Decoding a black hole;

from scrambling to information loss

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August 2018 @ Tokyo

Collaborators


Xiao-liang Qi (Stanford)


Daniel Roberts (facebook AI)


Alexei Kitaev (Caltech)

Based on

- Chaos in quantum channels, Pavan Hosur, Xiao-liang Qi, Daniel Roberts, BY (2015)
- Efficient decoding for Hayden-Preskill protocol, BY and Alexei Kitaev (2017)
- Verified quantum information scrambling, [experiment with C Monroe group] (2018)

Can we retrieve a quantum state from a black hole?

Information loss puzzle

- Quantum mechanics and general relativity are in serious conflicts !

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(a) Quantum mechanics says that information is never lost.

$$|\psi(t)\rangle = e^{-iHt}|\psi(0)\rangle$$

(b) General relativity says information is lost in black holes.

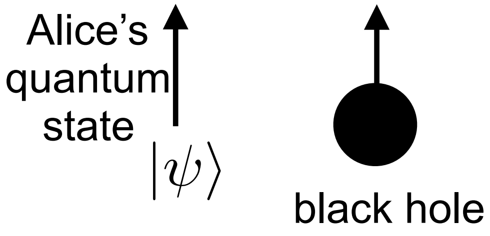
$|\psi\rangle$

Hawking radiation

"$e^{-\beta H}$"

Page's thought experiment

- Alice throws a quantum state into a black hole. Bob tries to reconstruct it from the Hawking radiation. Black hole = n-qubit system. (n = coarse-grained entropy)



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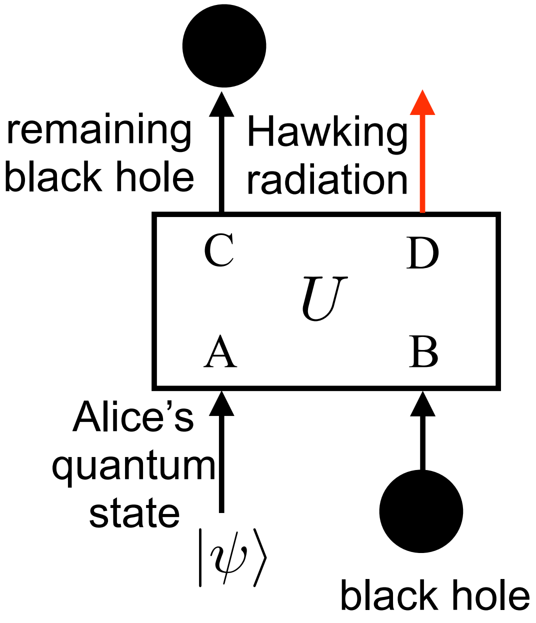

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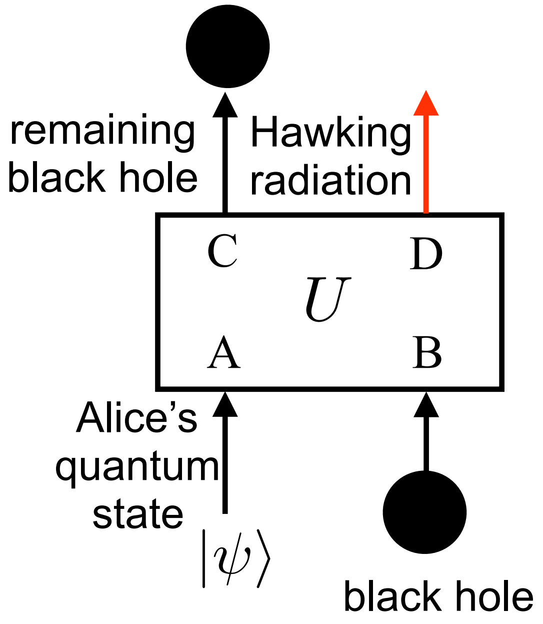
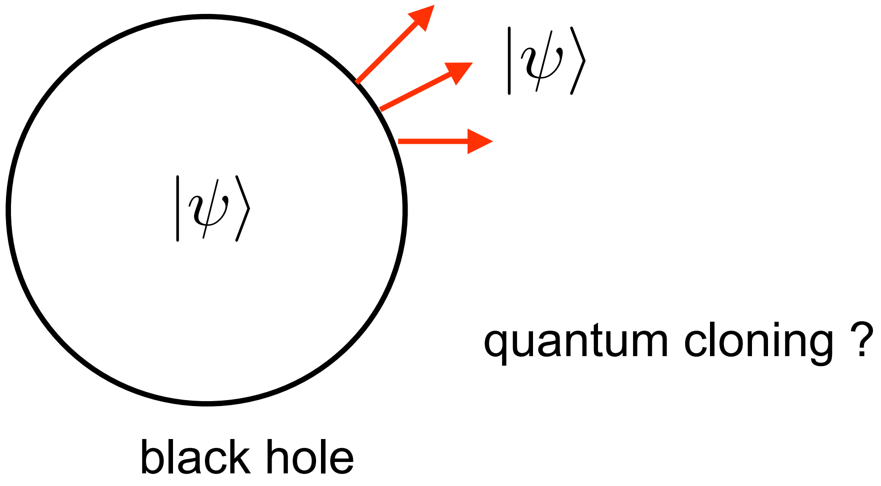
- Quantum Cloning ? Black hole complementarity ! (no observer can see a quantum cloning).





Hayden-Preskill thought experiment (2007)

- Bob holds a quantum memory M which is maximally entangled with a black hole

  (eg. black hole has emitted half of its content).

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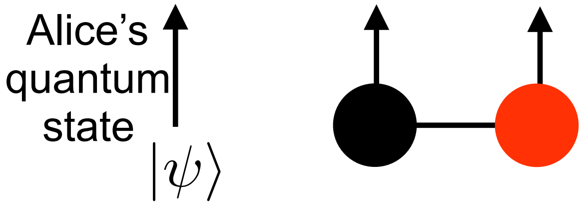

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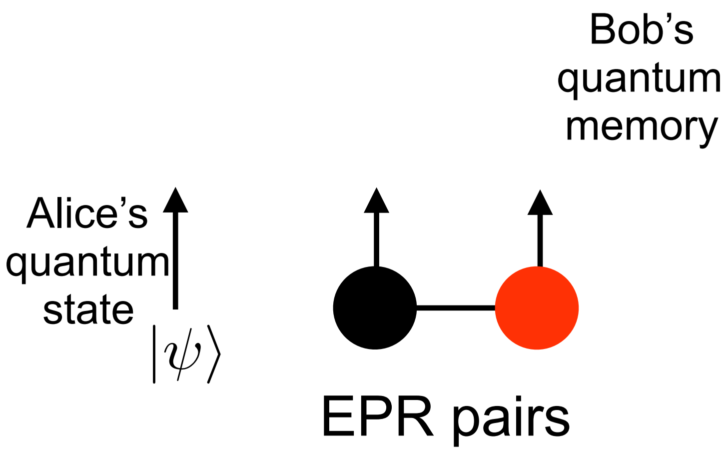

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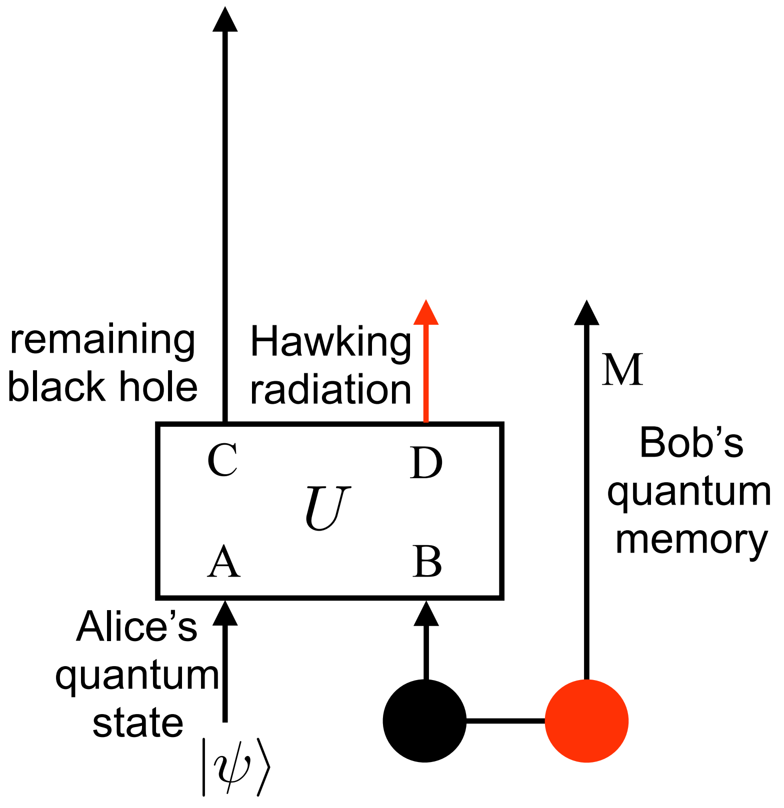

EPR pairs

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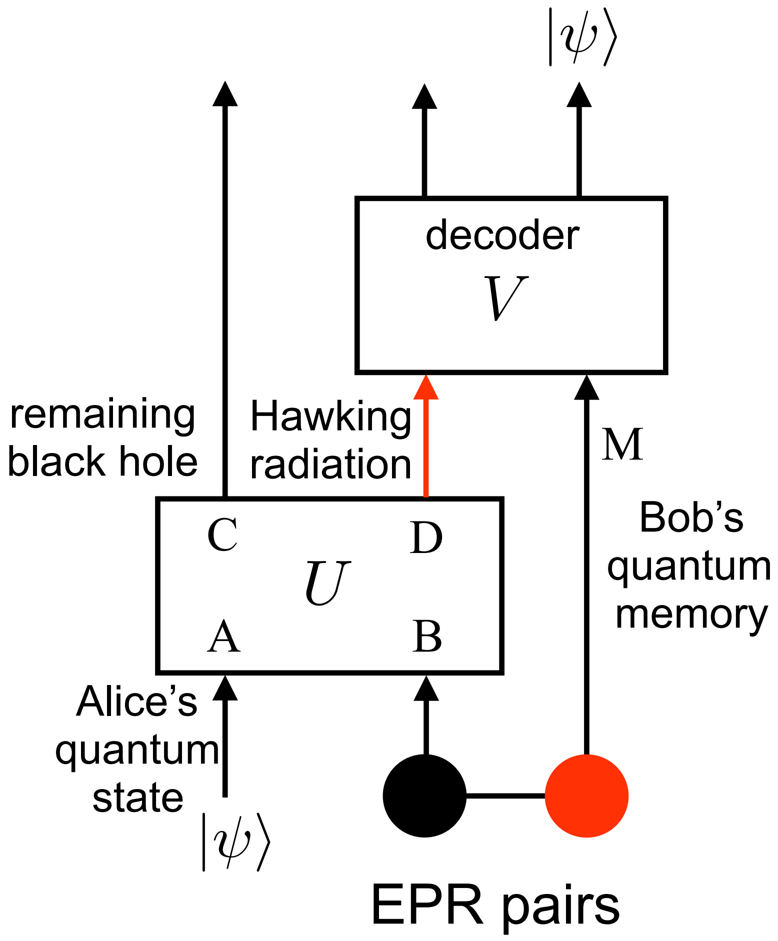

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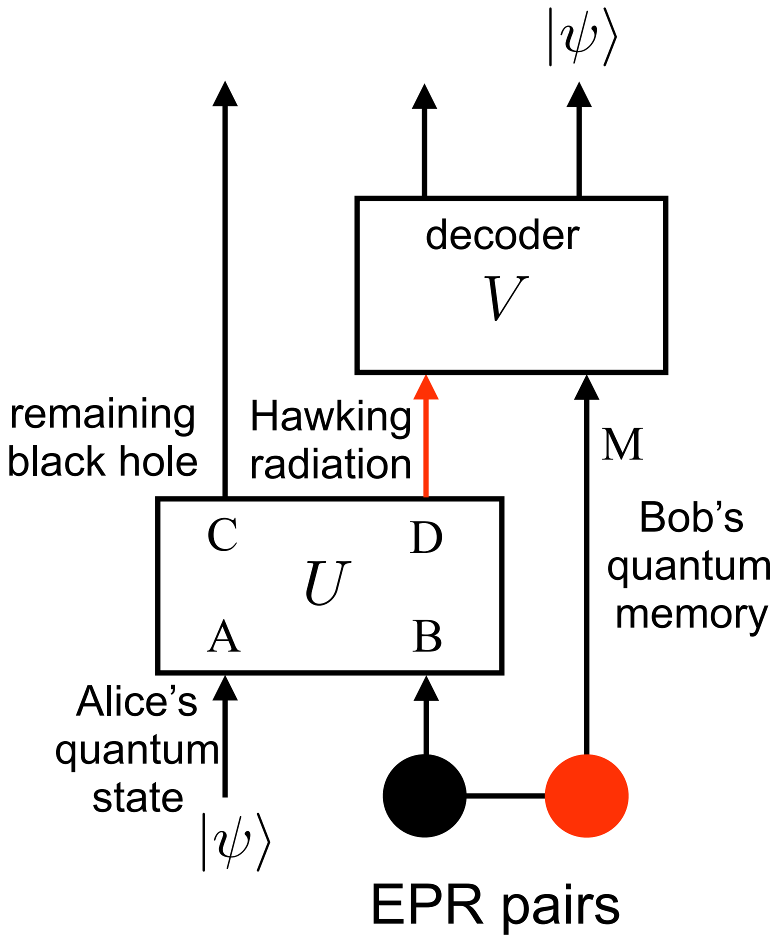

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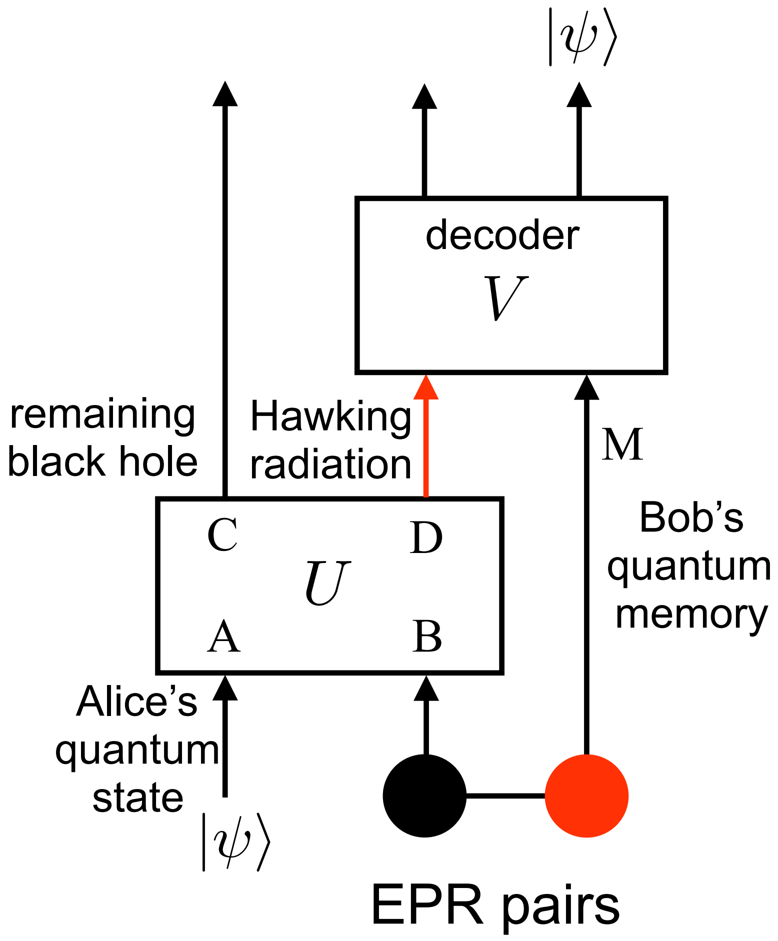

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How do we construct the decoder V ?

this talk !

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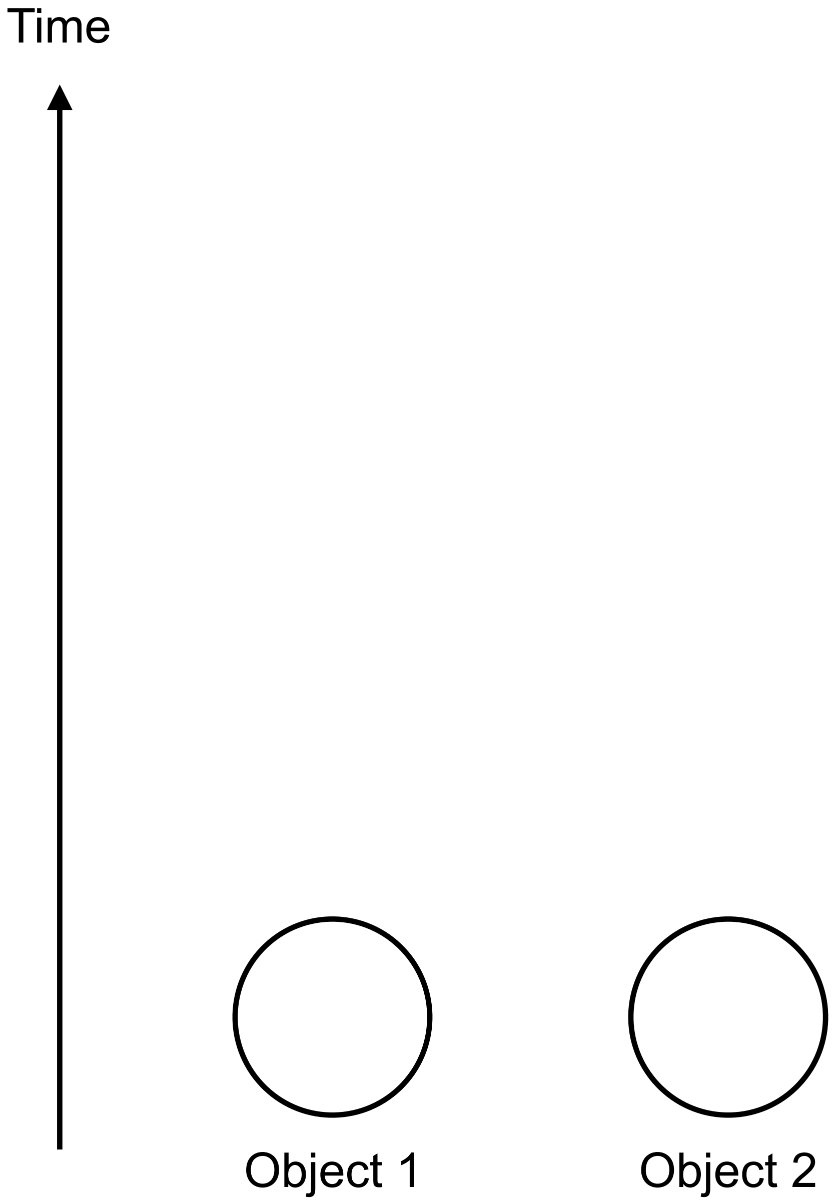
- Fast scrambling conjecture: Black hole is the "fastest" "scrambler" in nature ?

