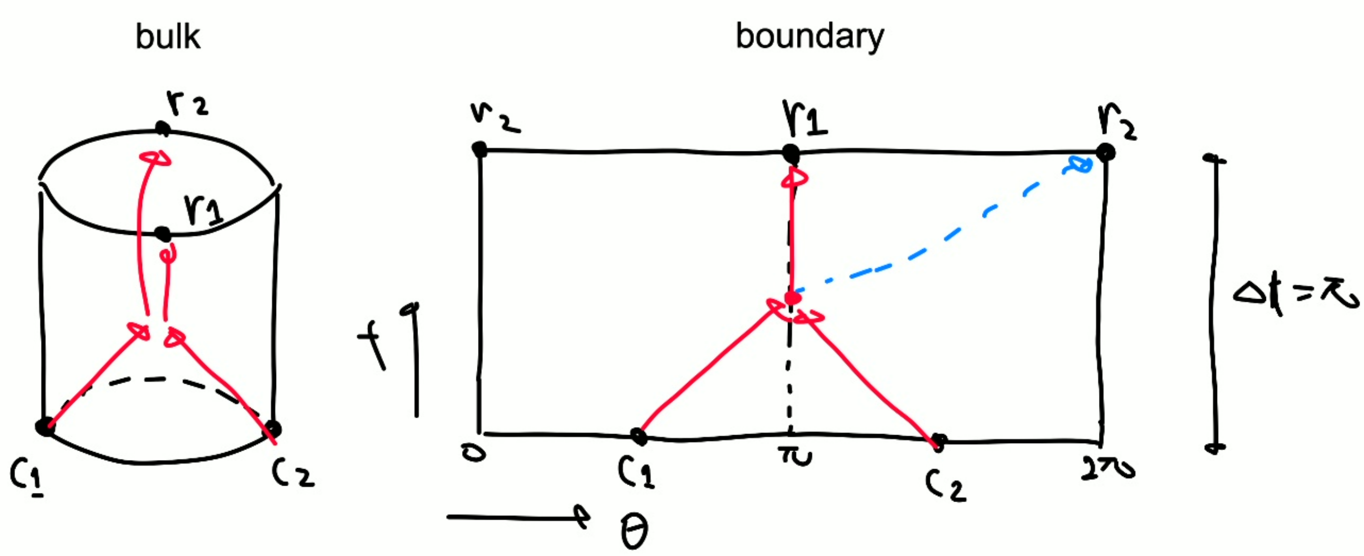


In principle, arbitrary unitary should be realizable.

Boundary causality puzzle

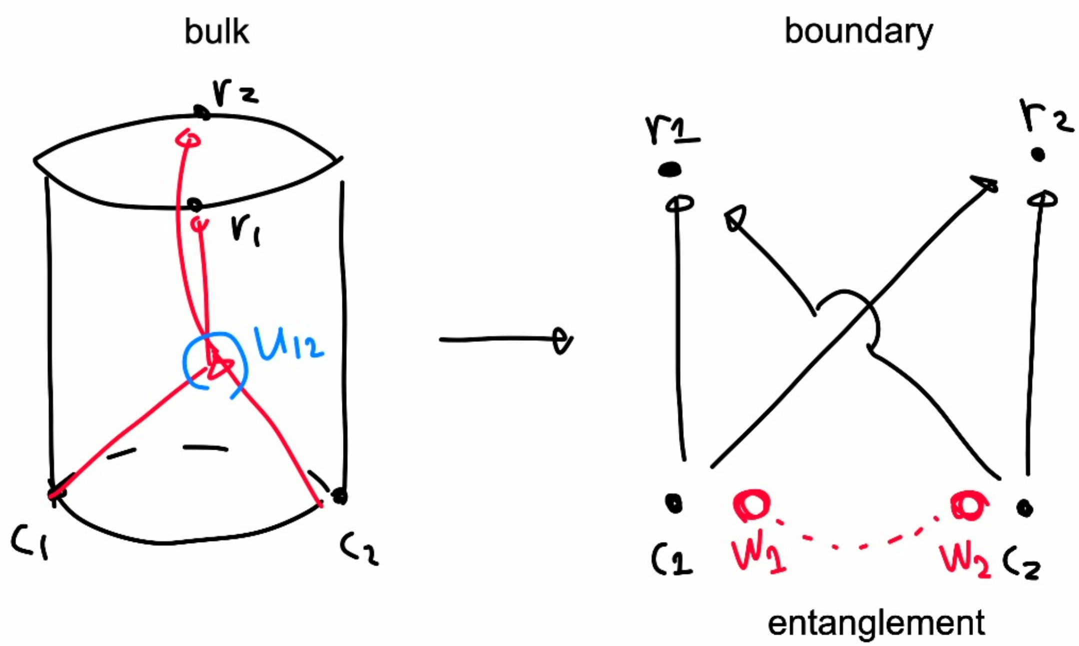
✤ On the boundary, there is not enough time for particles to interact.

- Particles in the AdS/CFT correspondence must be non-interacting… !?



Non-local quantum computation

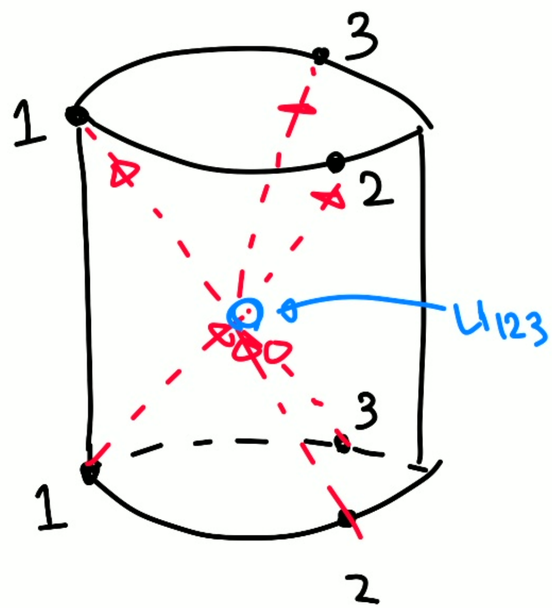
✤ By using the pre-shared entanglement, (in principle) one can induce arbitrary unitary interactions.