(Hayden-Preskill, Sekino-Susskind, later proven by Maldacena-Shenker-Stanford)

$$t_{\mathrm{scr}} \approx \log(n) \quad ??$$

Quantum chaos ? (2013)

- Classical chaos = sensitive dependence of dynamics on initial conditions



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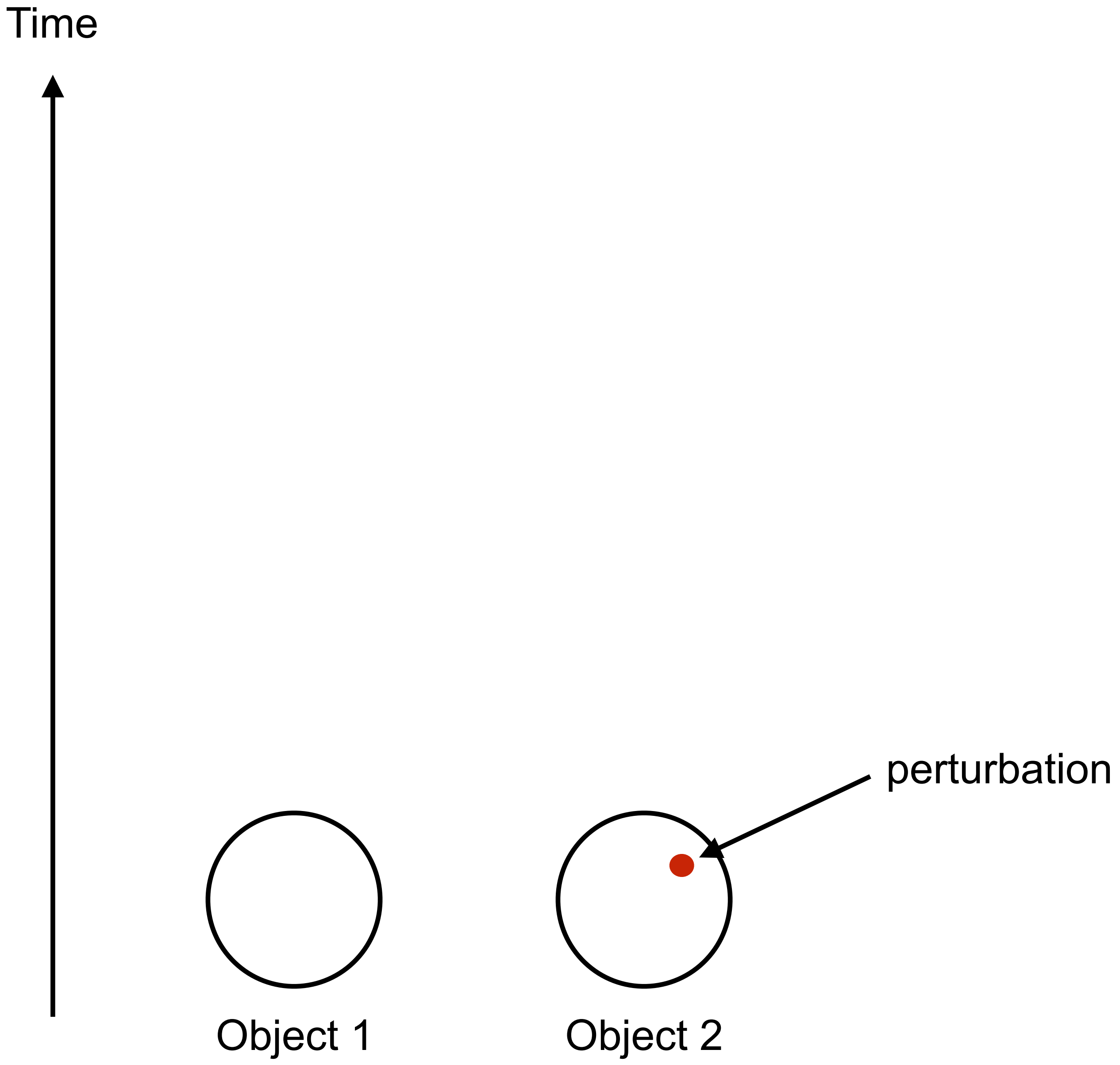

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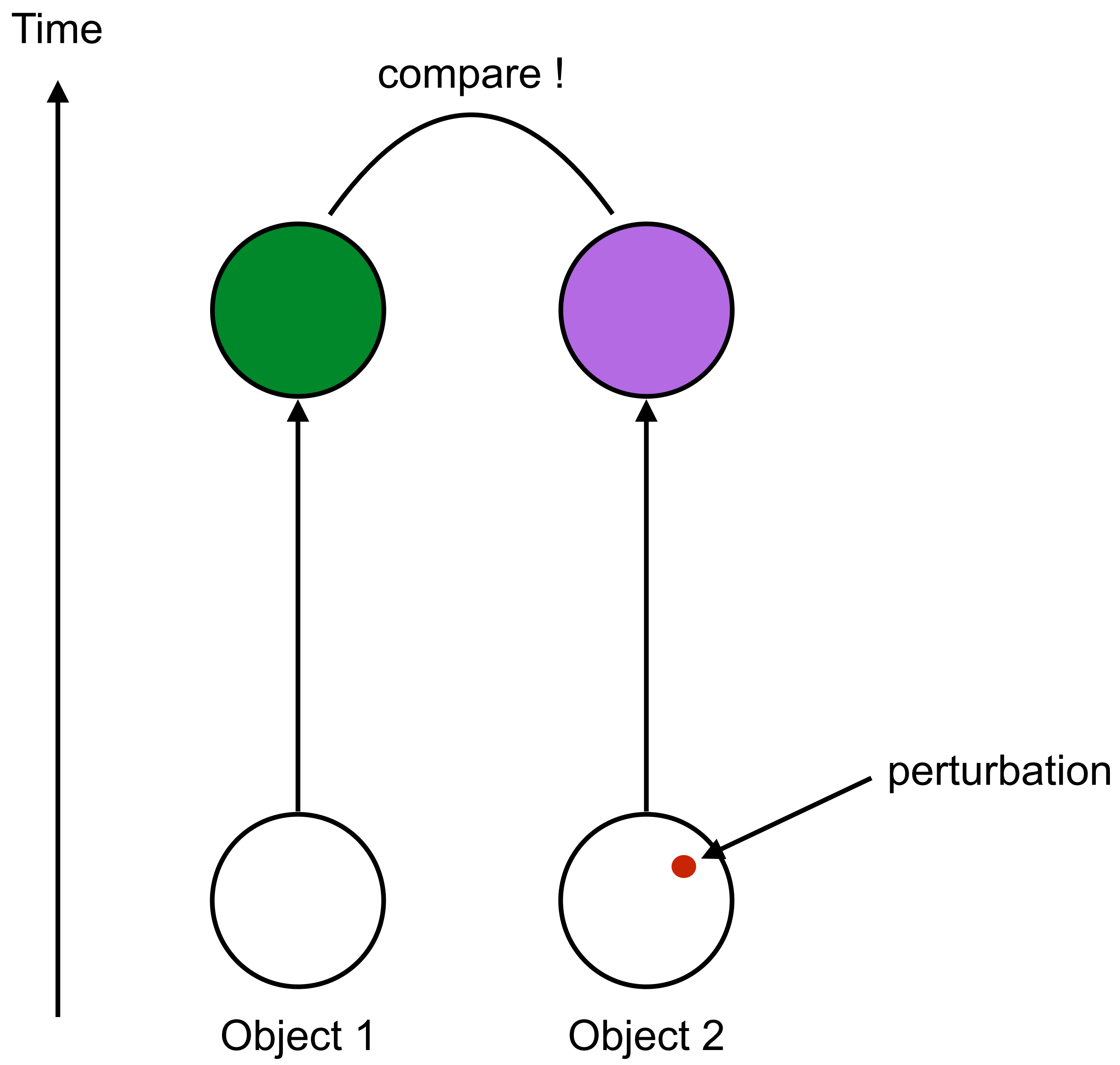

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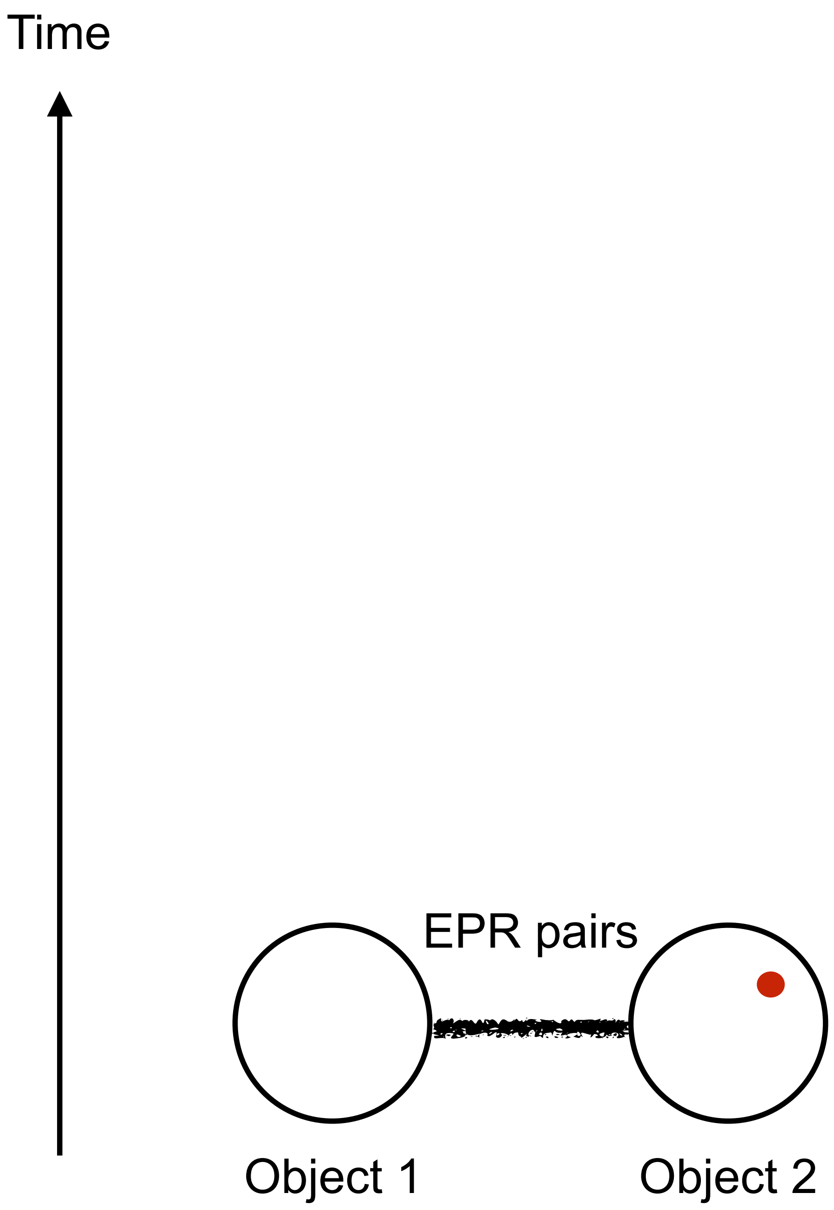

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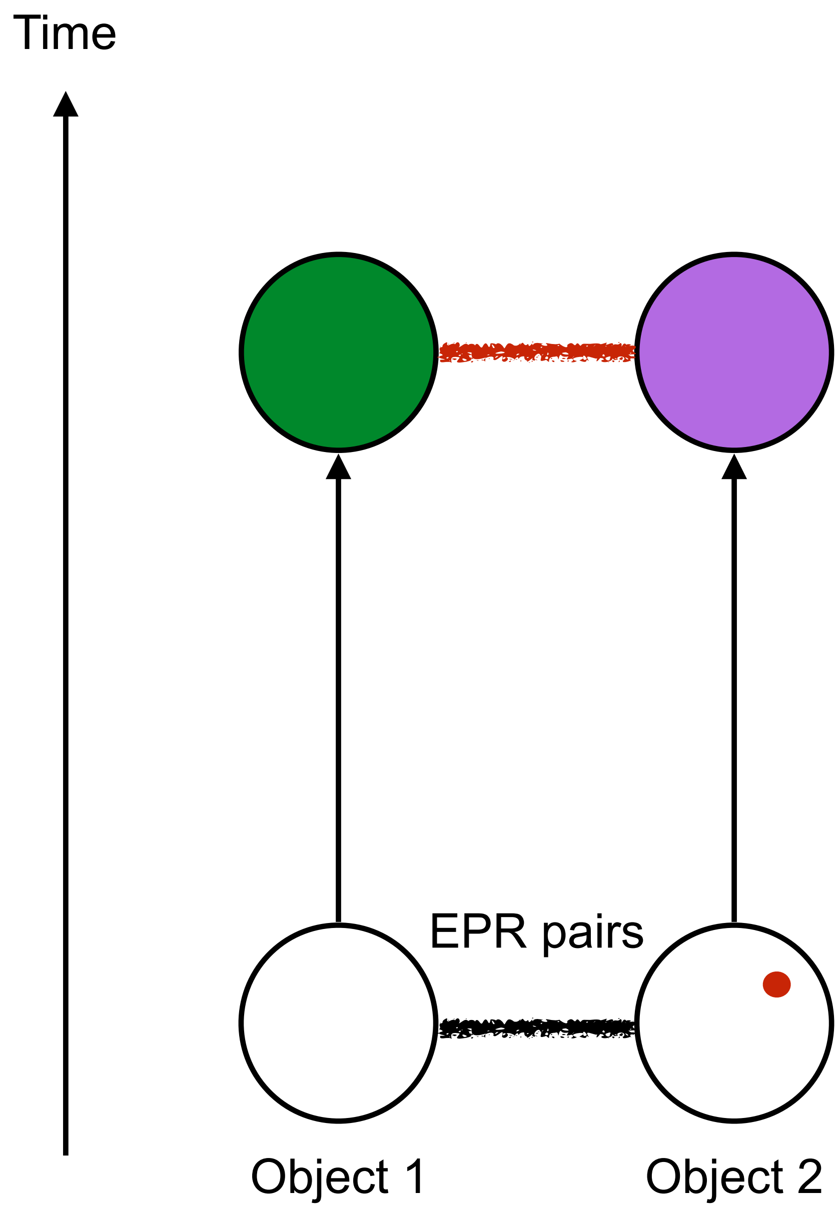

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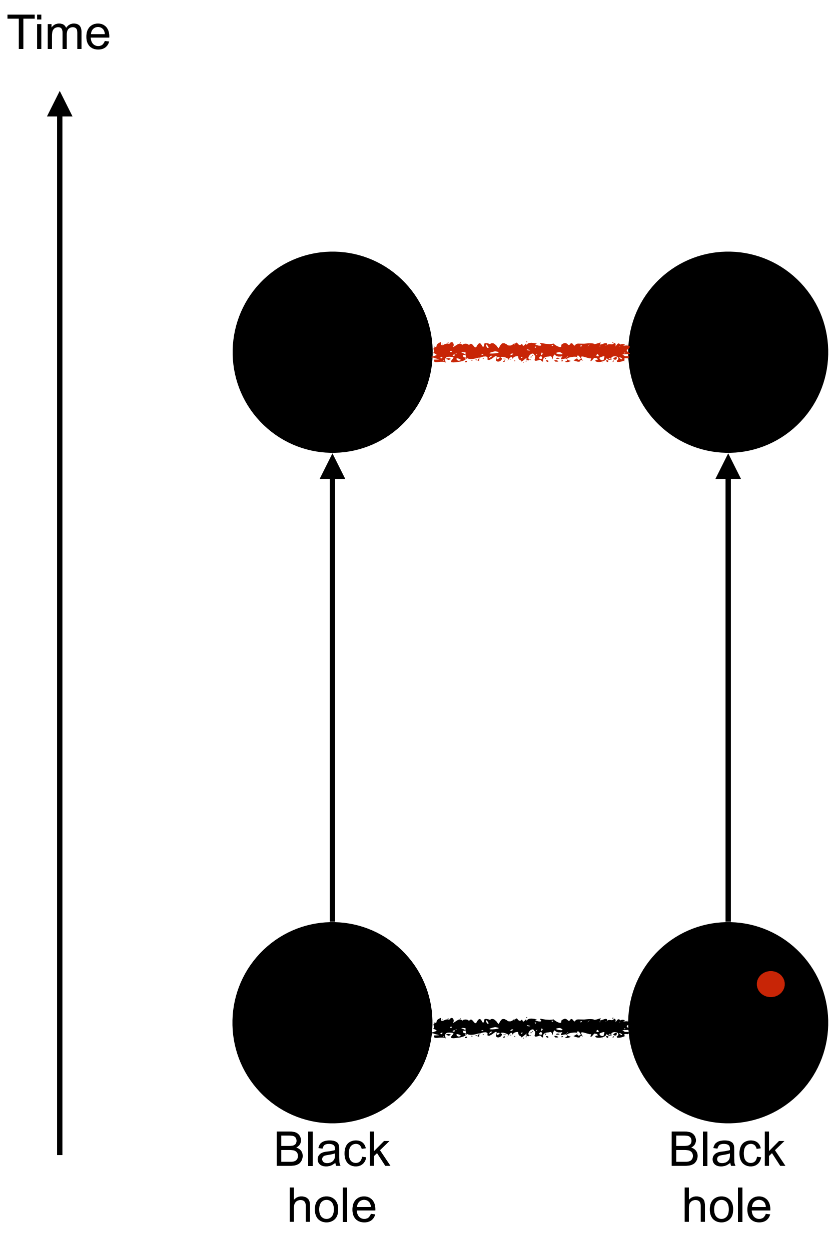
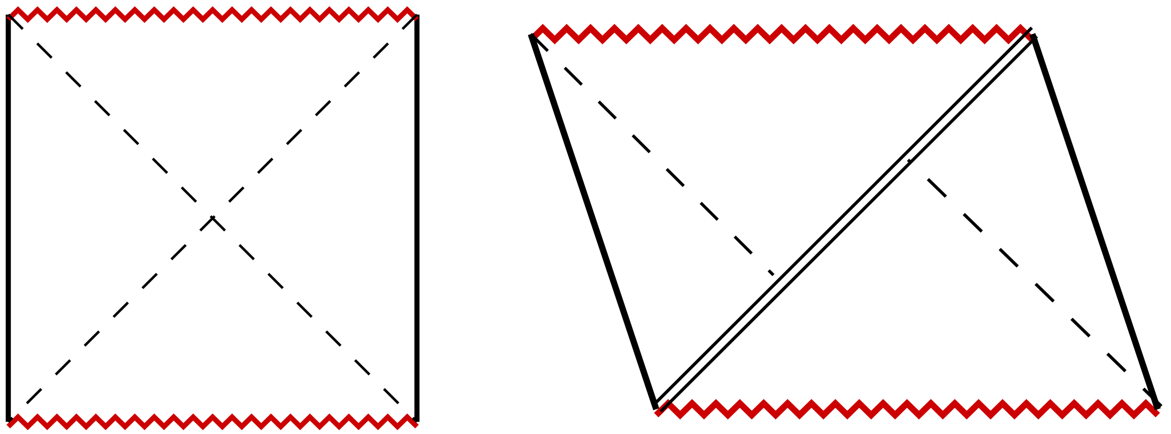
- Shenker-Stanford: Butterfly effect in an entangled black hole.



- Perturbation becomes a gravitational shockwave

('t Hooft-Dray 85) ('t Hooft 87, Kiem-Verlinde-Verlinde 95)

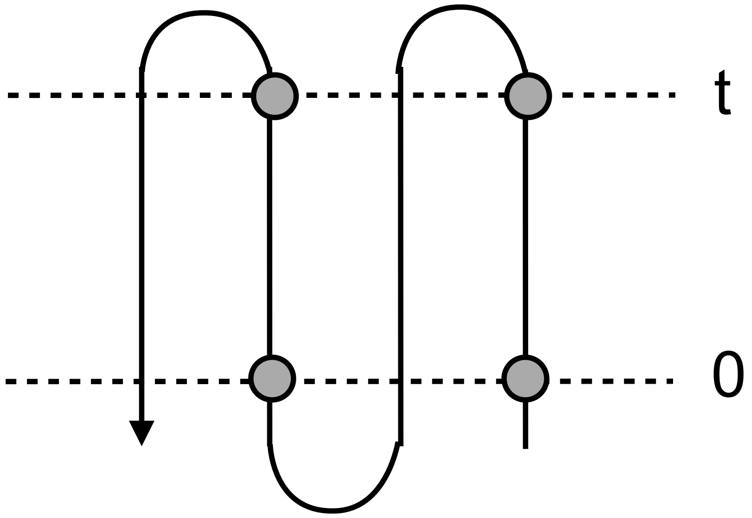


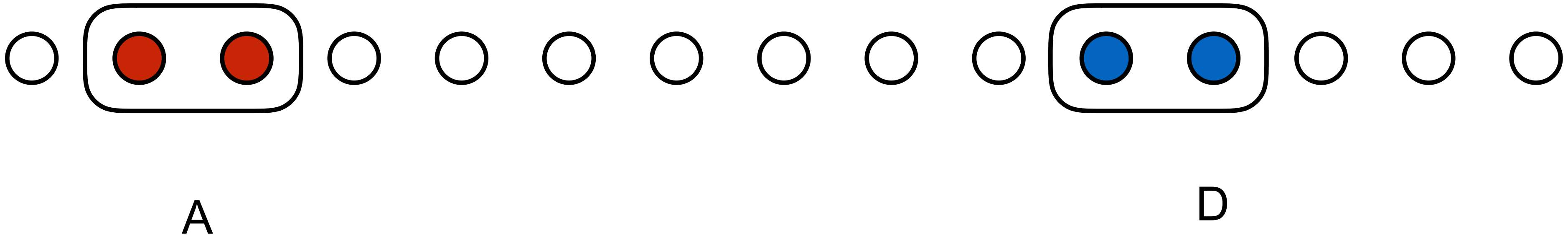
Out-of-time ordered correlation functions (2014)

- OTOCs : $\langle O_A O_D(t) O_A O_D(t) \rangle = \mathrm{Tr}\big(O_A O_D(t) O_A O_D(t) \rho_\beta \big)$

$$O_D(t) = e^{-iHt} O_D e^{iHt}$$

Infinite temperature





[Shenker-Stanford, Roberts-Stanford-Susskind, Kitaev]

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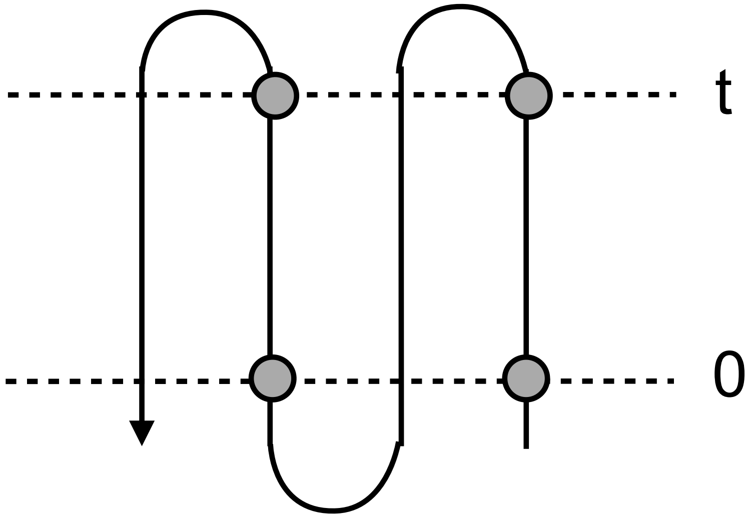

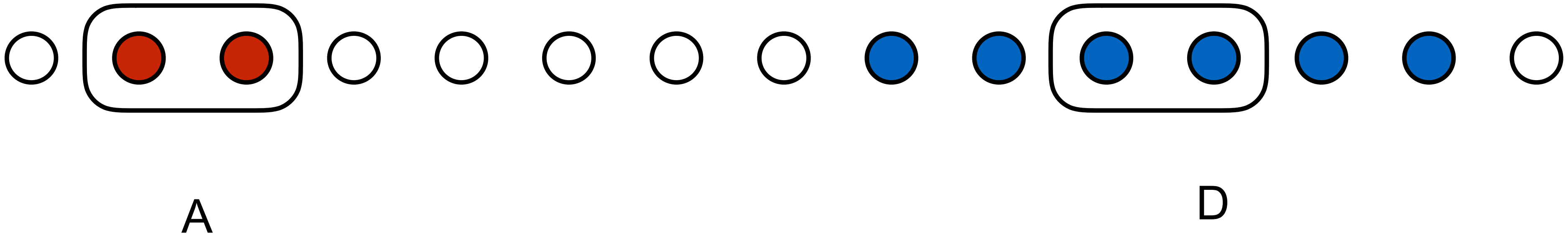

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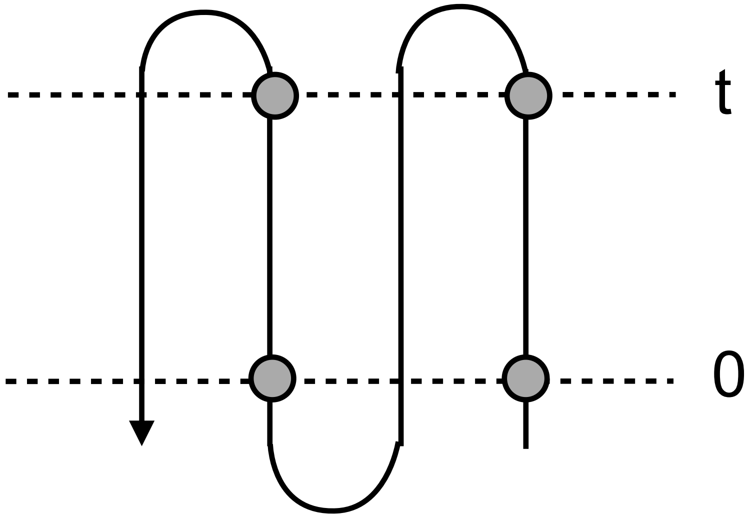
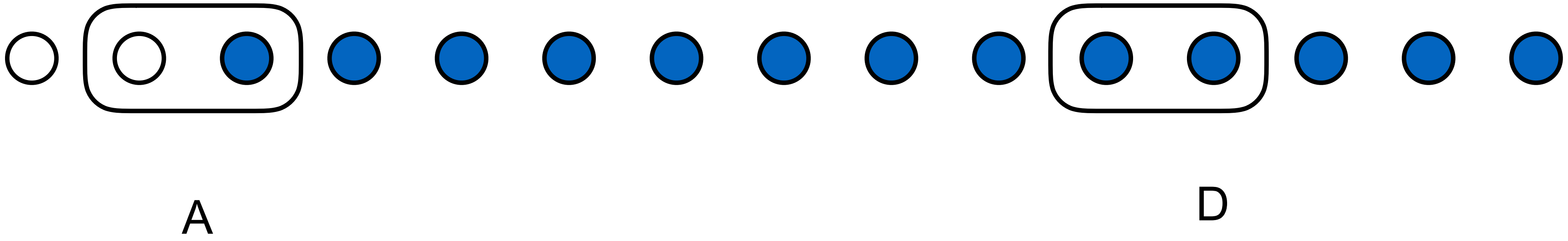
large t $O_D(t)$ becomes a non-local operator OTOC ~ 0

Two operators become non-commuting.





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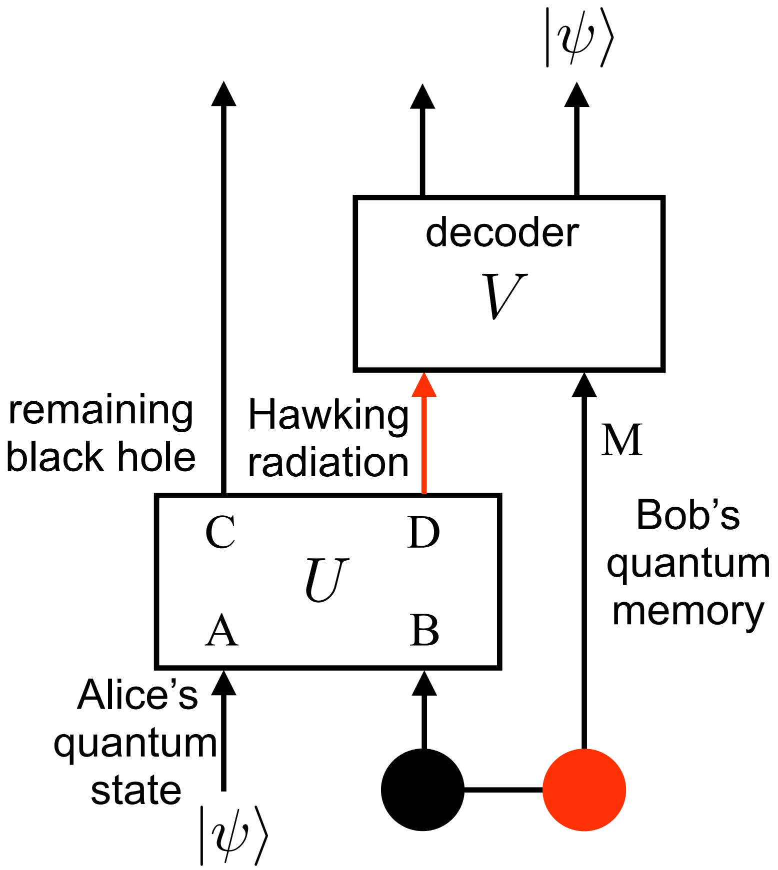
Hayden-Preskill and OTOC ?


$|\psi\rangle$

decoder

V

remaining black hole

Hawking radiation

M

C D

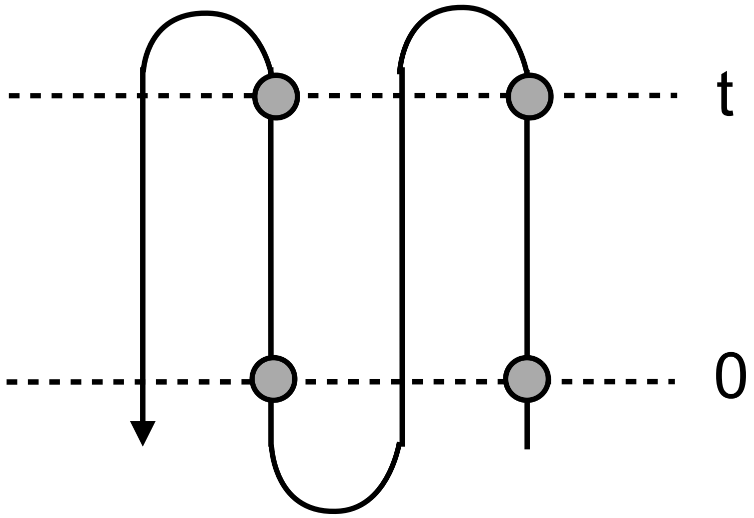
U

A B

Bob's quantum memory

Alice's quantum state

$|\psi\rangle$

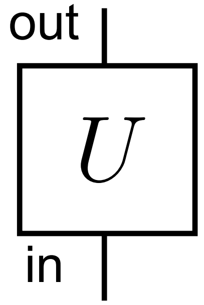


$$\langle O_A O_D(t) O_A O_D(t) \rangle$$

State-channel duality

- Unitary operator acting on n qubits can be viewed as a state on 2n qubits.

$$U = \sum_{i,j} U_{ij} |i\rangle\langle j|$$



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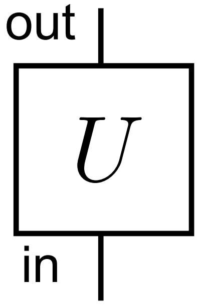

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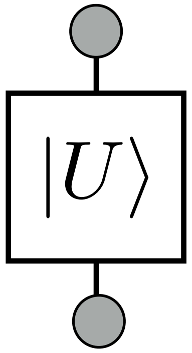

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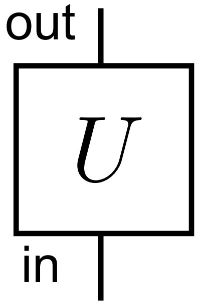

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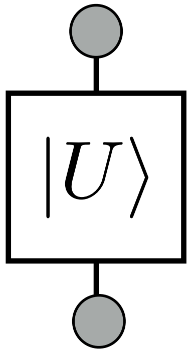

A dynamics can be studied via properties of entanglement !

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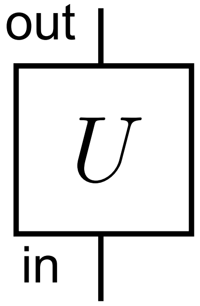

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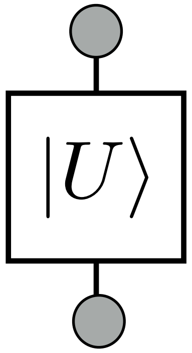
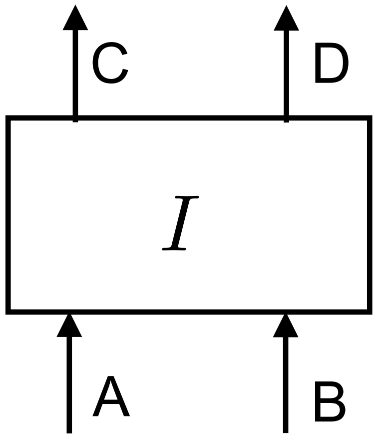


- An identity operator



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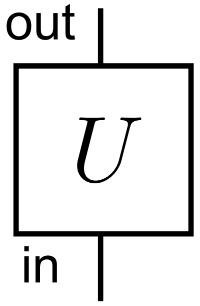

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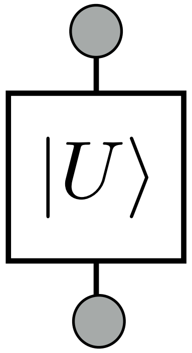

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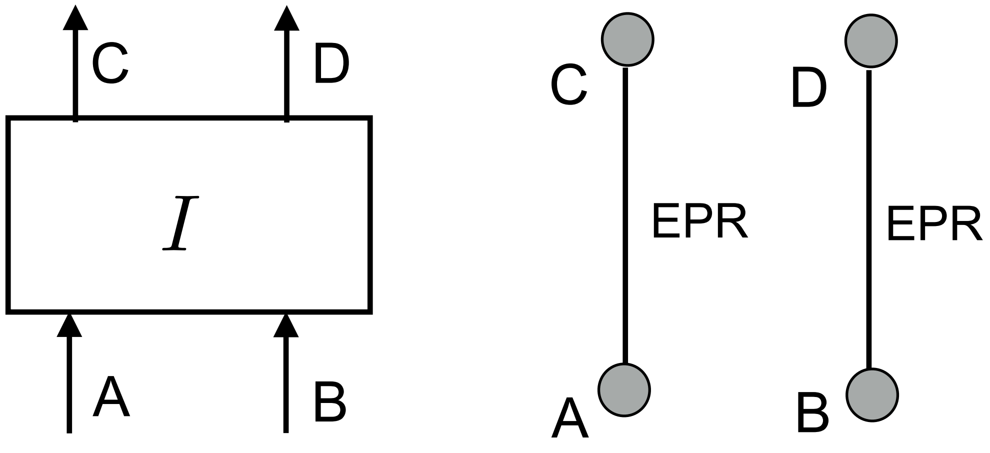

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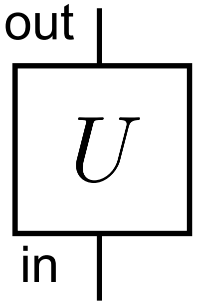

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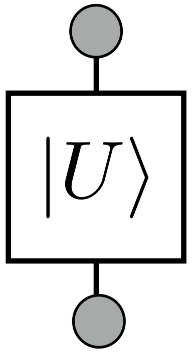

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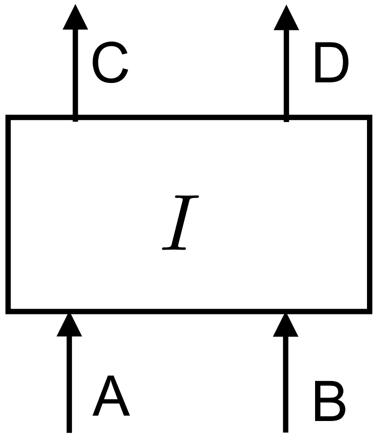
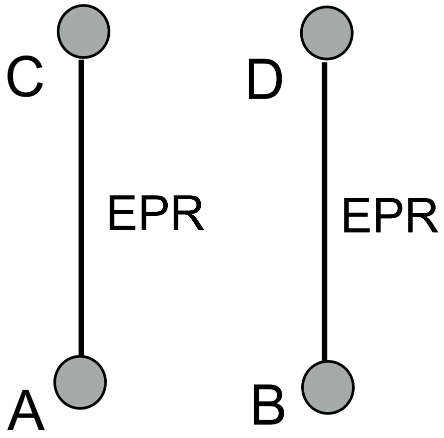
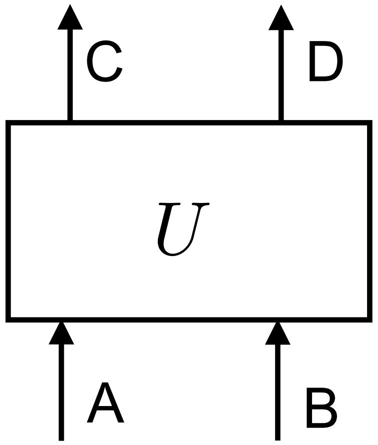




- “Scrambling” and/or “Interacting”



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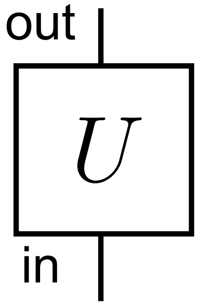

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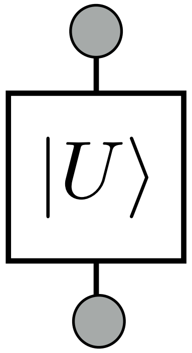

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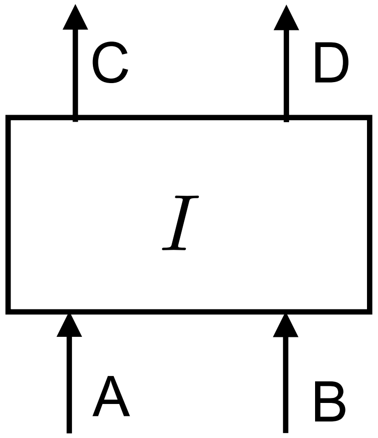

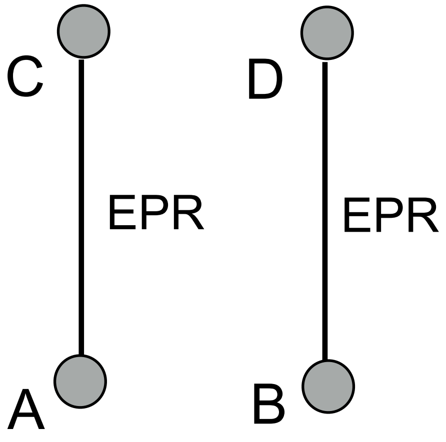

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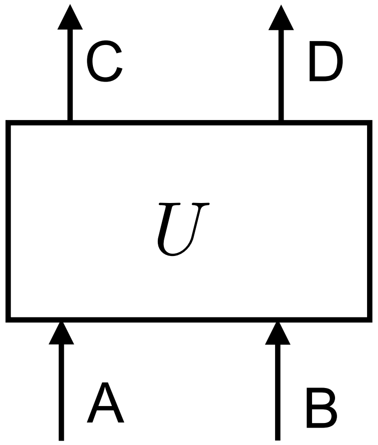

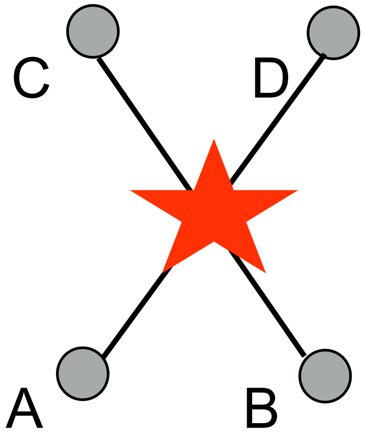

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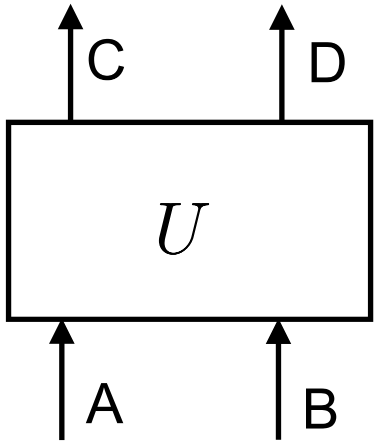
Multipartite entanglement

- Physical realization ?