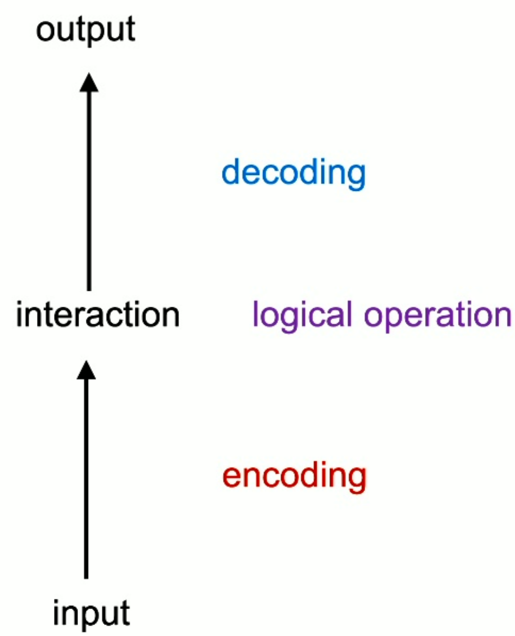


[May 2019]

Scattering and quantum error-correction

✤ Interactions must occur in a quantum error-correcting code.

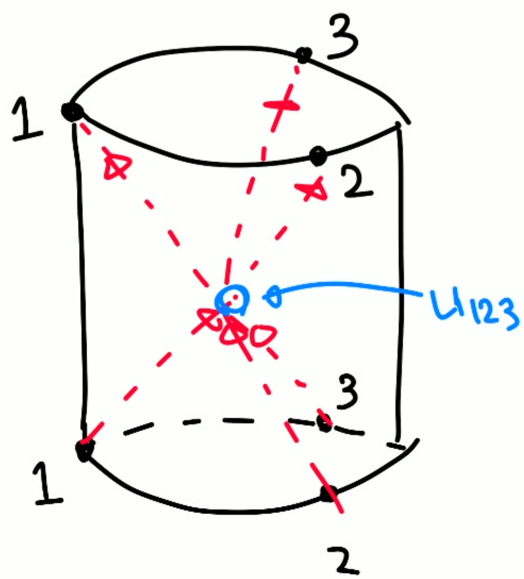


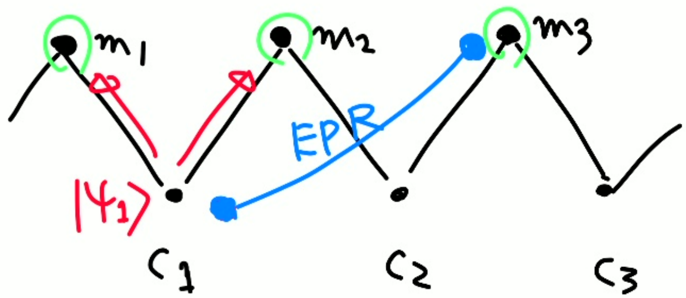


Entanglement-assisted quantum error-correction

✤ Pre-existing entanglement delocalizes the input to the whole system

- Non-local encoding is possible. Interactions are induced by transversal logical operators.

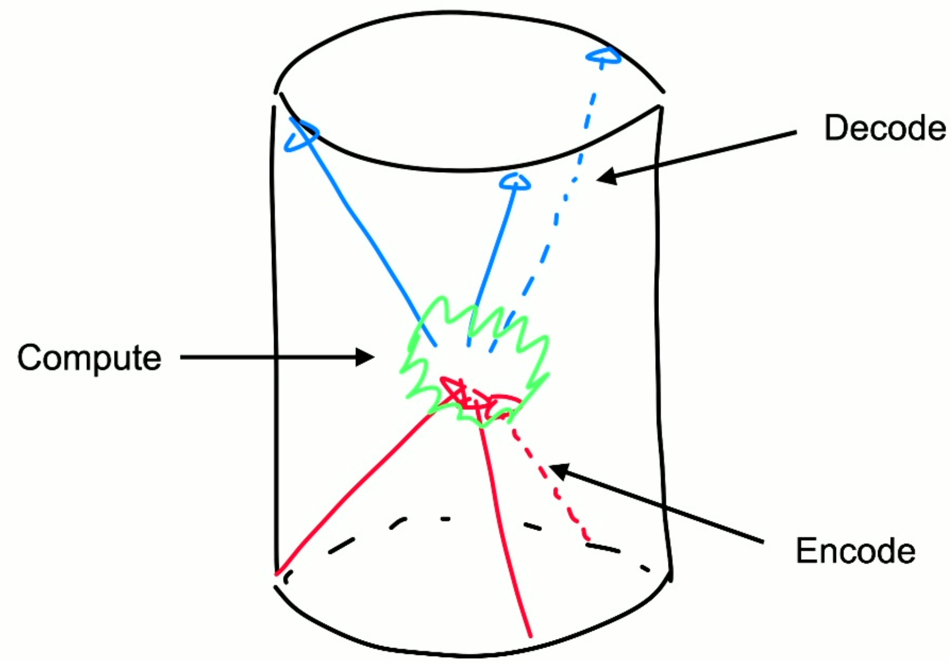




like a quantum computer…

✤ This is how a fault-tolerant quantum computer works.

- Creating a black hole is an error that spoils the quantum computation ?



Overview

- Bulk-boundary mapping in the AdS/CFT correspondence, and beyond
  - Holographic quantum error-correcting code (Harlow-Pastawski-Preskill-BY 2015)
  - Holographic scattering (May-Sorce-BY 2022)

- Quantum information scrambling and black holes
  - Information recovery from black hole (Hosur-Qi-Roberts-BY 2015, BY-Kitaev 2017)
  - Firewall puzzle and black hole interior (BY 2019)

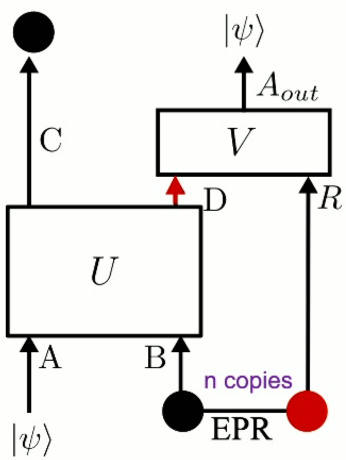
Hayden-Preskill thought experiment

✤ Alice throws an unknown quantum state into an old black hole. Bob collects the Hawking radiation and reconstructs the original state.

Bob has an access to both early and late radiations !

- Bob needs to collect just a few qubits from D.