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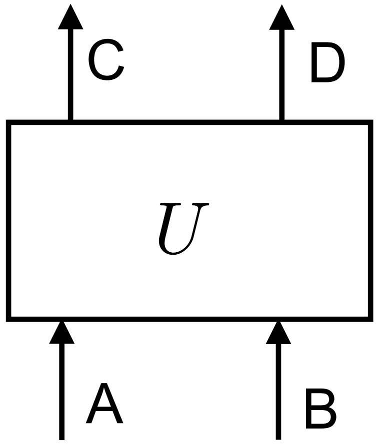
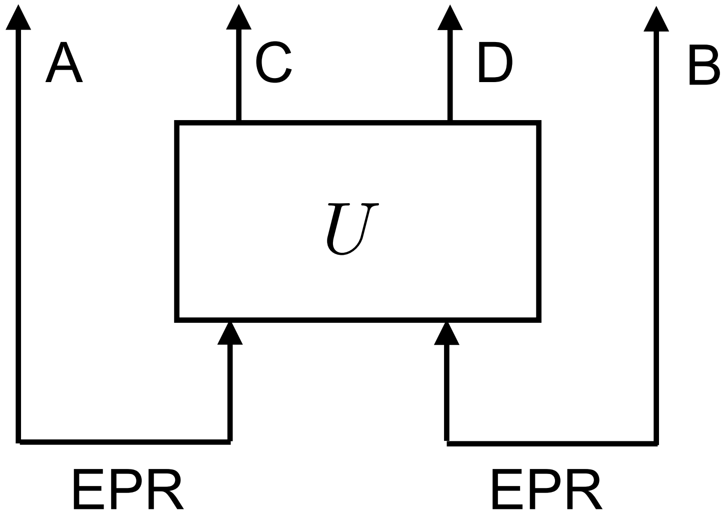
[Hosur-Qi-Roberts-BY]

Multipartite entanglement

- Physical realization ?



unitary operator



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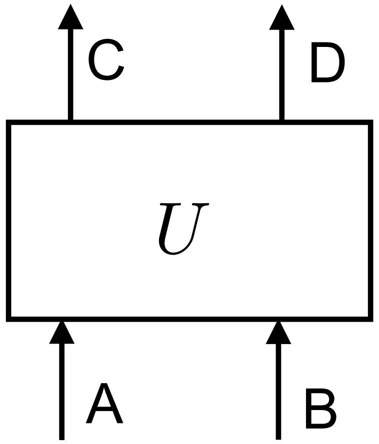

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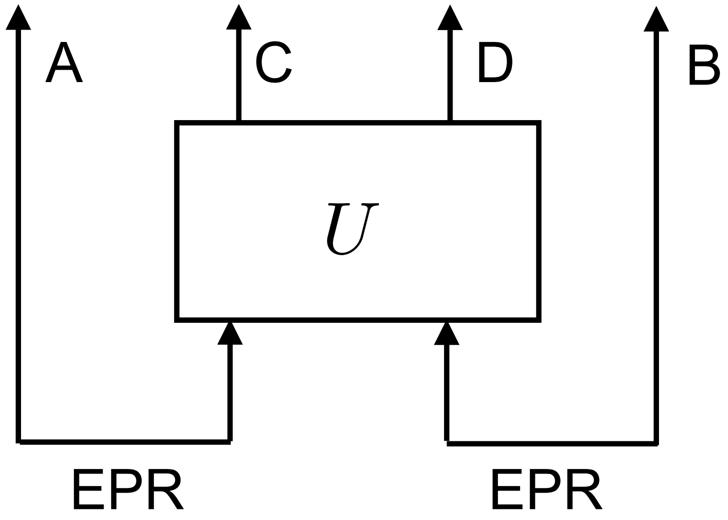

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- Multipartite entanglement (Tripartite mutual information)

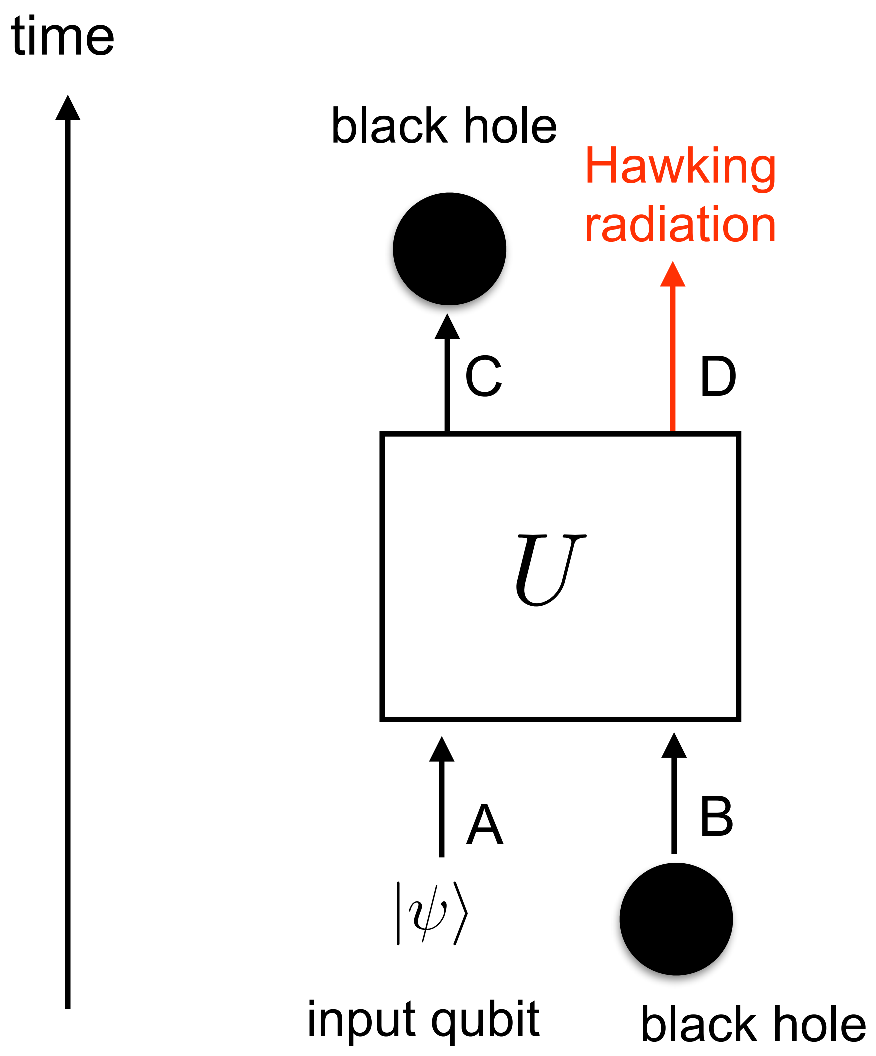
$$I_3 = S_A + S_B + S_C - S_{AB} - S_{BC} - S_{CA} + S_{ABC}$$

  - Non-interacting (eg free boson) $I_3 \simeq 0$
  - Interacting (eg Haar, late-time) $I_3 \simeq O(n)$

[Hosur-Qi-Roberts-BY]

Entanglement in black hole dynamics

- Viewing the black hole dynamics as a quantum state. (also Hartman-Maldacena 2013)



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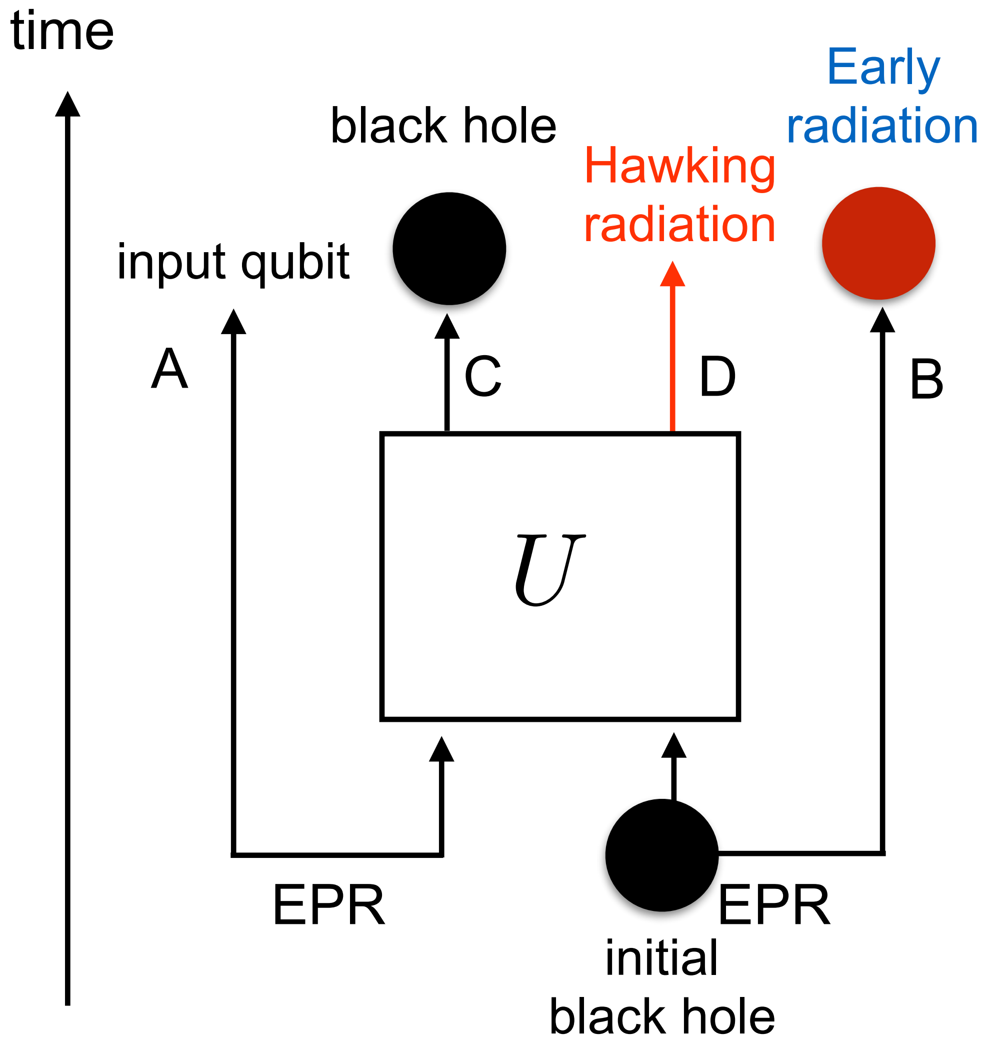

Mutual information I(A,B) = SA + SB - SAB.

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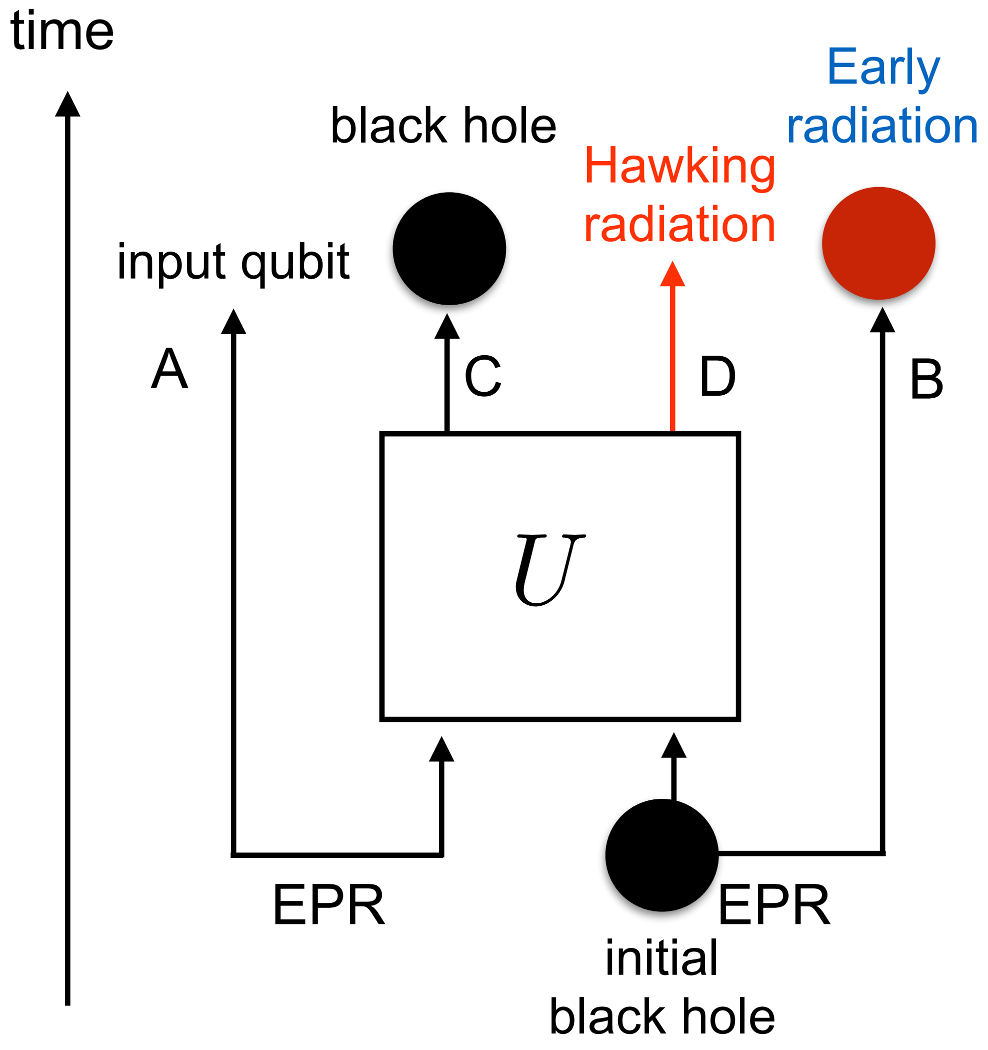

Page's experiment

Guess A from D ⟶ I(A,D)

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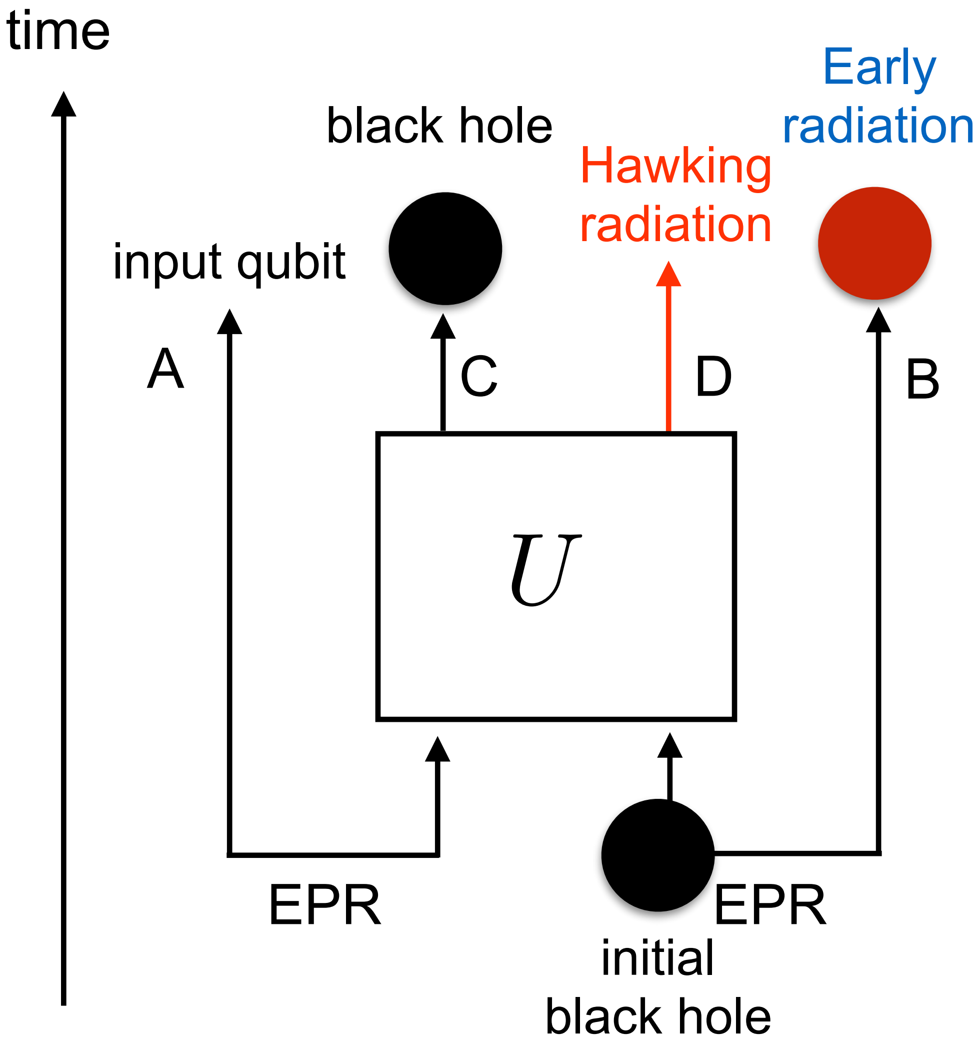


Page's experiment

Guess A from D ⟶ I(A,D)

Hayden-Preskill experiment

Guess A from B & D ⟶ I(A,BD)

I(A,BD) is nearly maximal for random U

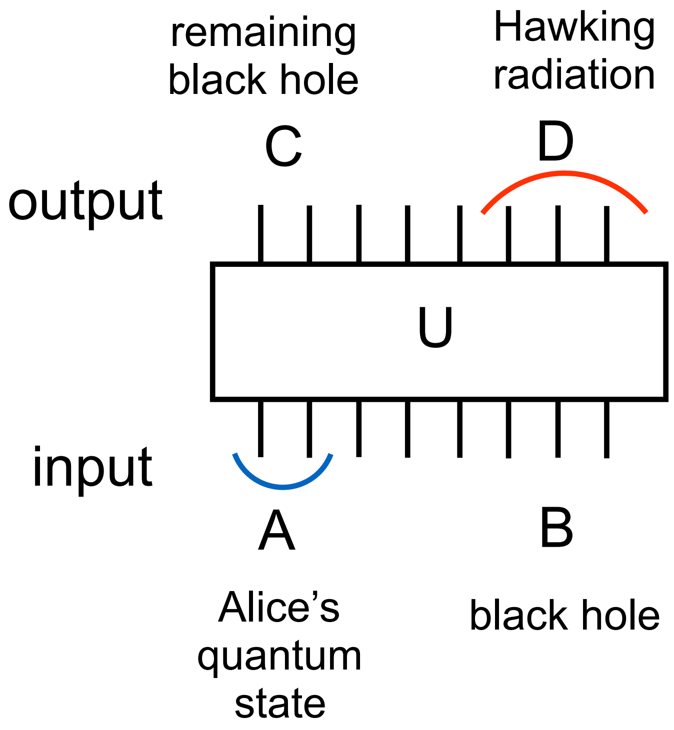
Mutual information I(A,B) = SA + SB - SAB.

OTOC and Hayden-Preskill

- The averaged OTOCs [with Hosur, Qi and Roberts]

$$\langle \mathrm{OTOC} \rangle_{\mathrm{ave}} \equiv \int dO_A dO_D \langle O_A(0) O_D(t) O_A^\dagger(0) O_D^\dagger(t) \rangle$$

average over all the basis operators (eg Pauli operators)



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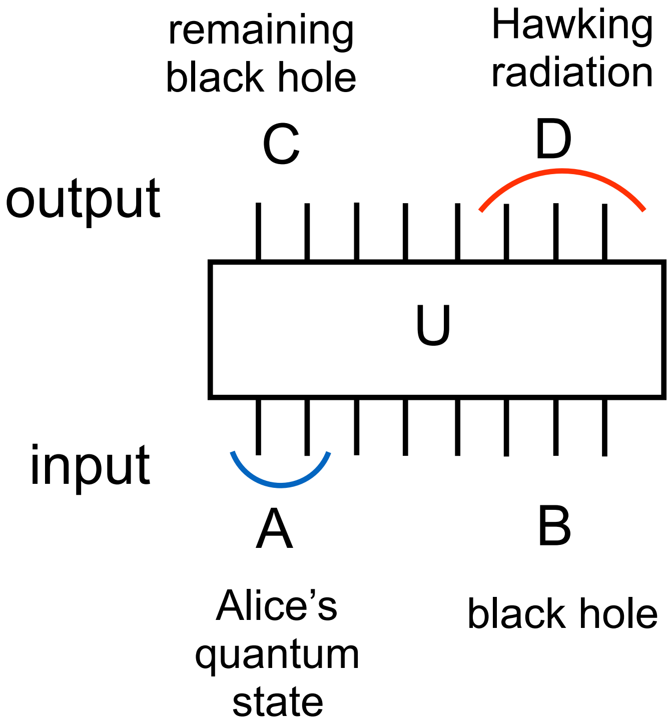

theorem (infinite temperature)

$$\boxed{-\log_2 |\langle \mathrm{OTOC} \rangle_{\mathrm{ave}}| = I^{(2)}(A, BD)}$$

Small OTOC ⟶ Bob's success

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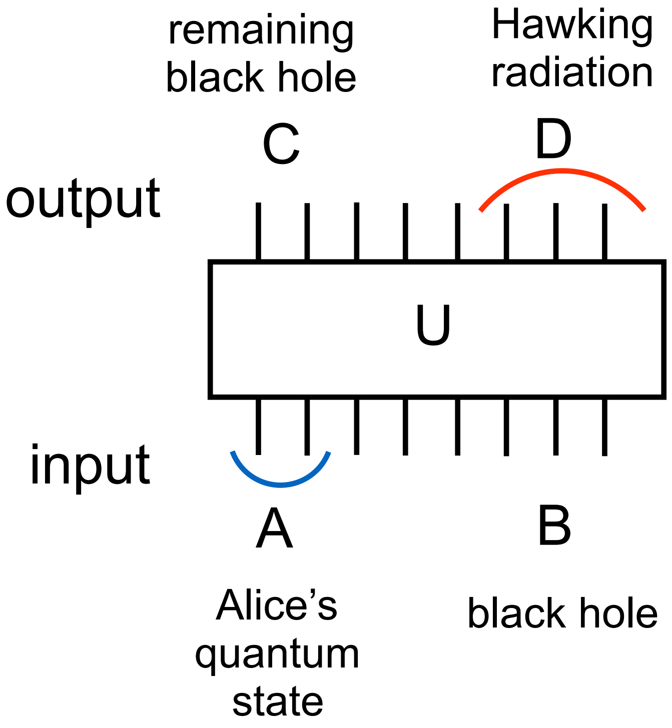

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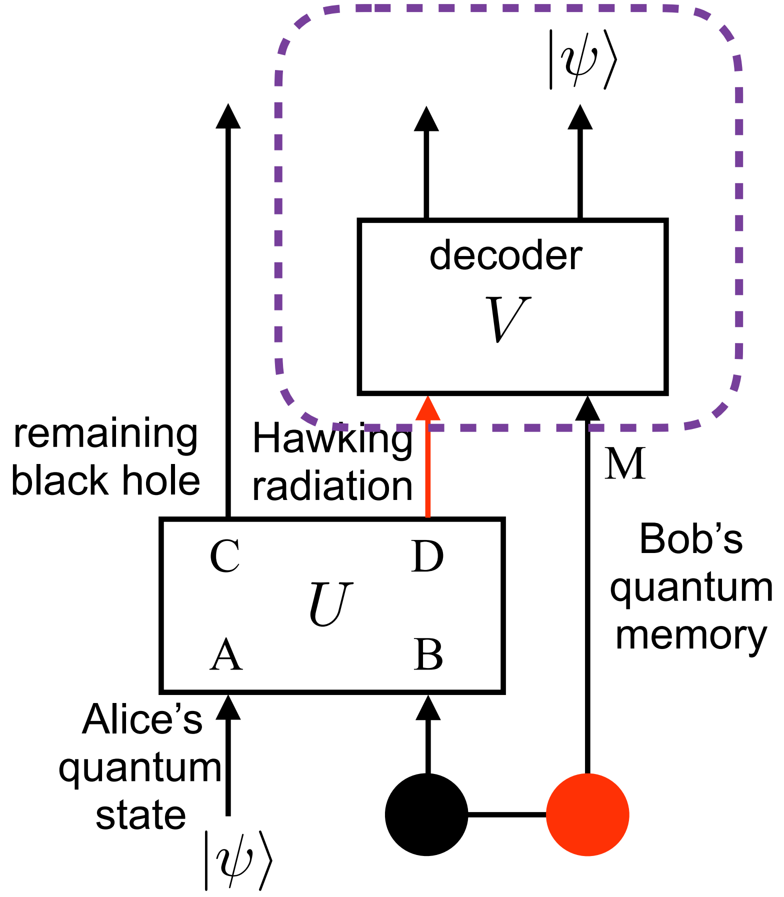
- For factorizable input and output, a certain averaged OTOC is related to (Sandwiched) Renyi-2 divergence.

Can we really decode the Hawking radiation?

How do we construct this ?



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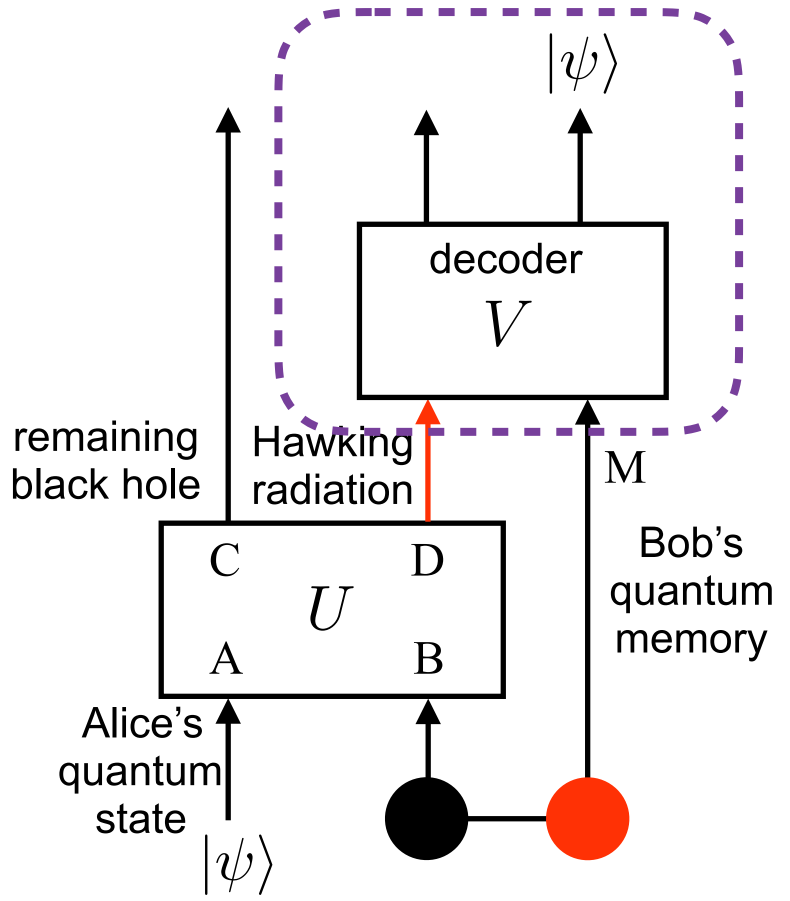

- Simple decoders (with Kitaev)

  Version 1 : very simple, but probabilistic. traversable wormhole.

  Version 2 : a bit involved, but deterministic.

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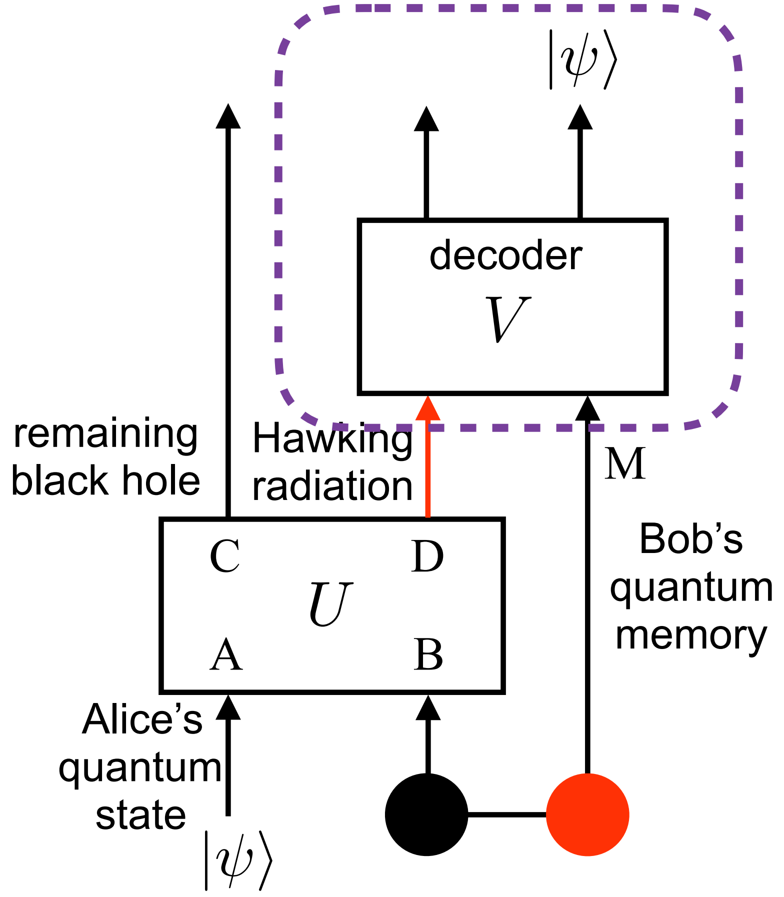

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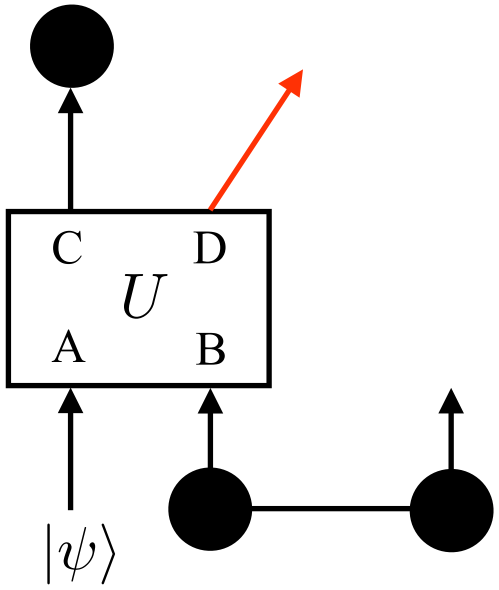
Crucial assumption

●—● = EPR pairs

$$\frac{1}{\sqrt{d}}\sum_{j=1}^{d}|j\rangle\otimes|j\rangle$$

Probabilistic decoding protocol

- Bob "teleports" Alice's quantum state to his register qubits via postselection.



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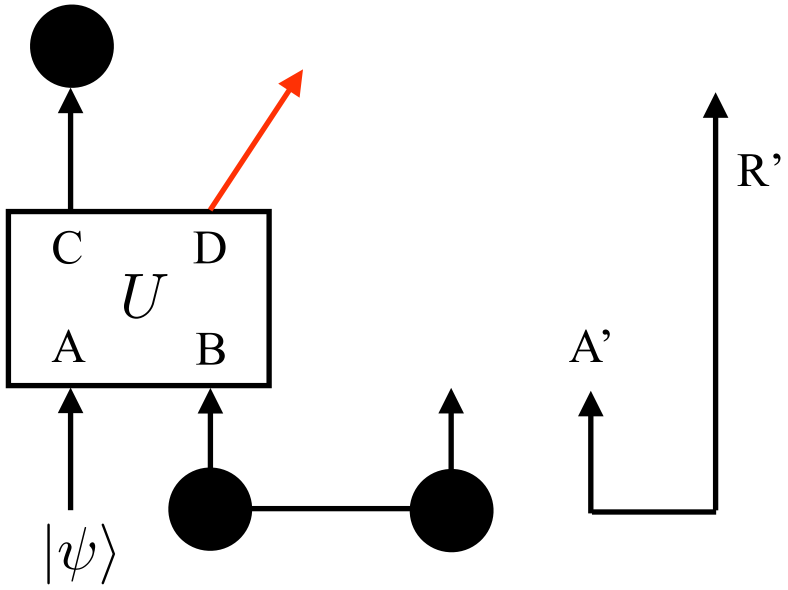

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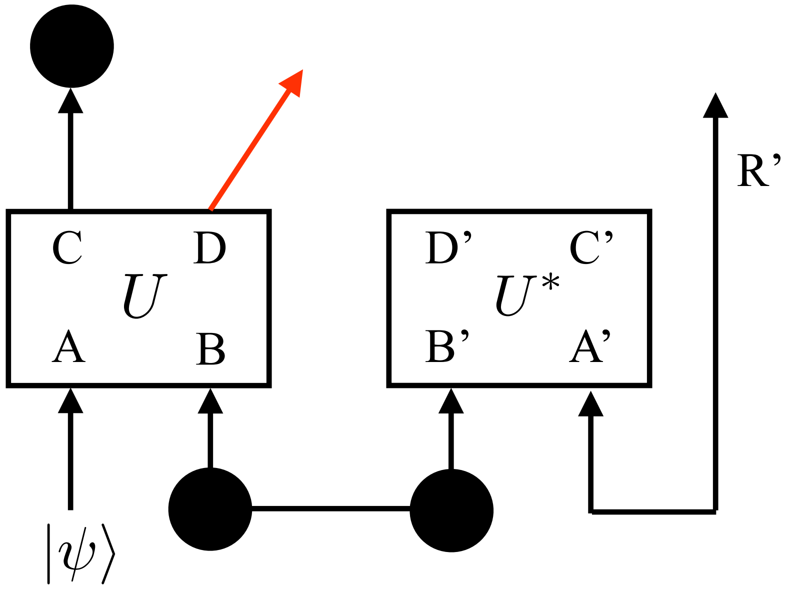

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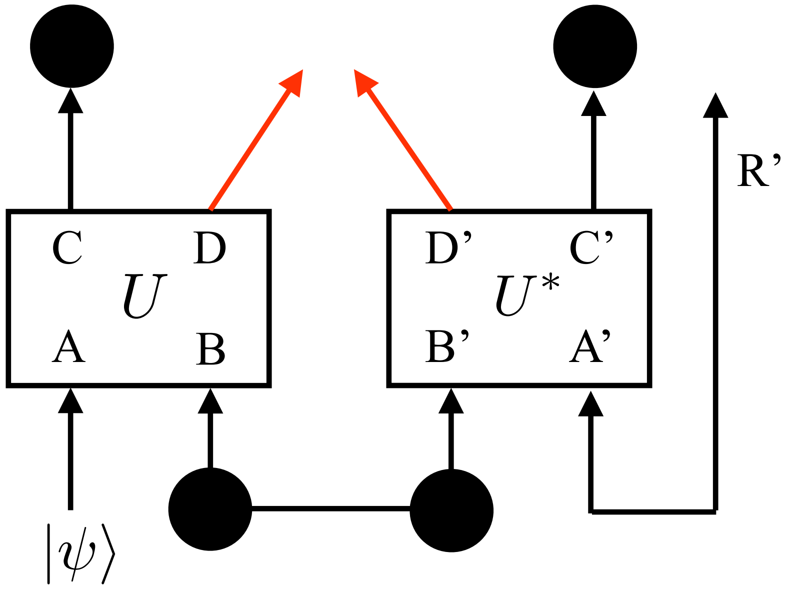

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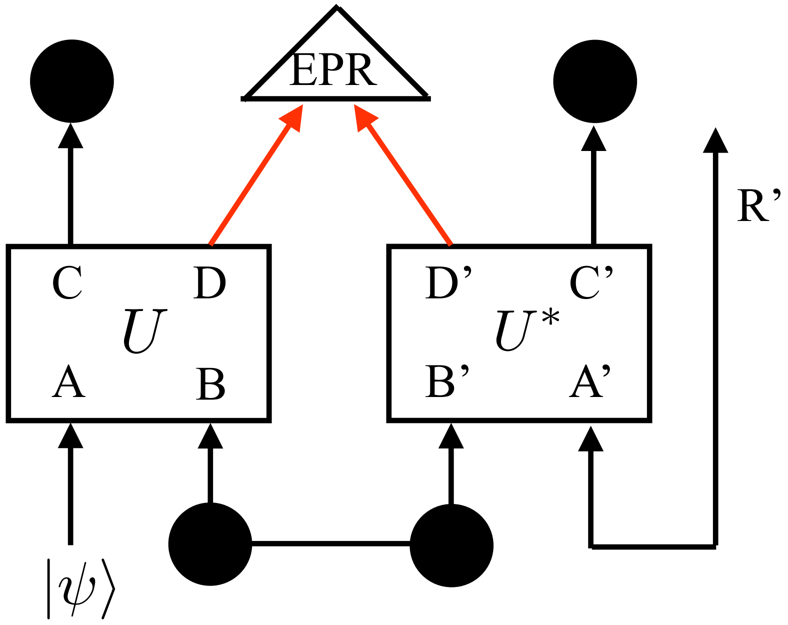
(d) Bob performs Bell measurements

$$\frac{1}{\sqrt{2}}(|00\rangle+|11\rangle) \quad \frac{1}{\sqrt{2}}(|01\rangle+|10\rangle) \quad \frac{1}{\sqrt{2}}(|01\rangle-|10\rangle) \quad \frac{1}{\sqrt{2}}(|00\rangle-|11\rangle).$$



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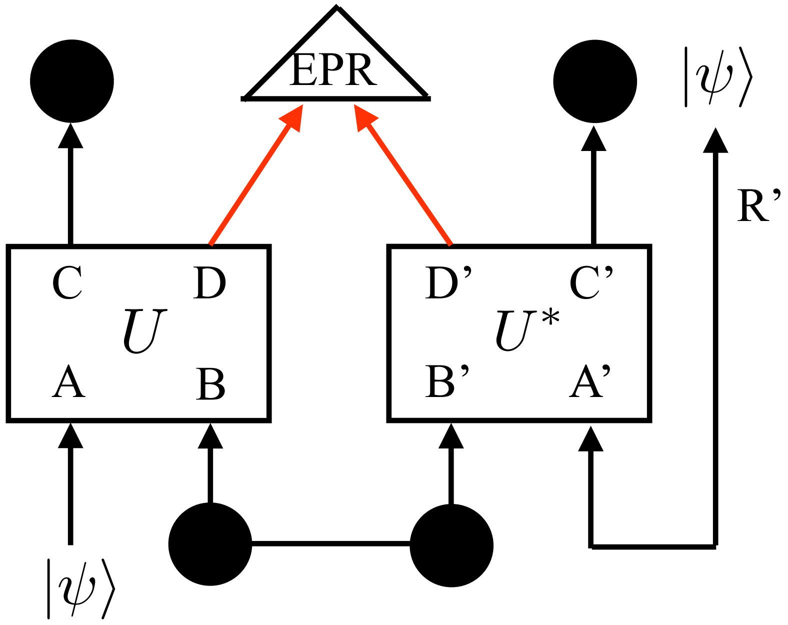
$$\frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) \quad \frac{1}{\sqrt{2}}(|01\rangle + |10\rangle) \quad \frac{1}{\sqrt{2}}(|01\rangle - |10\rangle) \quad \frac{1}{\sqrt{2}}(|00\rangle - |11\rangle).$$

(e) If he measured an EPR pair, he immediately obtains a faithful reconstruction of Alice's state.



* The protocol works as long as U is strongly scrambling

* Success probability is ~ 1/4.

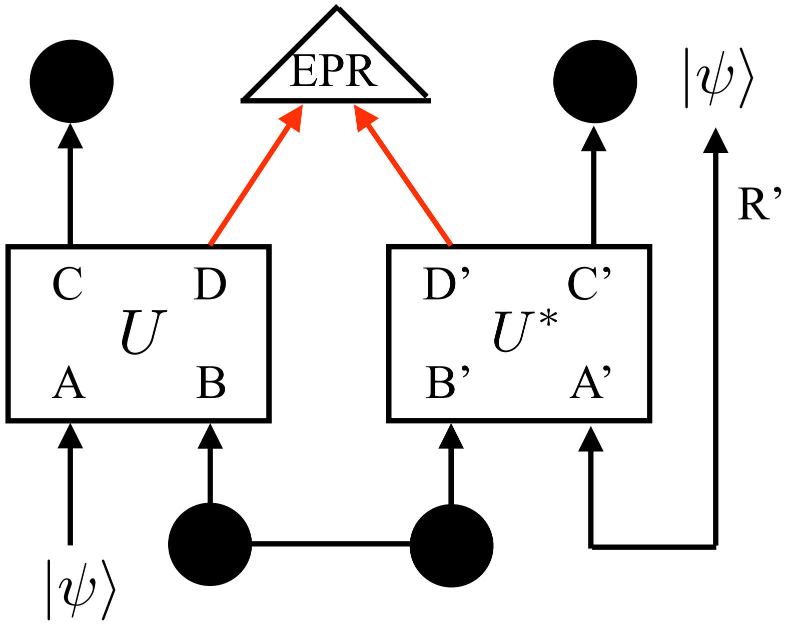
Reconstruction probabilities

- Decoding protocol crucially relies on “scrambling”.