(Hayden-Preskill 2007)



(maximally entangled)

C : Remaining BH

D : Late radiation

R : Early radiation

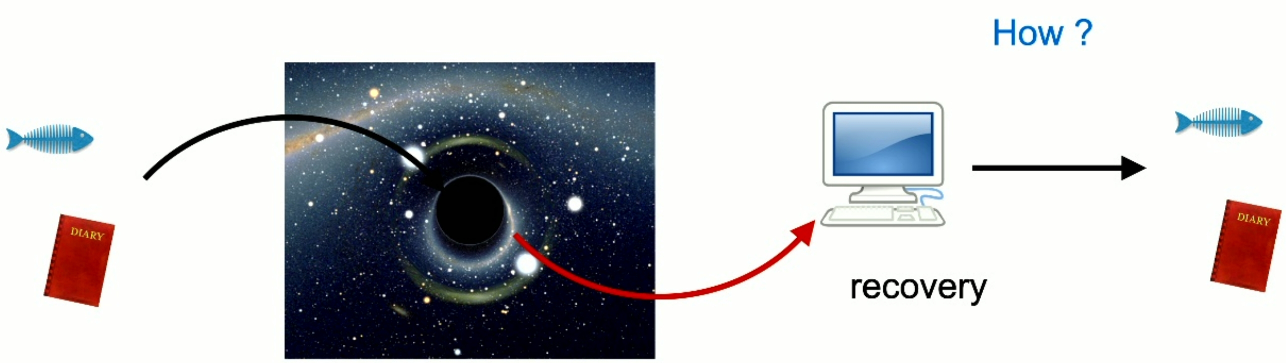
Can we really recover information?

- Haar random unitary

$$e^{iHt} \approx \text{Haar random unitary}$$

→ Does it really work for actual black holes?

- How do we actually recover information?



Scrambling is *operator* growth

- Operator growth

Size of operators becomes bigger under chaotic time-evolution.

e^{-iHt}  $W(t)$

Scrambling is *operator* growth

✤ Operator growth

Size of operators becomes bigger under chaotic time-evolution.

e^{-iHt}  $W(t)$

- Operator-to-state mapping (Hosur-Qi-Roberts-BY15)

n-qubit Hilbert space 2n-qubit Hilbert space

$$\hat{\mathcal{O}} \longleftrightarrow |\hat{\mathcal{O}}\rangle$$

Operator size growth *Operator entanglement growth*

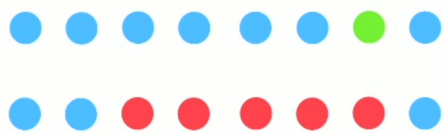
Choi isomorphism

Out-of-time order correlation function

✤ Out-of-time order correlator (Kitaev)

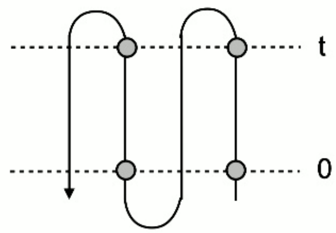
$V(0)$

$W(t)$



$\langle V(0)W(t)V(0)W(t)\rangle$

⟶ small



✤ Black hole scrambles quantum information

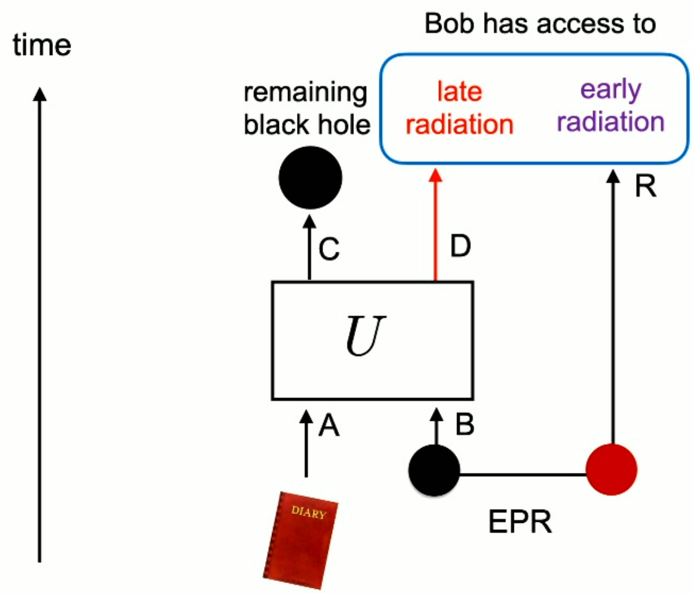
- Gravitational shockwave calculations

  ’t Hooft (1980s) and Kiem-Verlinde-Verlinde (1990s)

  Shenker-Stanford and Kitaev (2014) for AdS black hole

- This goes beyond Hawking’s semi-classical calculation

Decoupling theorem from scrambling



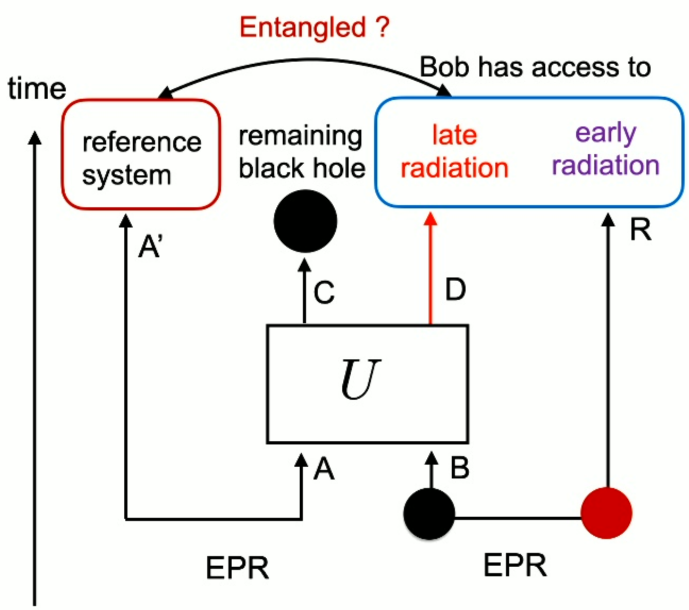
Decoupling theorem from scrambling

Theorem 1. *Suppose that the black hole's dynamics is scrambling and $d_D \gtrapprox d_A$. Then, the subsystems A' and C are decoupled:*

OTOCs $\langle O_A(0) O_D(t) O_A(0) O_D(t) \rangle$

$$\rho_{A'C} \approx \rho_{A'} \otimes \rho_C. \quad (1)$$

(BY-Kitaev17)



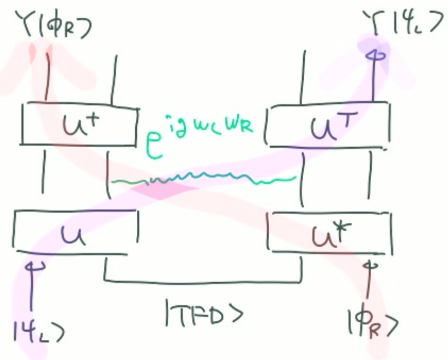
The reference A' will be (nearly maximally) entangled with DR.

Corollary

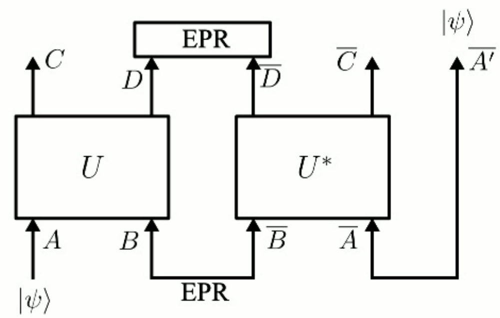
Information can be recovered from a black hole !