- Probability of measuring an EPR pair

$$P_{\text{EPR}} = 2^{-I^{(2)}(A,BD)} = \langle \text{OTOC} \rangle_{\text{ave}} \approx \frac{1}{d_A^2}$$

The probability decreases as the message size d_A increases….



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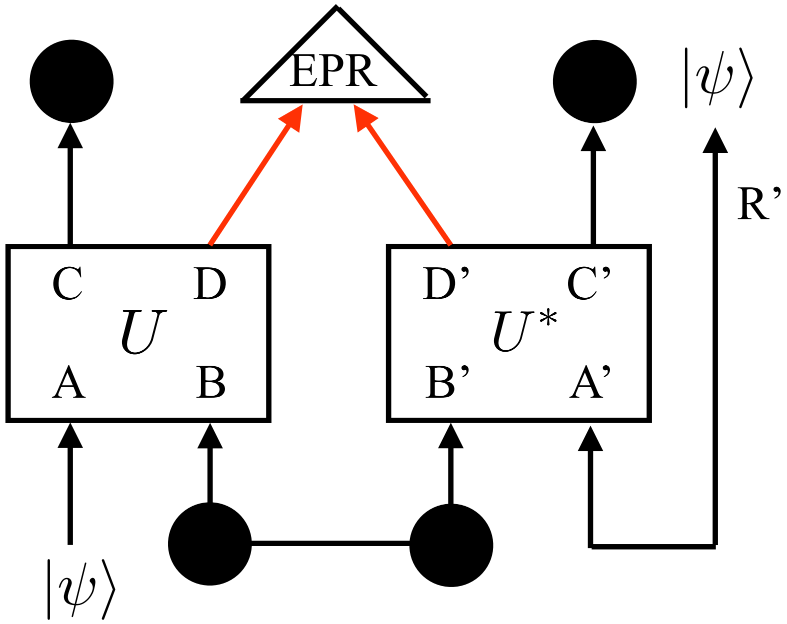
- Probability of successful teleportation (measured by fidelity)

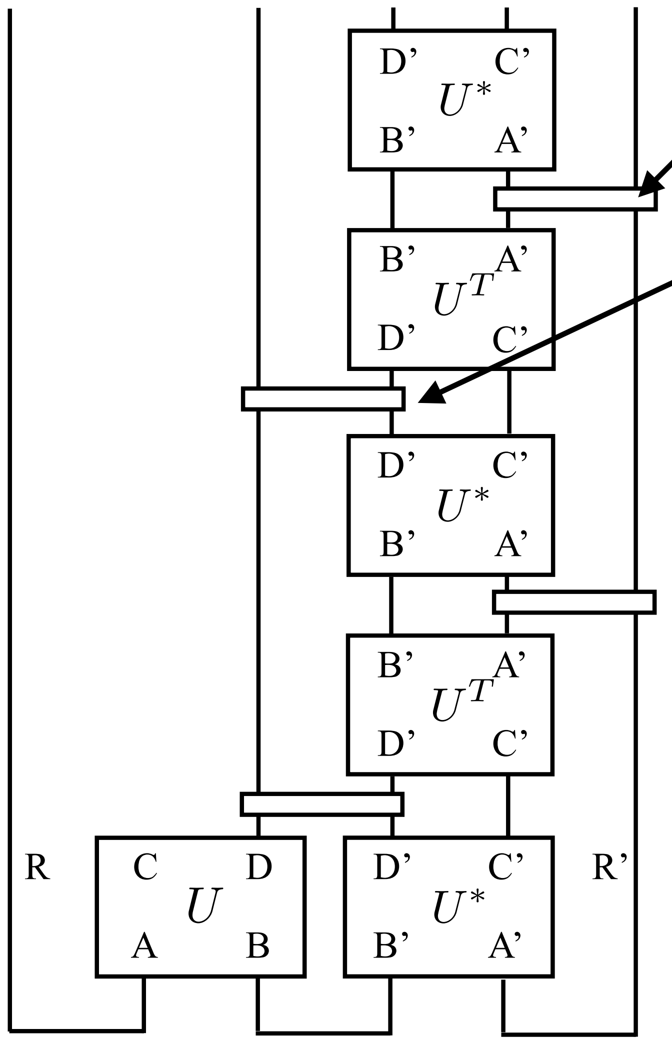
$$F_{\mathrm{EPR}} = \frac{2^{I^{(2)}(A,BD)}}{d_A^2} = \frac{1}{d_A^2 \langle \mathrm{OTOC} \rangle_{\mathrm{ave}}} \approx 1$$

If maximally chaotic, then the fidelity is unity.



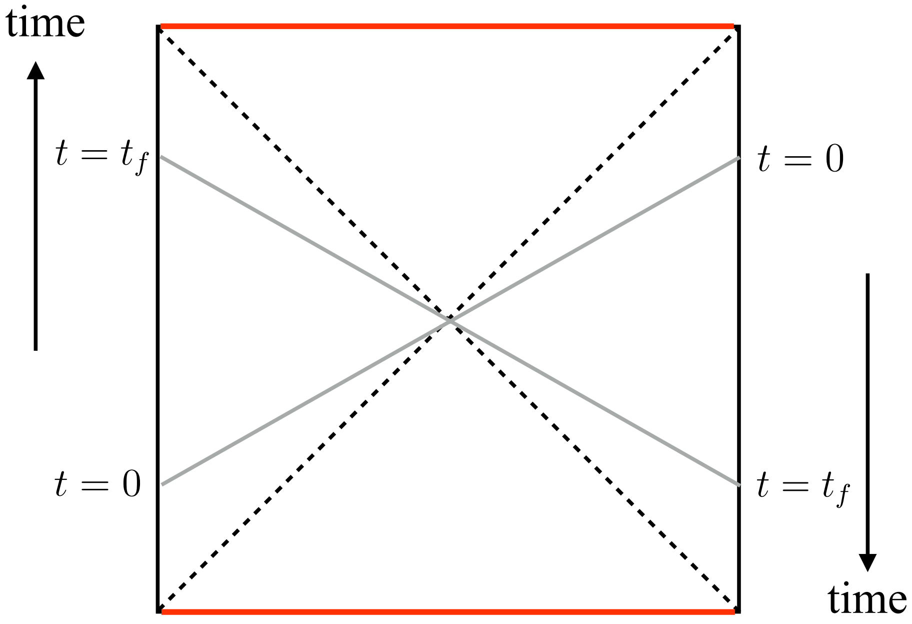
Deterministic decoding protocol

- “Search for an EPR pair” (rotates to an EPR pair) by incorporating the Grover search algorithm



$V_A = 1 - 2|\mathrm{EPR}\rangle\langle\mathrm{EPR}|$

$V_D = 1 - 2|\mathrm{EPR}\rangle\langle\mathrm{EPR}|$



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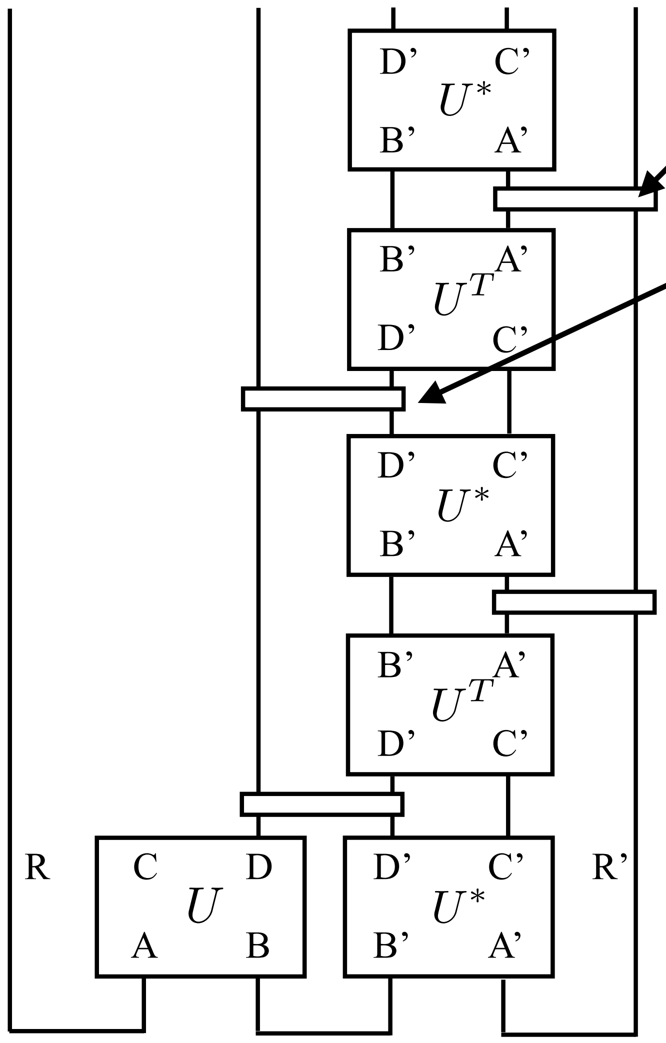

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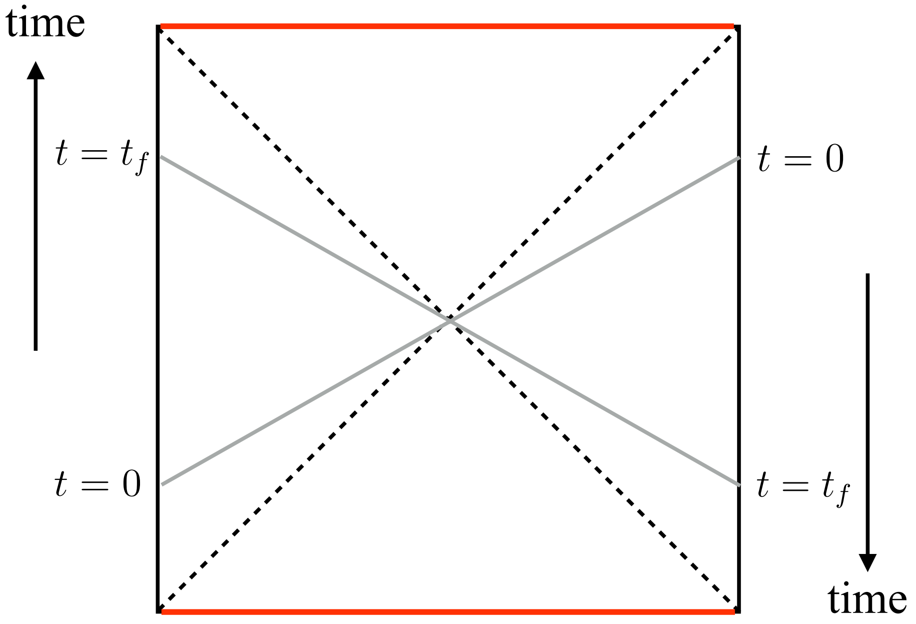


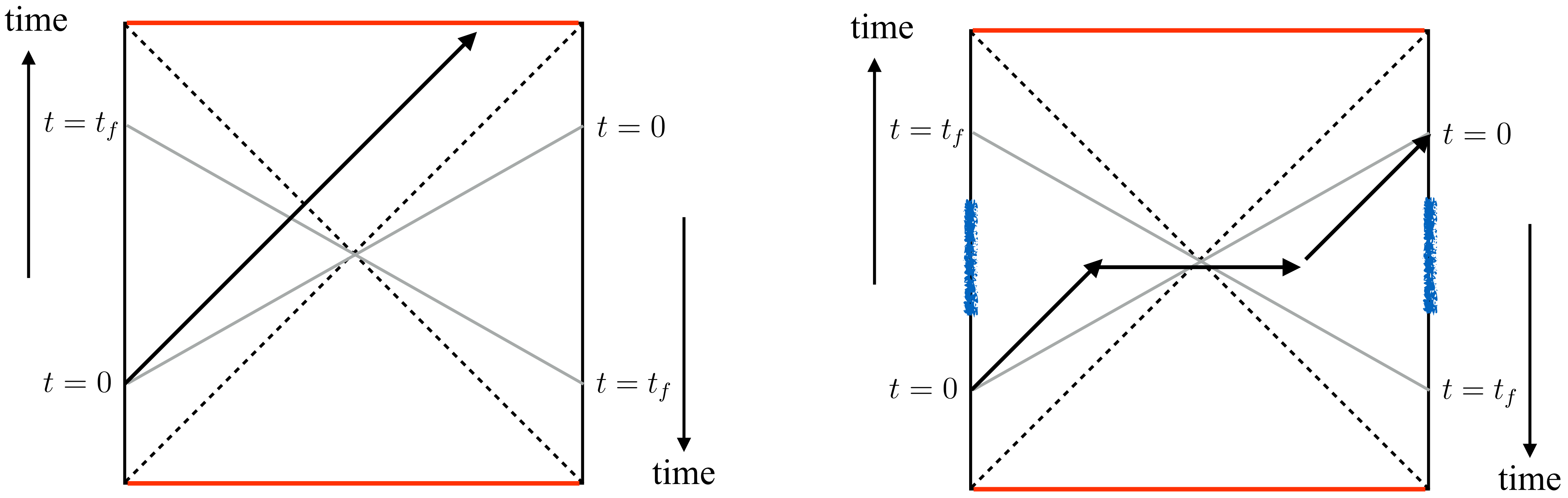
- Repeat this for $\boxed{\frac{\pi d_A}{4}}$ times

- Corresponds to higher-point OTOCs…

Traversable wormhole in AdS black hole ?

- By coupling the left and right boundary appropriately, a wormhole becomes traversable

[Gao-Jafferis-Wall, Maldacena-Stanford-Yang]



Traversable wormhole in AdS black hole ?

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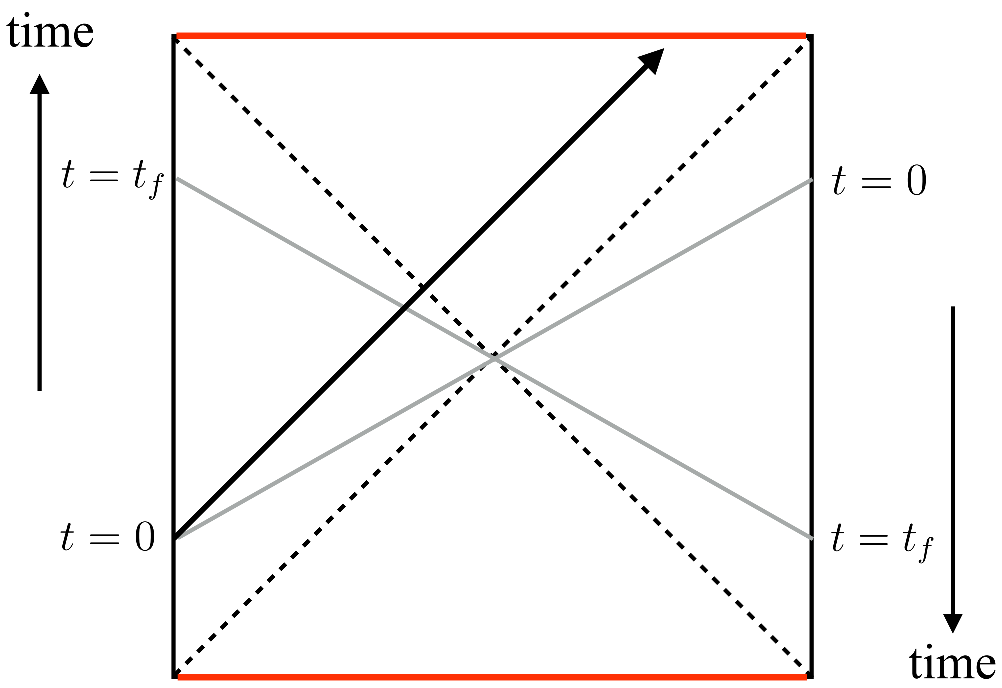
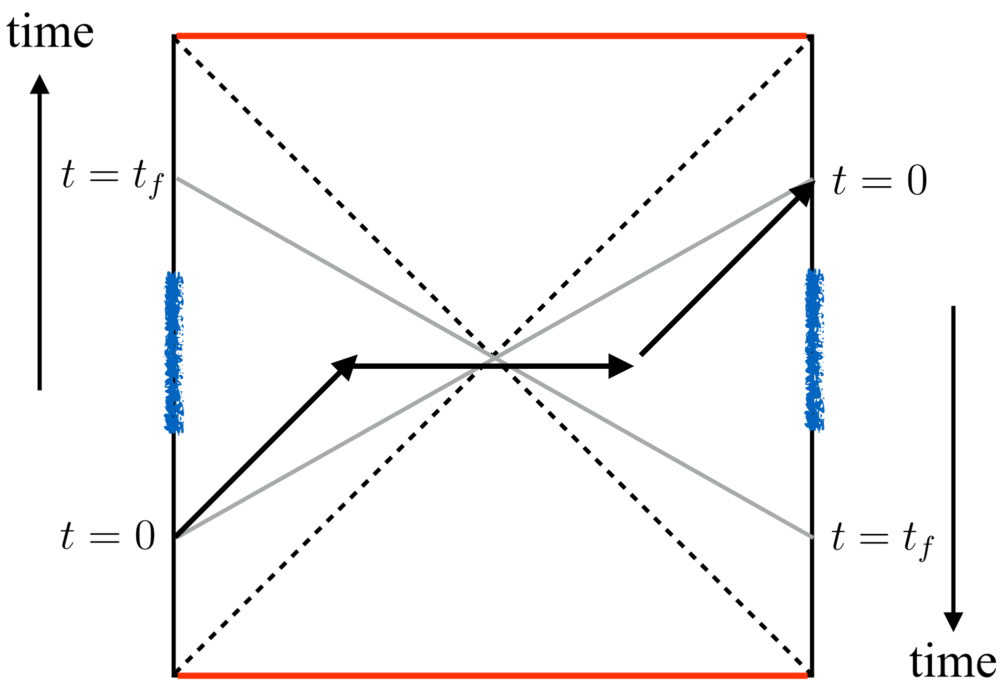
- Decoder for Hayden-Preskill may be interpreted as a traversable wormhole ?



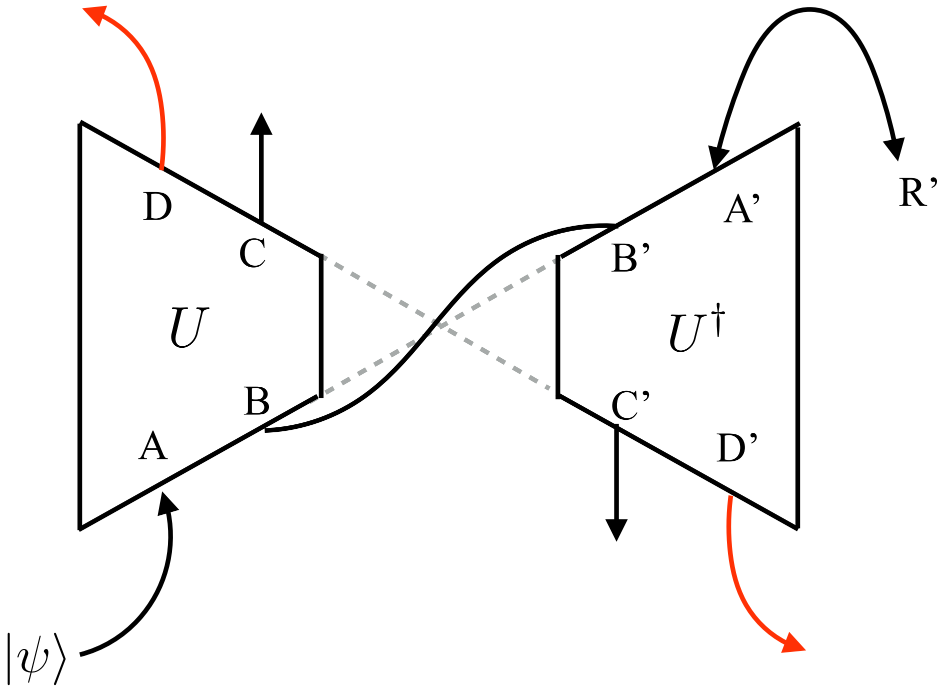


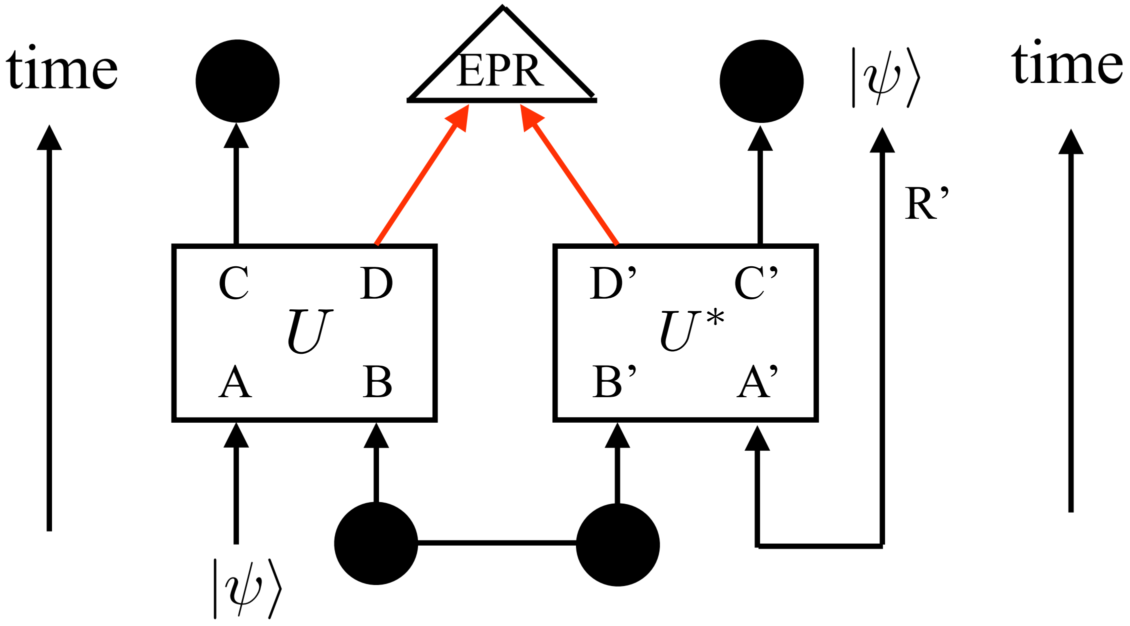
Holographic interpretation ?

- Reverse the time direction !

A,D Infalling/outgoing radiations

B,C field modes and high energy things





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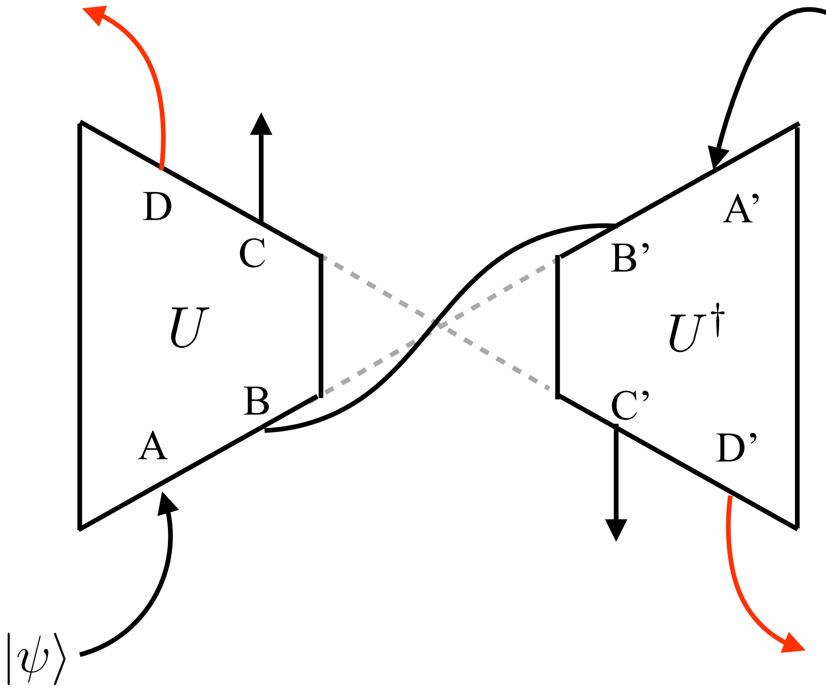

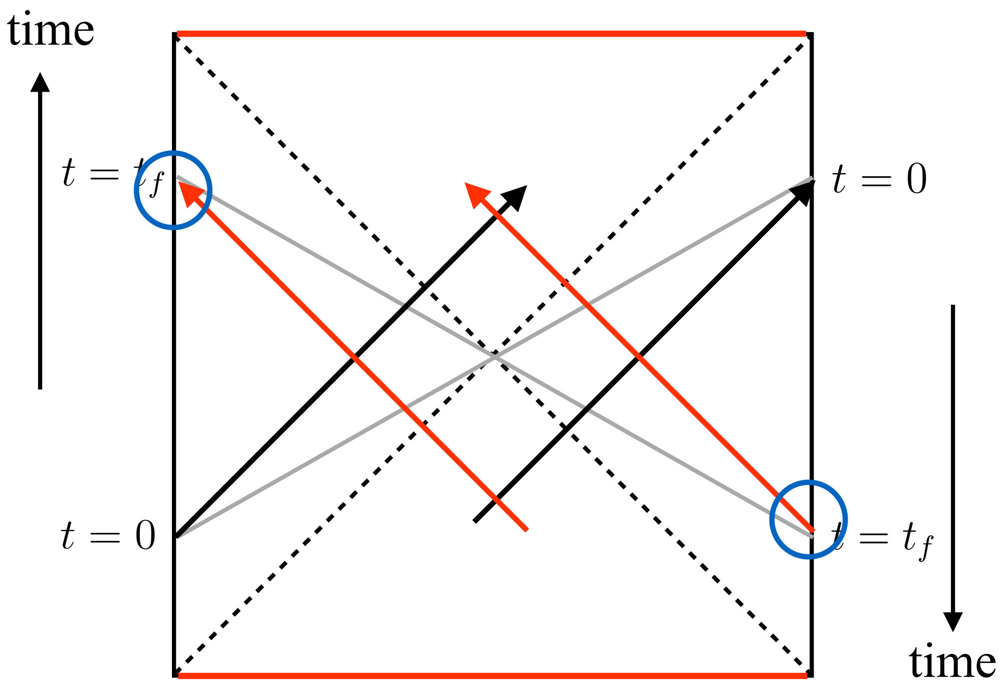

Holographic interpretation ?

- Reverse the time direction !
  - Projection onto an EPR pair makes the wormhole traversable?

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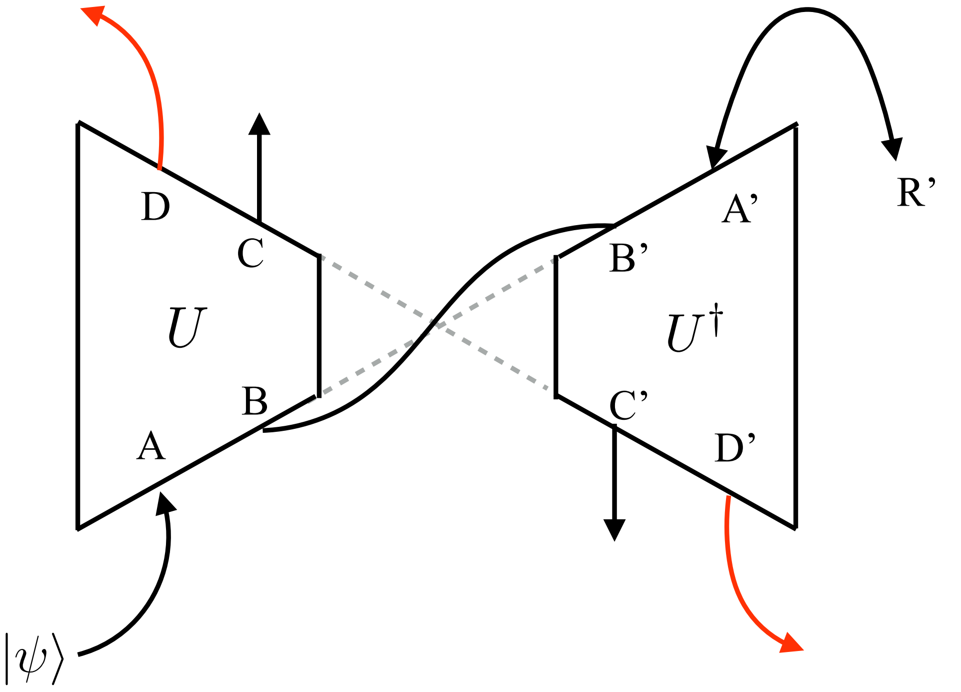
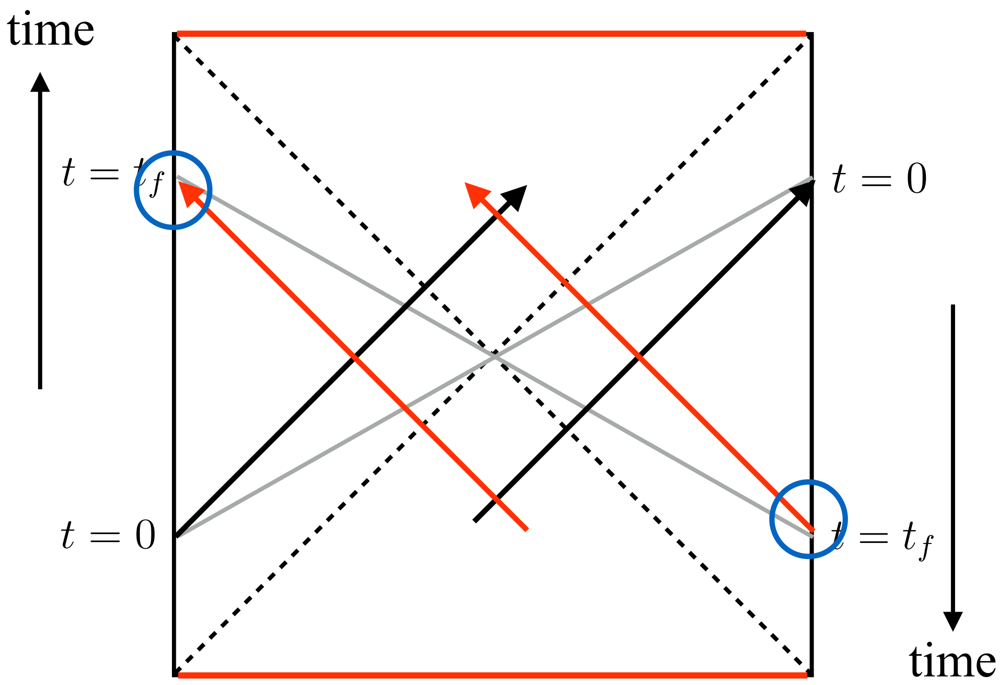


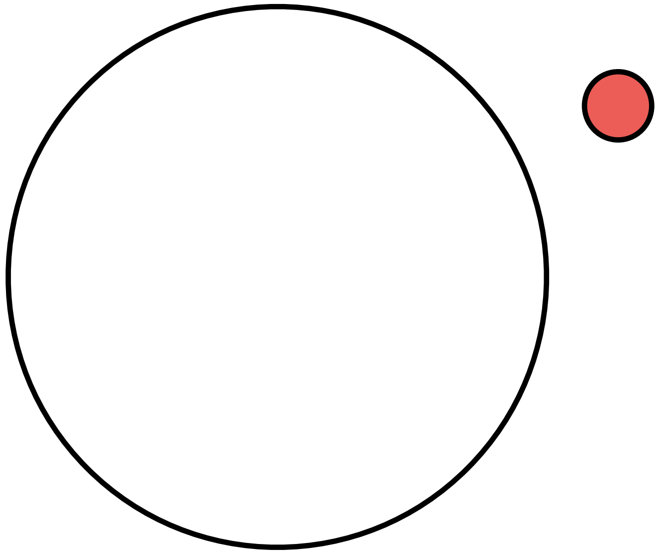


Back to information loss…

- We should update “black hole complementarity”.

  - There is no quantum cloning. An object can be pulled back from a black hole !

previously….



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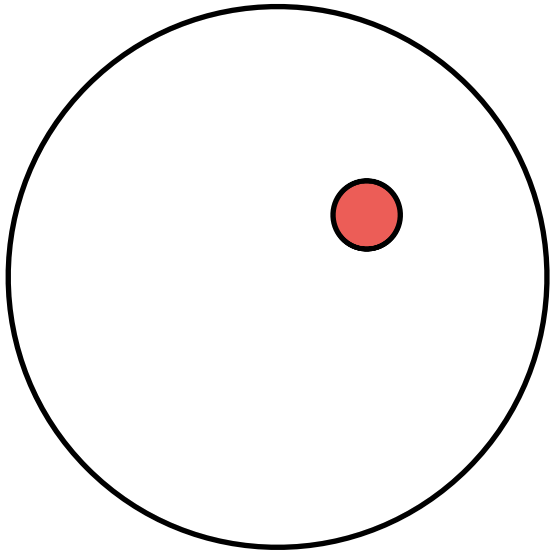

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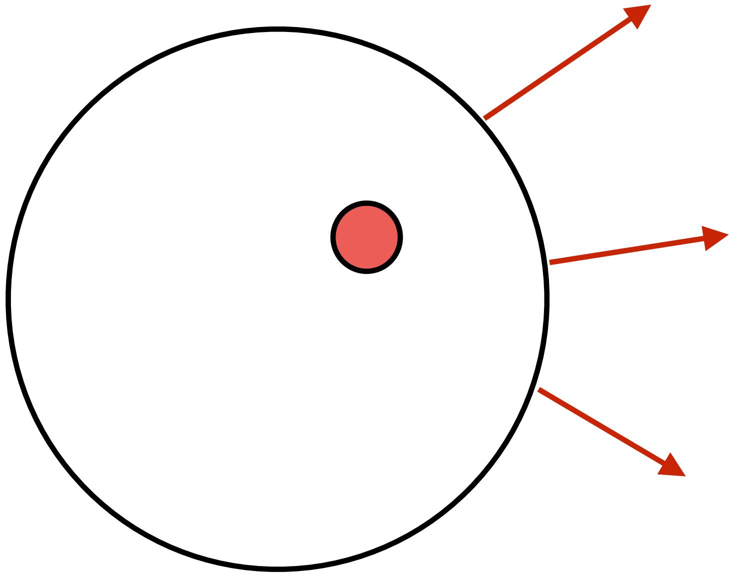

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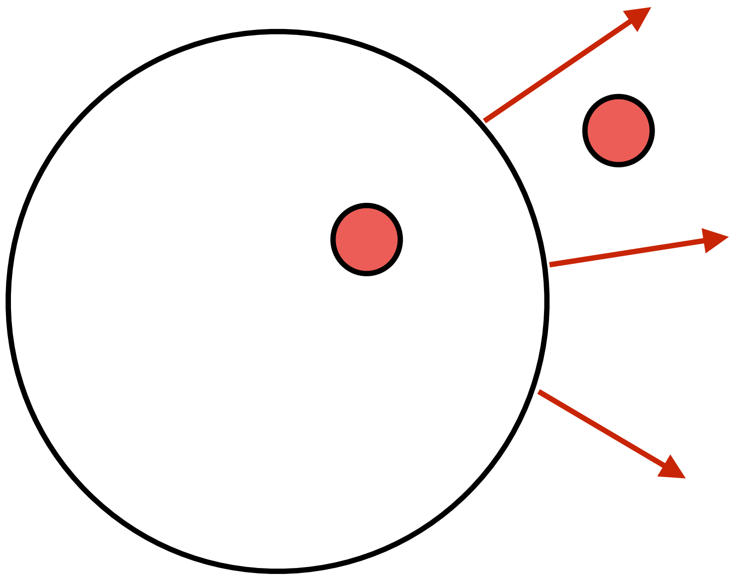

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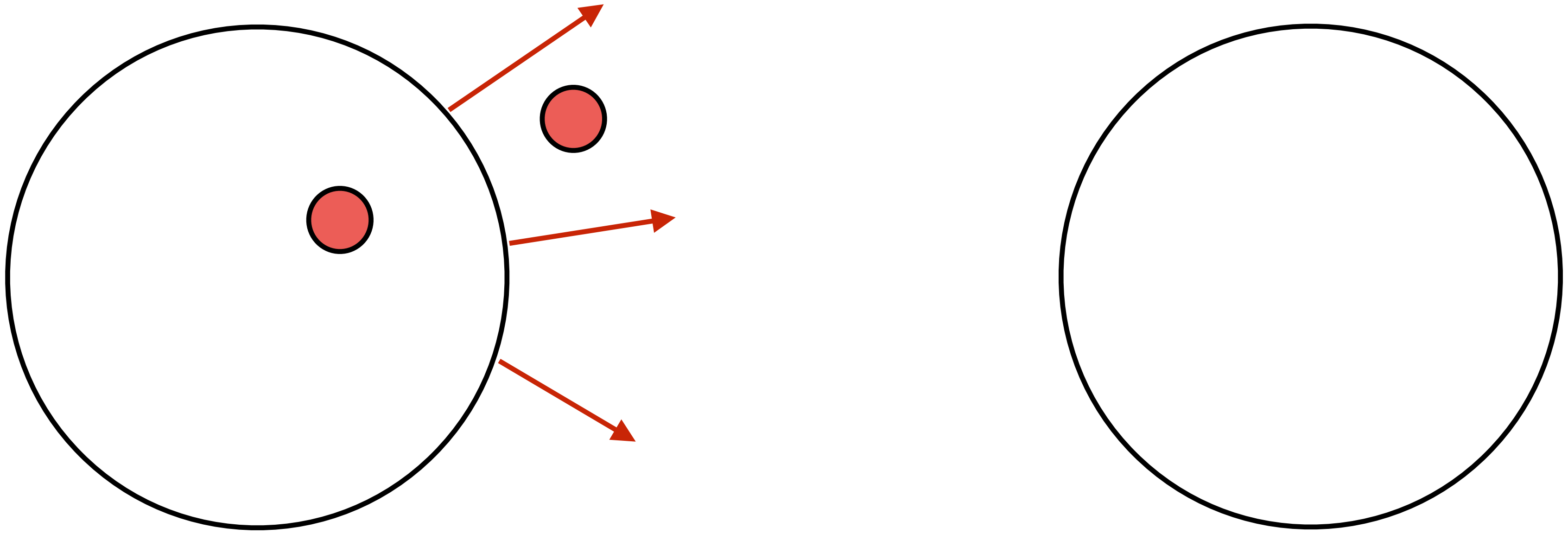

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modern interpretation

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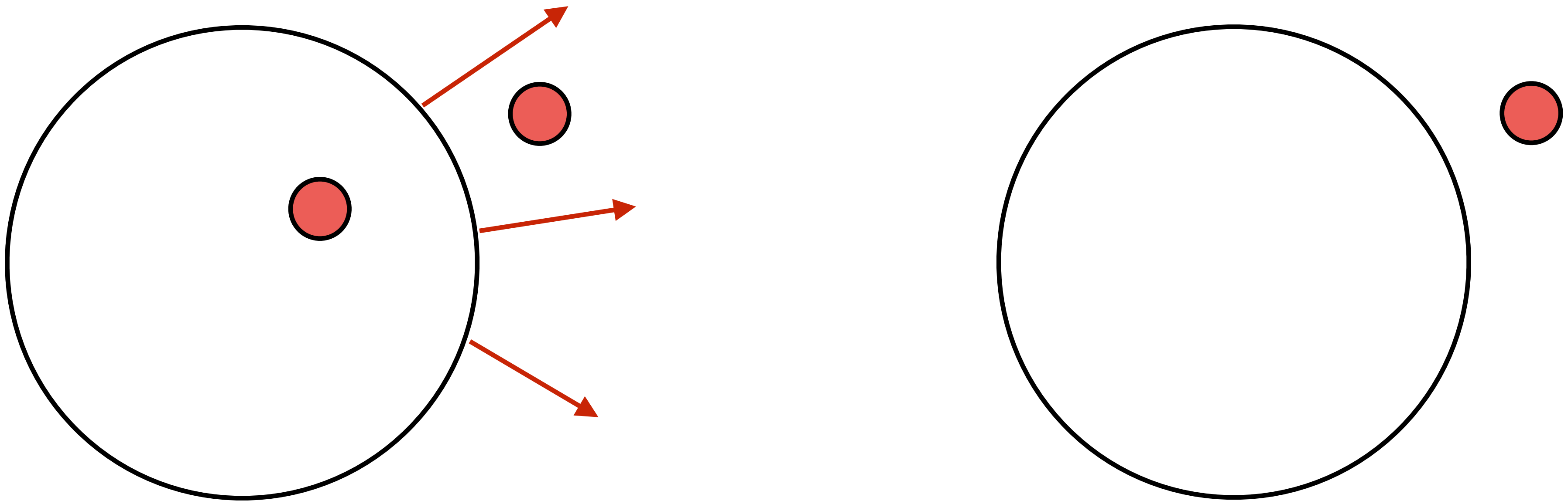