Recovery protocols

Traversable wormhole (Gao-Jafferis-Wall)



Decoding via Petz map (Kitaev-BY)



Google group (Brown-Gharibyan-Leichenauer-Lin-Nezami-Salton-Susskind-Swingle-Walter)

Our followup (Schuster-Kobrin-Gao-Cong-Khabiboulline-Linke-Lukin-Monroe-BY-Yao)

Recovery protocols

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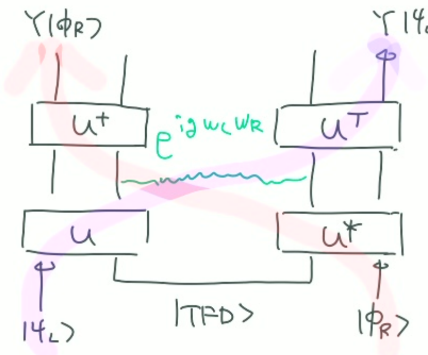

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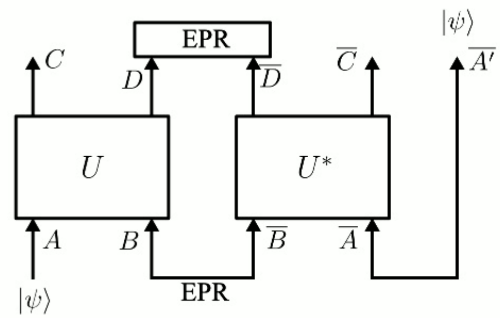


before scrambling time

after scrambling time

time scale

"computational complexity"
phase transition

Google group (Brown-Gharibyan-Leichenauer-Lin-Nezami-Salton-Susskind-Swingle-Walter)

Our followup (Schuster-Kobrin-Gao-Cong-Khabiboulline-Linke-Lukin-Monroe-BY-Yao)

Experiment !

LETTER

https://doi.org/10.1038/s41586-019-0952-6

Verified quantum information scrambling

K. A. Landsman[1]*, C. Figgatt[1,6], T. Schuster[2], N. M. Linke[1], B. Yoshida[3], N. Y. Yao[2,4] & C. Monroe[1,5]

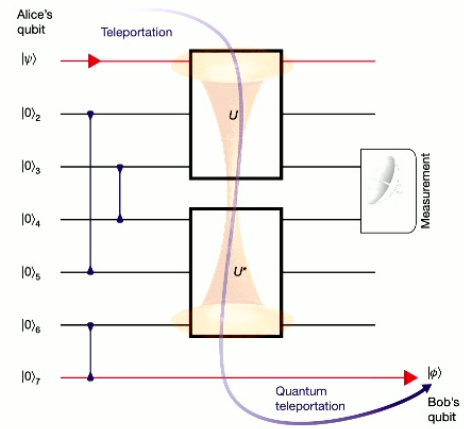
Quantum scrambling is the dispersal of local information into many-body quantum entanglements and correlations distributed throughout an entire system. This concept accompanies the dynamics of thermalization in closed quantum systems, and has recently emerged as a powerful tool for characterizing chaos in black holes[1–4]. However, the direct experimental measurement of quantum scrambling is difficult, owing to the exponential complexity of ergodic many-body entangled states. One way to characterize quantum scrambling is to measure an out-of-time-ordered correlation function (OTOC); however, because scrambling leads to their decay, OTOCs do not generally discriminate between quantum scrambling and ordinary decoherence. Here we implement a quantum circuit that provides a positive test for the scrambling features of a given unitary process[5,6]. This approach conditionally teleports a quantum state through the circuit, providing an unambiguous test for whether scrambling has occurred, while simultaneously measuring an OTOC. We engineer quantum scrambling processes through a tunable three-qubit unitary operation as part of a seven-qubit circuit on an ion trap quantum computer. Measured teleportation fidelities are typically about 80 per cent, and enable us to experimentally bound the scrambling-induced decay of the corresponding OTOC measurement.

For example, non-unitary time-evolution arising from depolarization or classical noise processes naturally lead the OTOC to decay, even in the absence of quantum scrambling. A similar decay can also originate from even slight mismatches between the purported forward and backwards time-evolution of $\hat{W}(t)$ (refs [6,16] and [24]). Although full quantum tomography can in principle distinguish scrambling from decoherence and experimental noise, this requires a number of measurements that scales exponentially with system size and is thus impractical.

In this work, we overcome this challenge and implement a quantum teleporation protocol that robustly distinguishes information scrambling from both decoherence and experimental noise[5,6]. Using this protocol, we demonstrate verifiable information scrambling in a family of unitary circuits and provide a quantitative bound on the amount of scrambling observed in the experiments.

The intuition behind our approach lies in a re-interpretation of the black-hole information paradox[9,10], under the assumption that the dynamics of the black hole can be modelled as a random unitary operation $\hat{U}$ (Fig. 1). Schematically, an observer (Alice) throws a secret quantum state into a black hole, while an outside observer (Bob) attempts to reconstruct this state by collecting the Hawking radiation emitted at a later time[1,10].

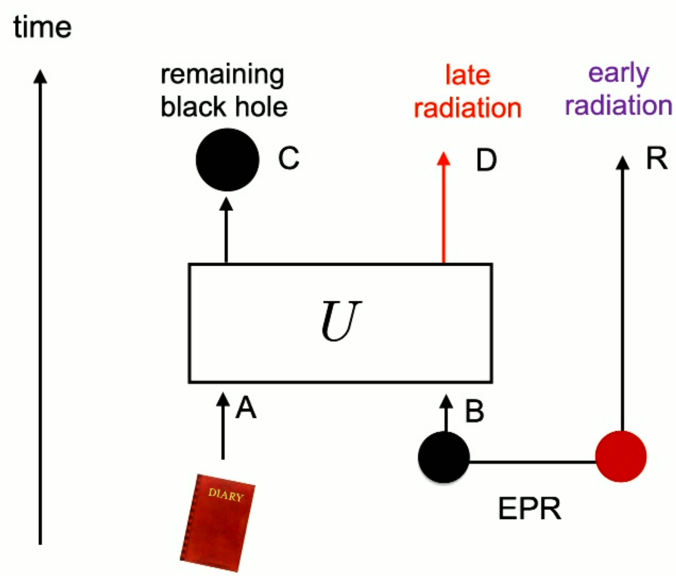
An explicit decoding protocol has been recently proposed[5,6], which



Entanglement-assisted QECCs

- Information is delocalized over CDR due to the preexisting entanglement.

- Recoverable from CD, DR, CR. (losing one subsystem is fine).



Overview

- ✤ Bulk-boundary mapping in the AdS/CFT correspondence, and beyond
  - Holographic quantum error-correcting code (Harlow-Pastawski-Preskill-BY 2015)
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  - Firewall puzzle and black hole interior (BY 2019)

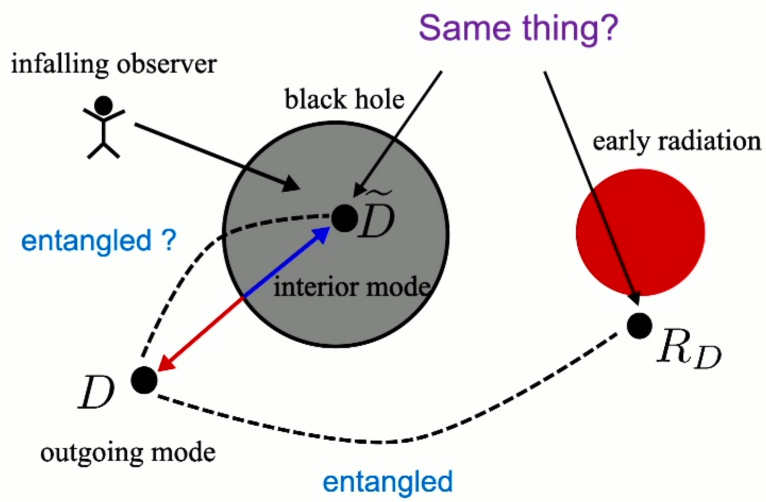
Firewall puzzle

✤ The outgoing mode D is entangled with the interior mode $\widetilde{D}$ as well as with the early radiation R_D ?

- Monogamy of entanglement suggests a firewall ?

✤ ER=EPR proposal : interior mode is embedded on the early radiation ?

- Suffers from the non-locality problem ! (Also violation of extended quantum Church-Turing thesis)



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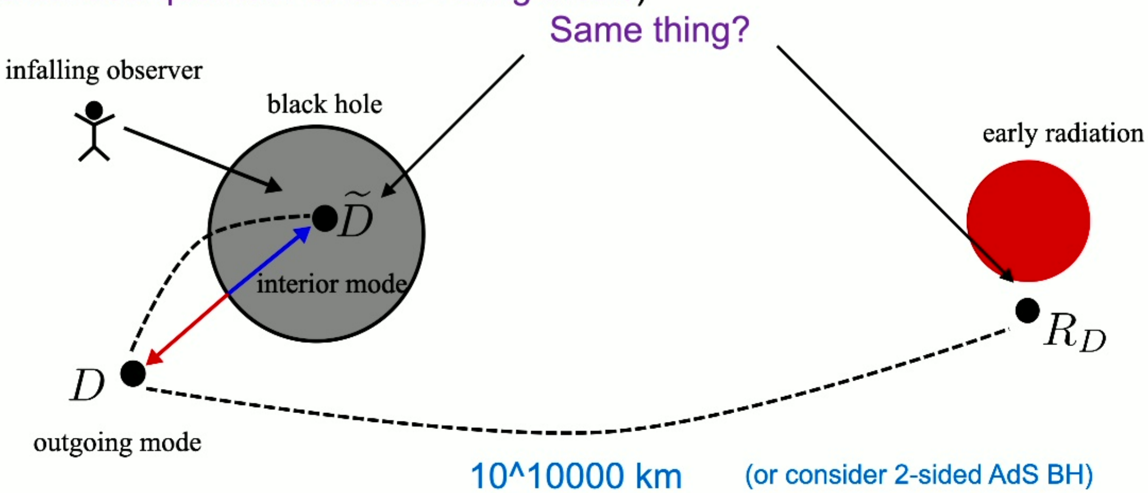
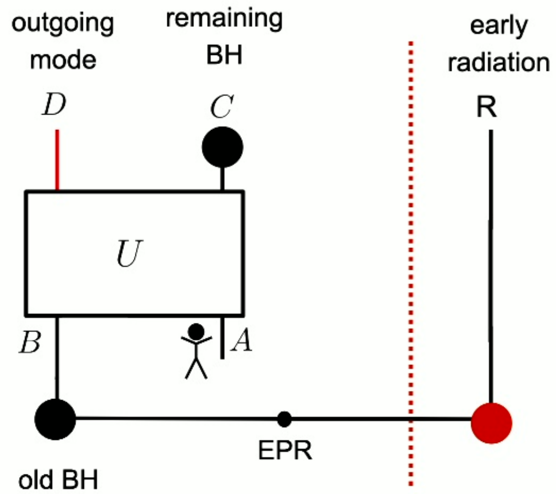


Black hole with infalling observer

✤ An observer (finite energy) jumps into a black hole at t=0.



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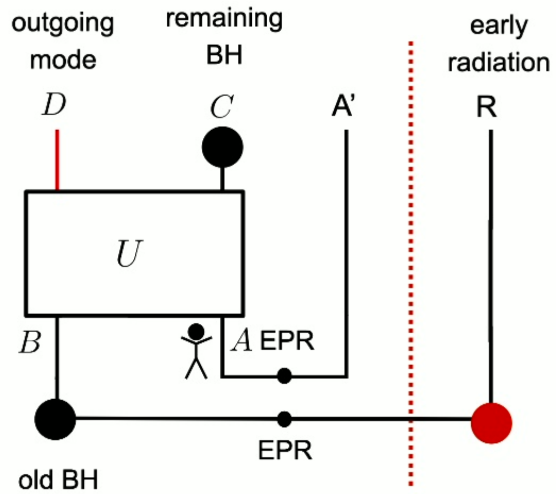
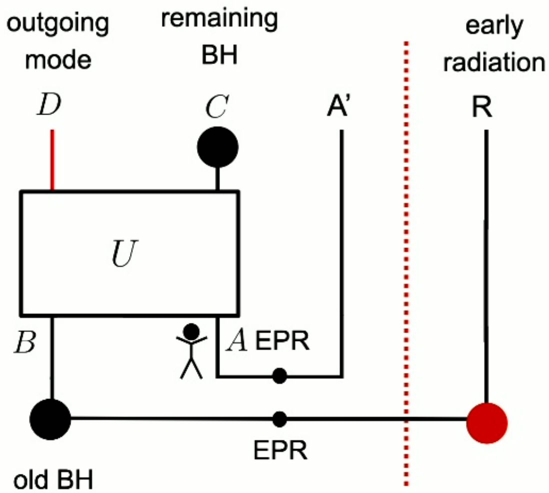


Black hole with infalling observer

✤ An observer (finite energy) jumps into a black hole at t=0.

Without infalling observer ⟶ Interior mode would be in R

With infalling observer ⟶ Where is the interior mode ?



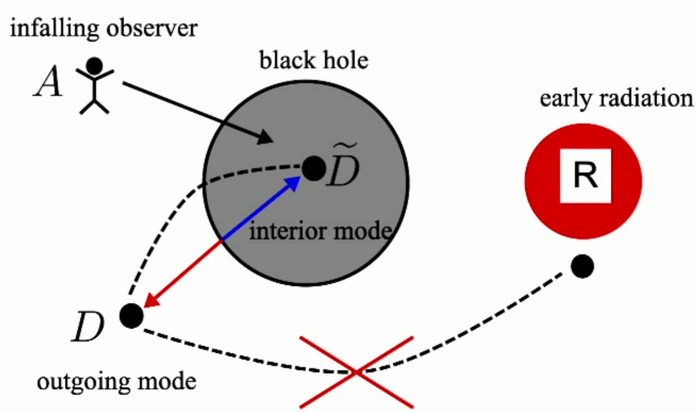
Black Hole decoupling theorem

Theorem 1. *Suppose that the black hole's dynamics is scrambling and* $d_A \gtrsim d_D$. *Then, the subsystems* D *and* R *are decoupled:*

OTOCs $\langle O_A(0) O_D(t) O_A(0) O_D(t) \rangle$

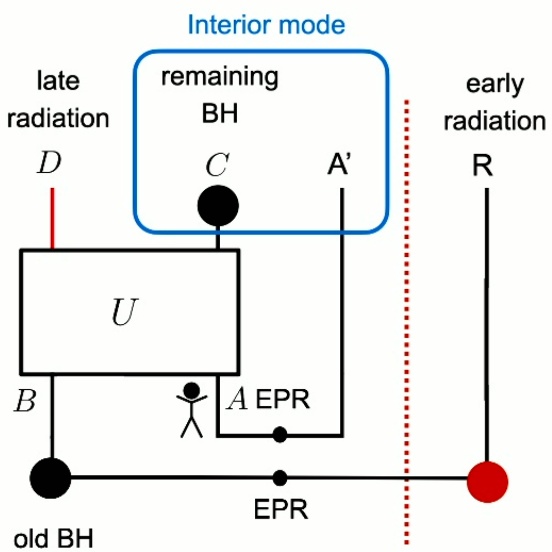
$$\rho_{D\mathsf{R}} \approx \rho_D \otimes \rho_{\mathsf{R}}. \tag{8}$$

(BY-Kitaev17)



State-independent and Observer-dependent

✤ Interior partner mode can be found on CA'. Non-locality is avoided.



State-independent and Observer-dependent

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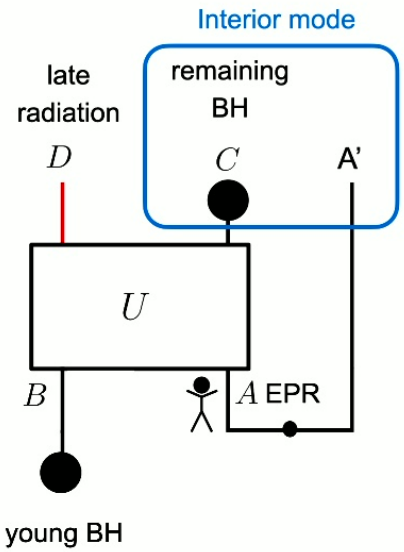
  ⟶ Construction is state-independent

- The same interior partner mode works well for young black hole as well



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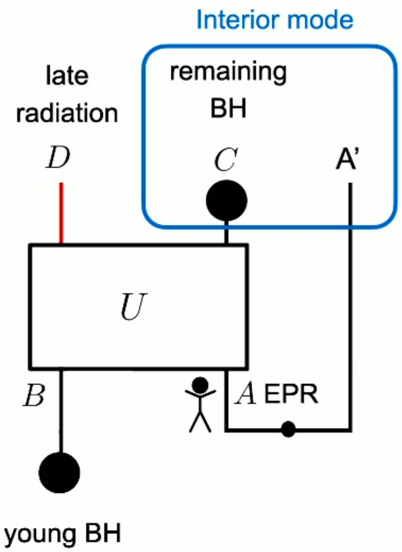
  → This resolves the "typical state" puzzle due to Marolf-Polchinski.



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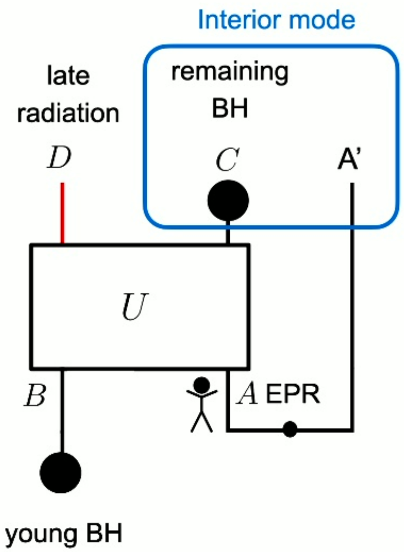
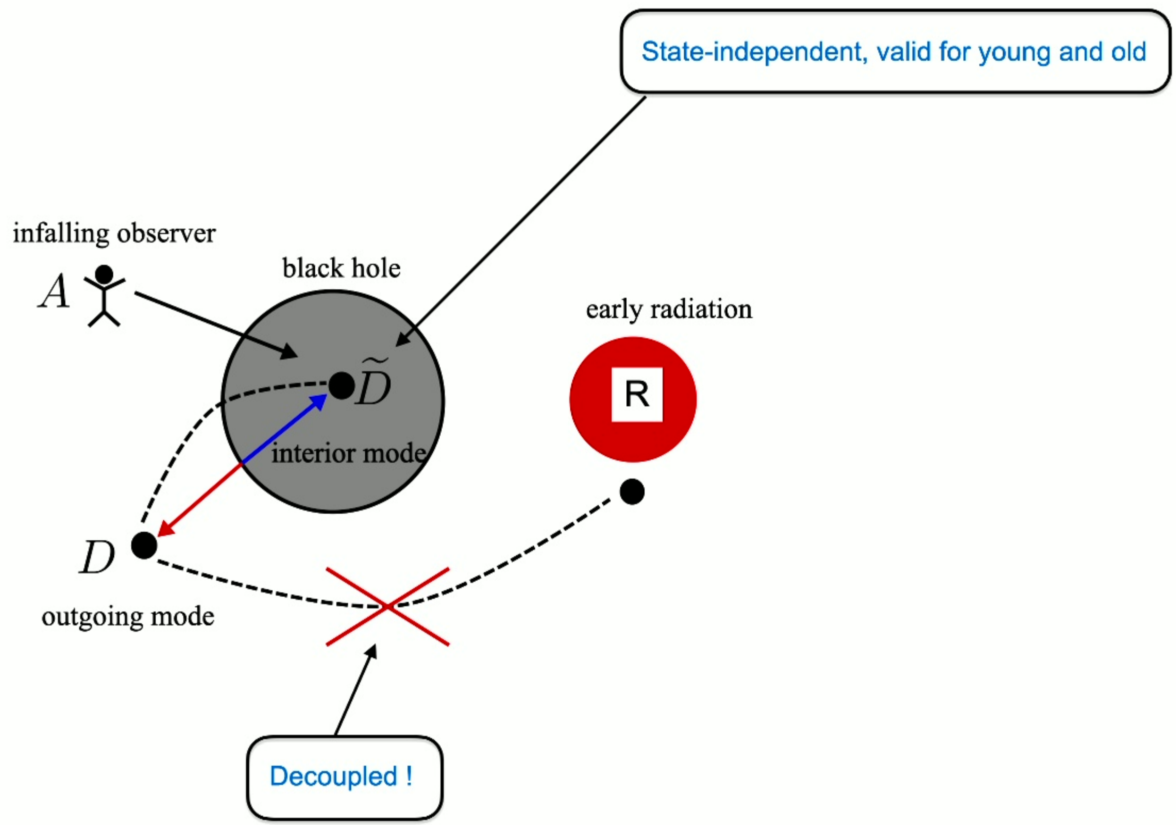


- The construction is observer-dependent.

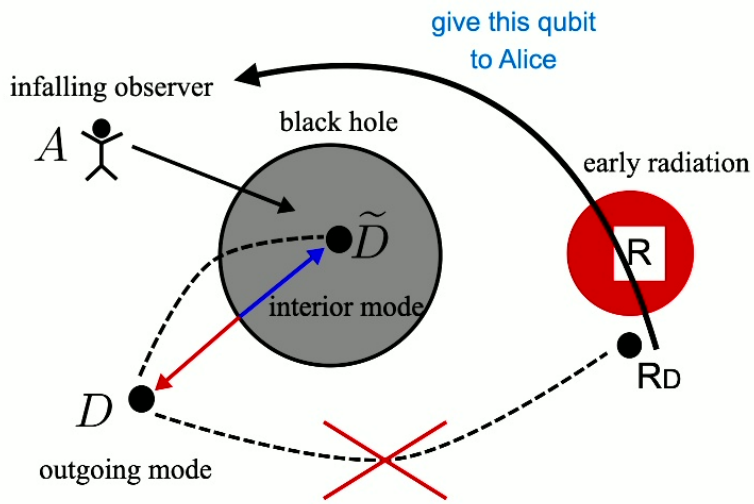
⟶ Interior operators change dynamically, depending on the observer's initial state

Summary


State-independent, valid for young and old
infalling observer
A
black hole
early radiation
$\widetilde{D}$
R
interior mode
D
outgoing mode
Decoupled !

AMPS thought experiment

- Alice jumps into a black hole with R_D. Will she cross the horizon safely?



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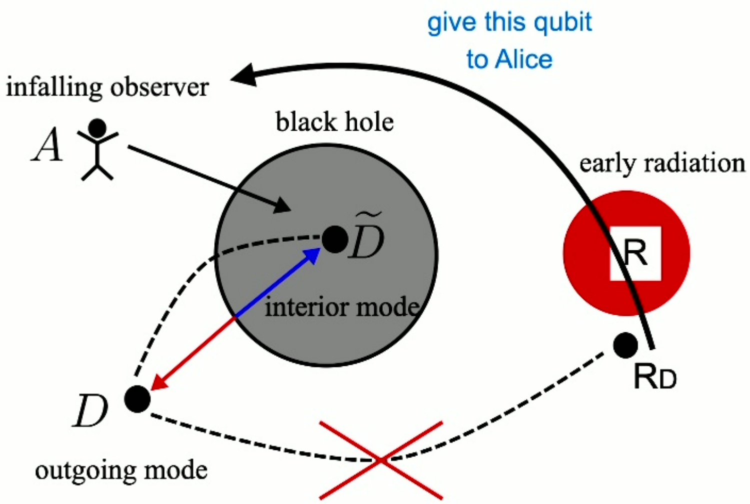
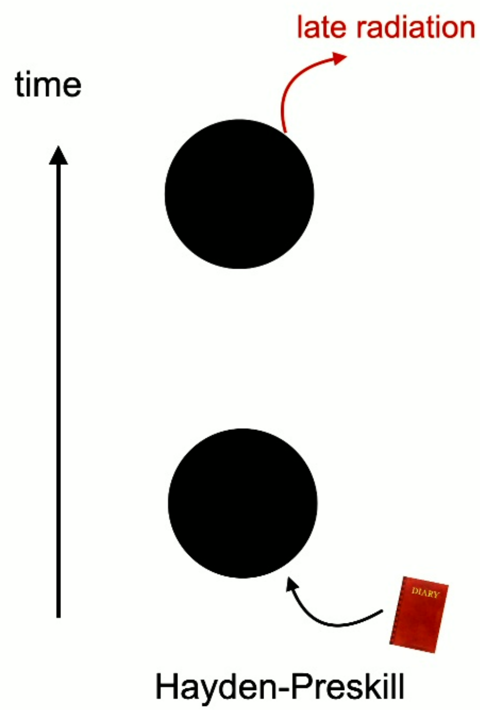


Hayden-Preskill and AMPS



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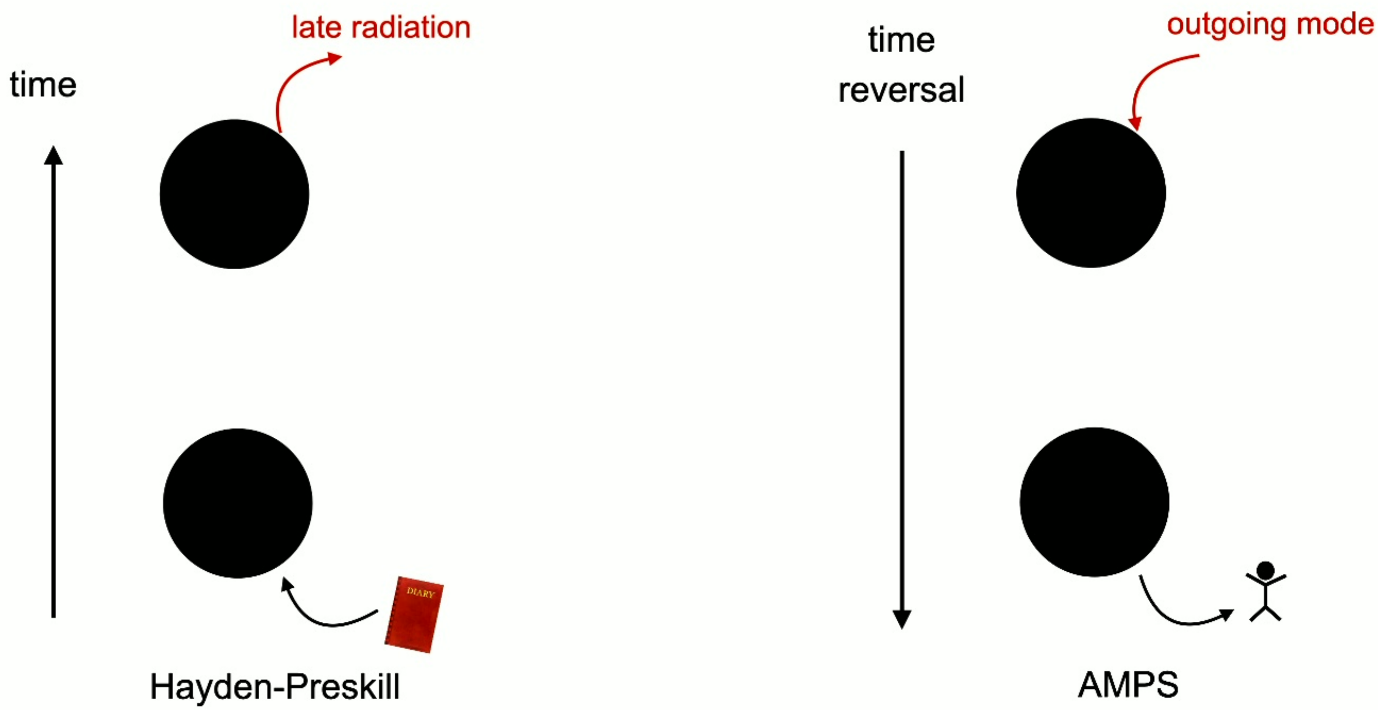

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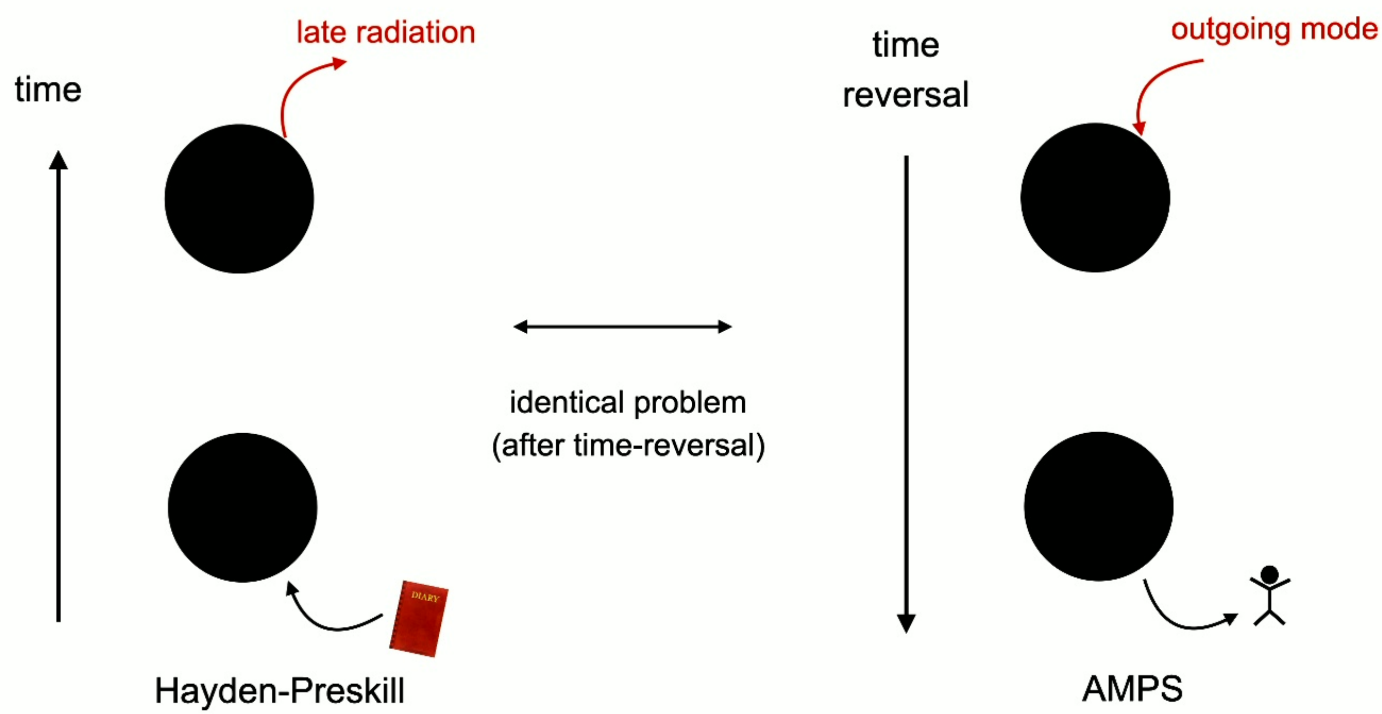

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Future directions

- ✤ Going beyond AdS
  - de Sitter horizon puzzles
  - entanglement in de Sitter
- ✤ Emergence of interaction from entanglement
  - calculate it in “holographic” CFT

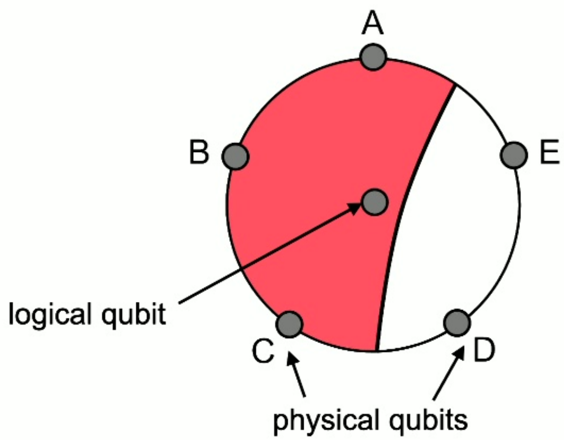
A simple toy model ?

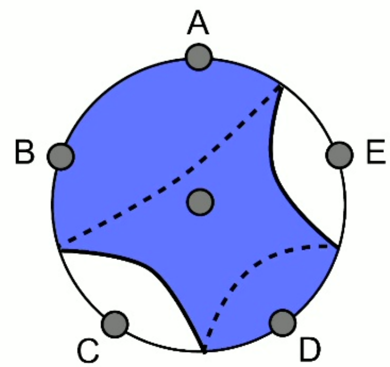
1 bulk qubit

5 boundary qubits

in total, just 6 qubits

A bulk operator must have representations on any region with three qubits.





Entanglement wedge reconstruction !