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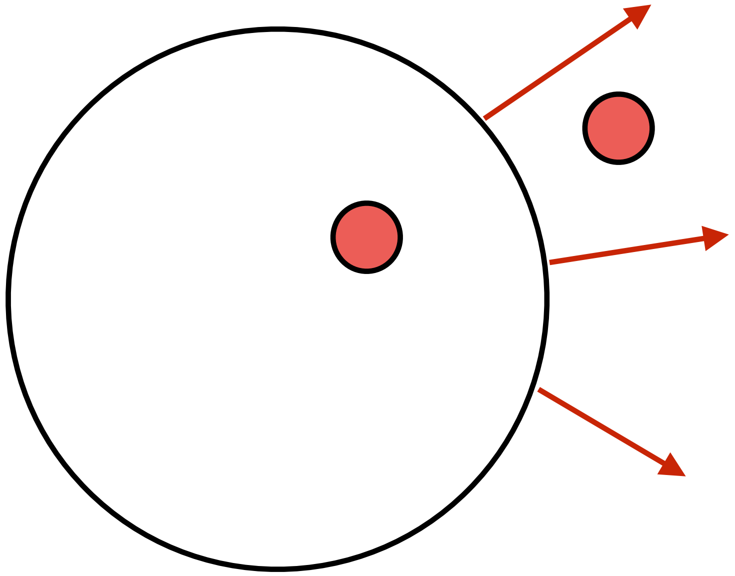

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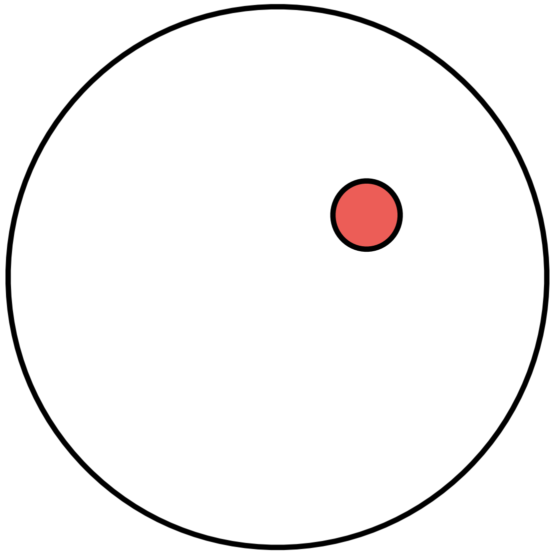

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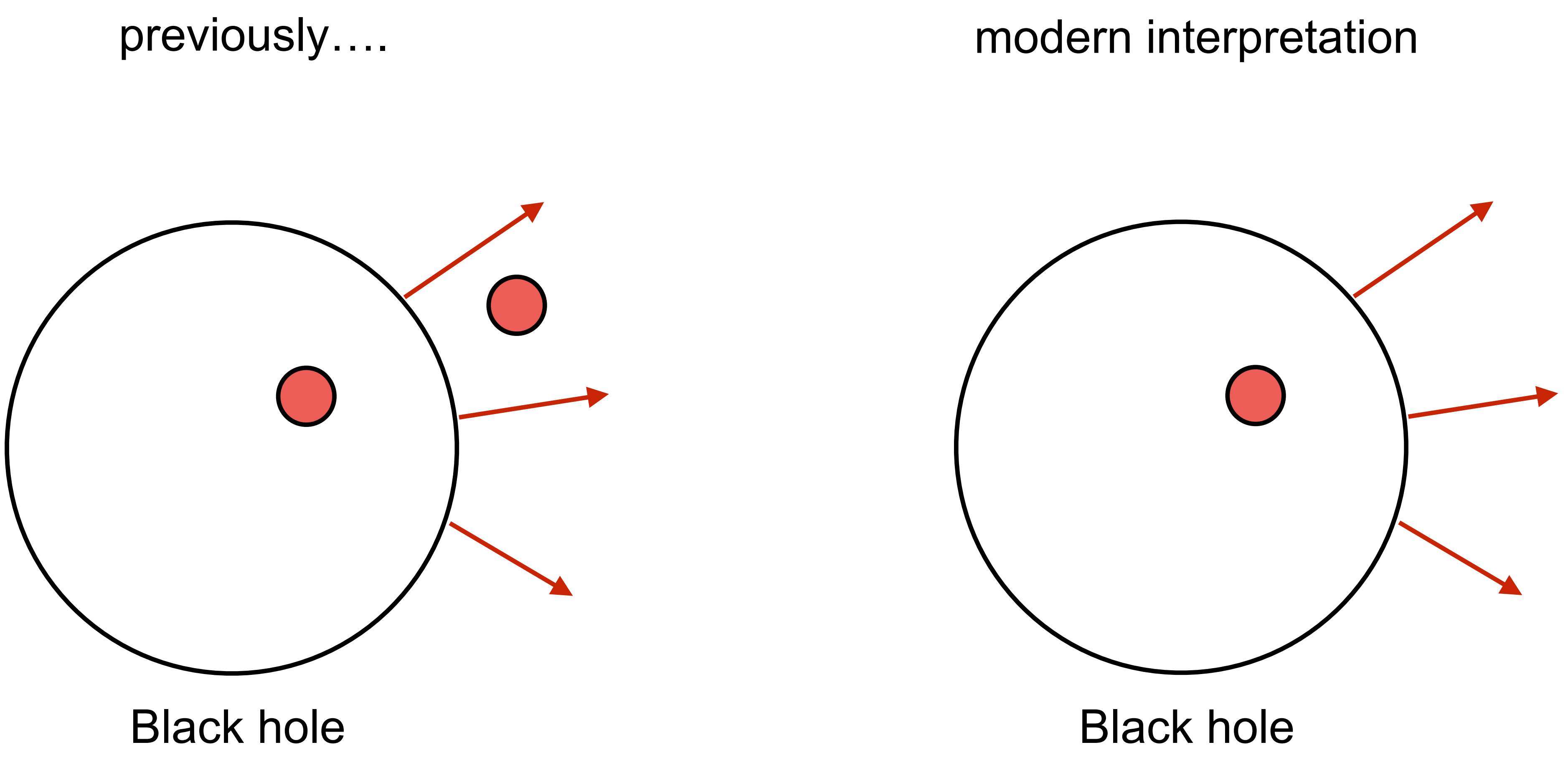

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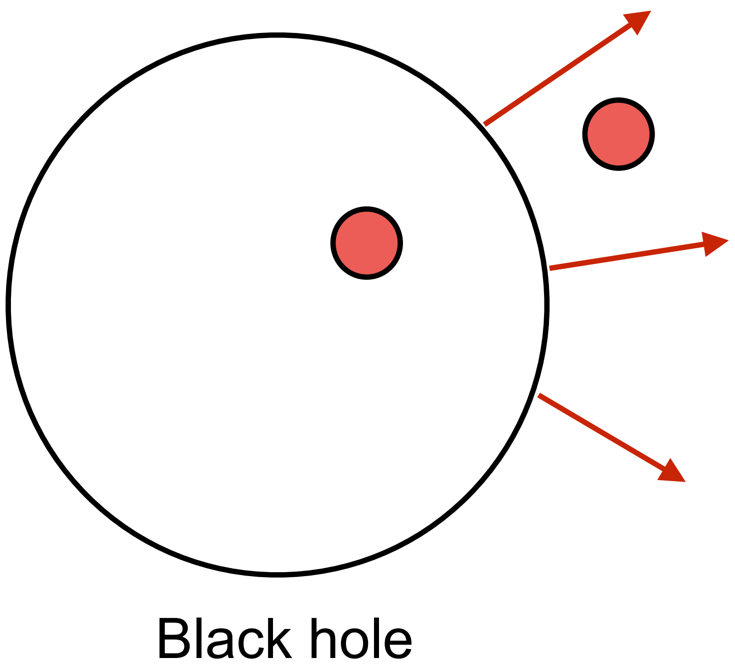

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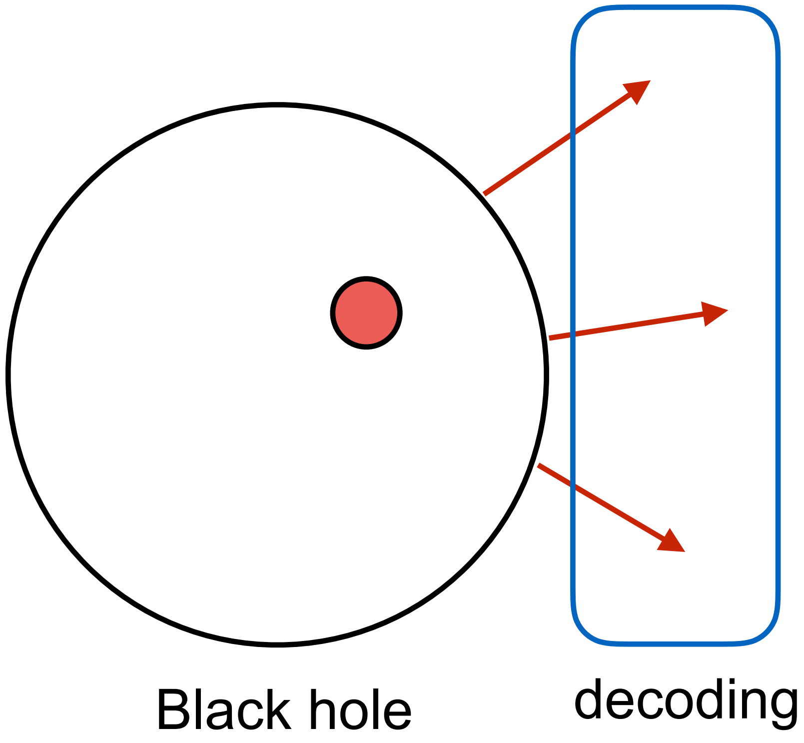

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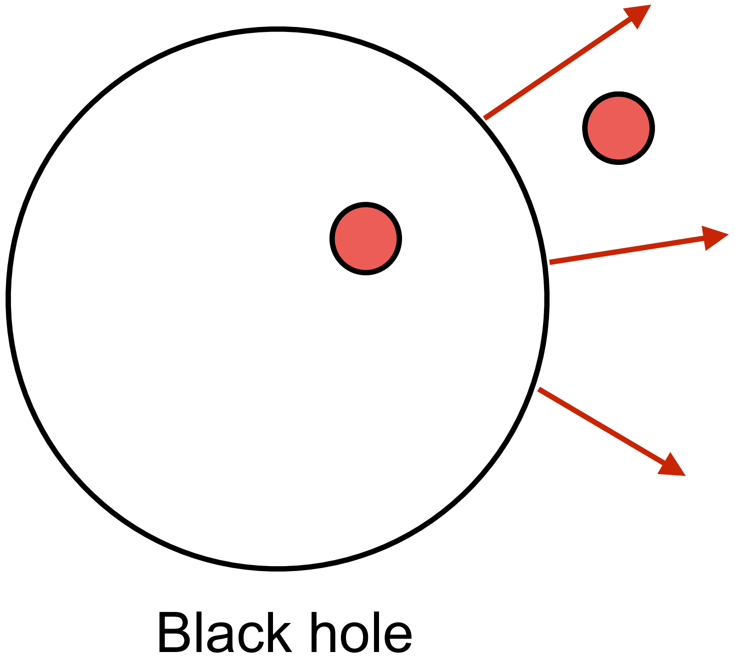
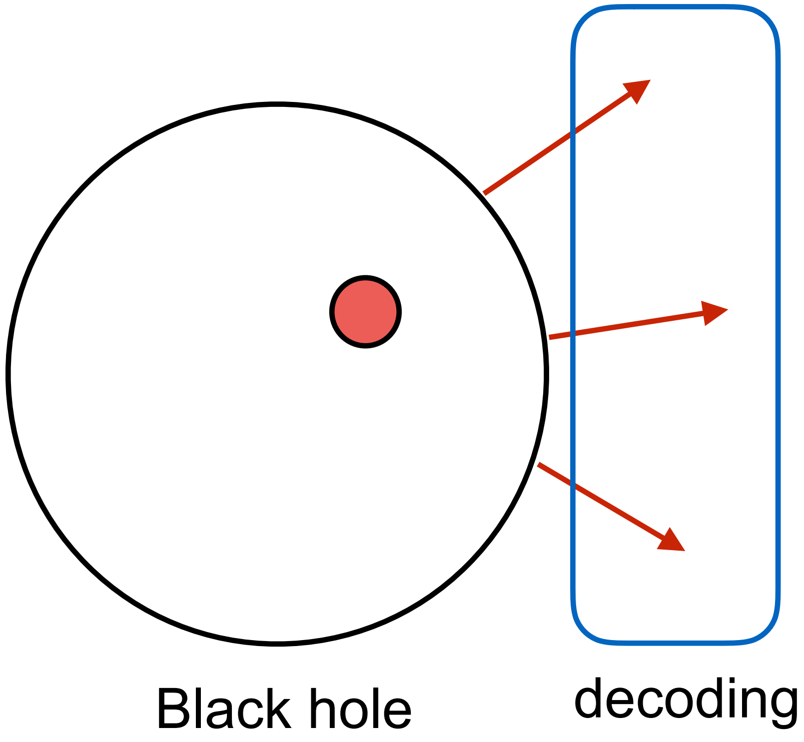


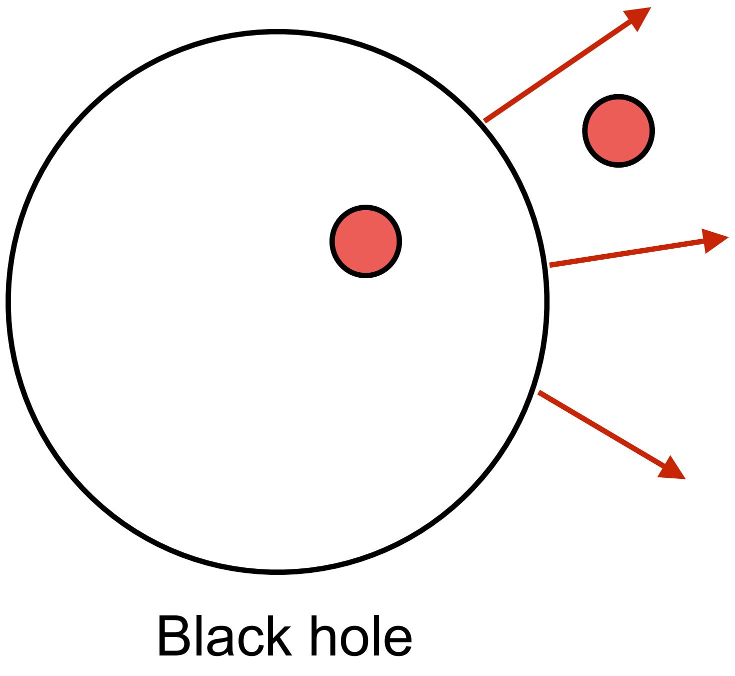
modern interpretation



Back to information loss…

- We should update “black hole complementarity”.
  - There is no quantum cloning. An object can be pulled back from a black hole !

previously….



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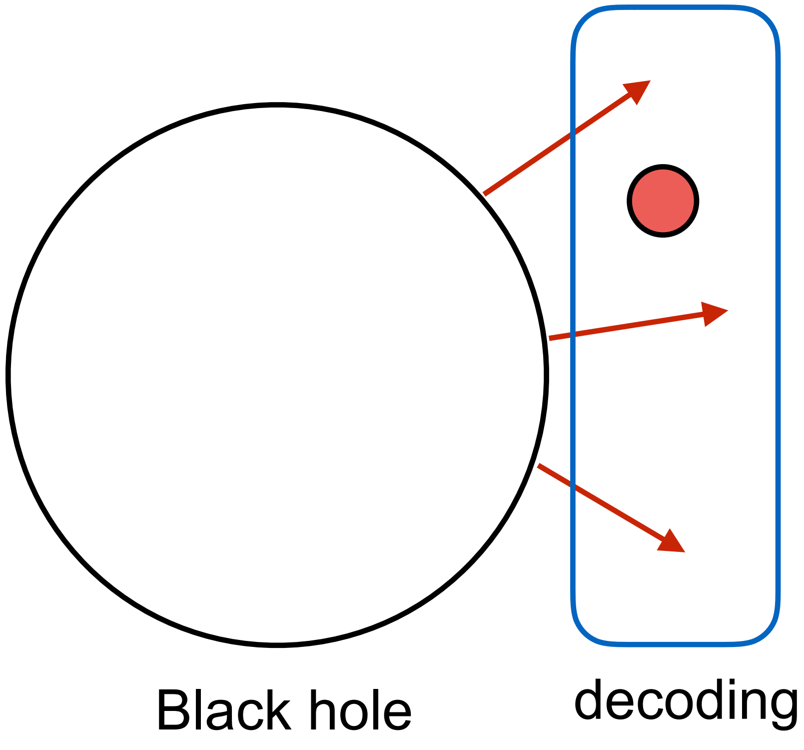

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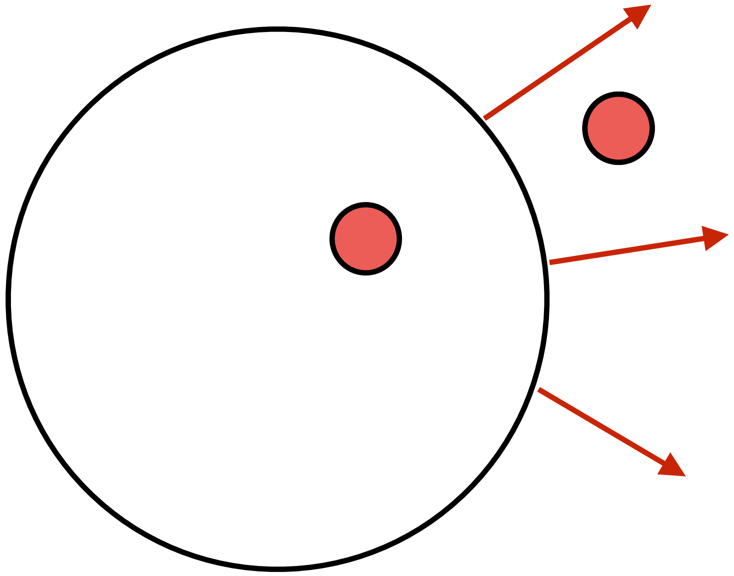

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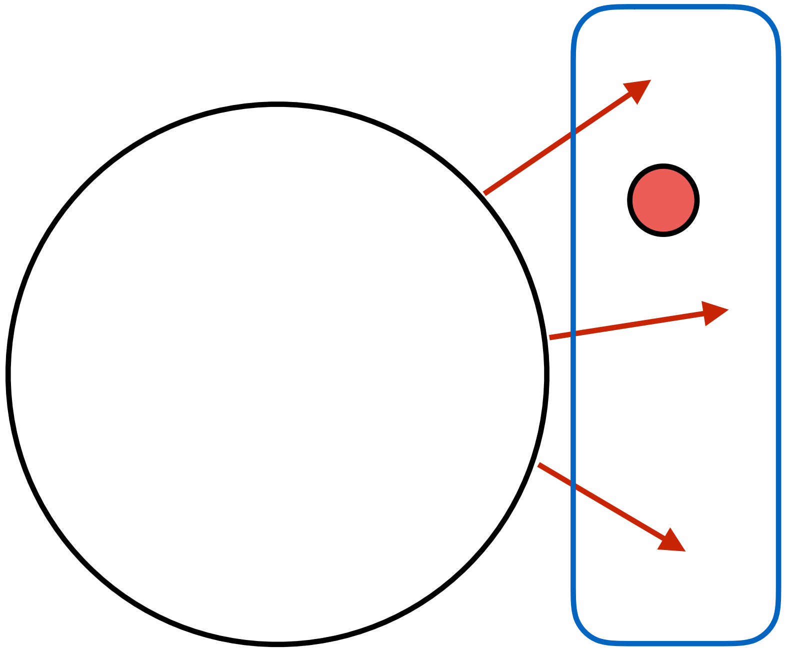


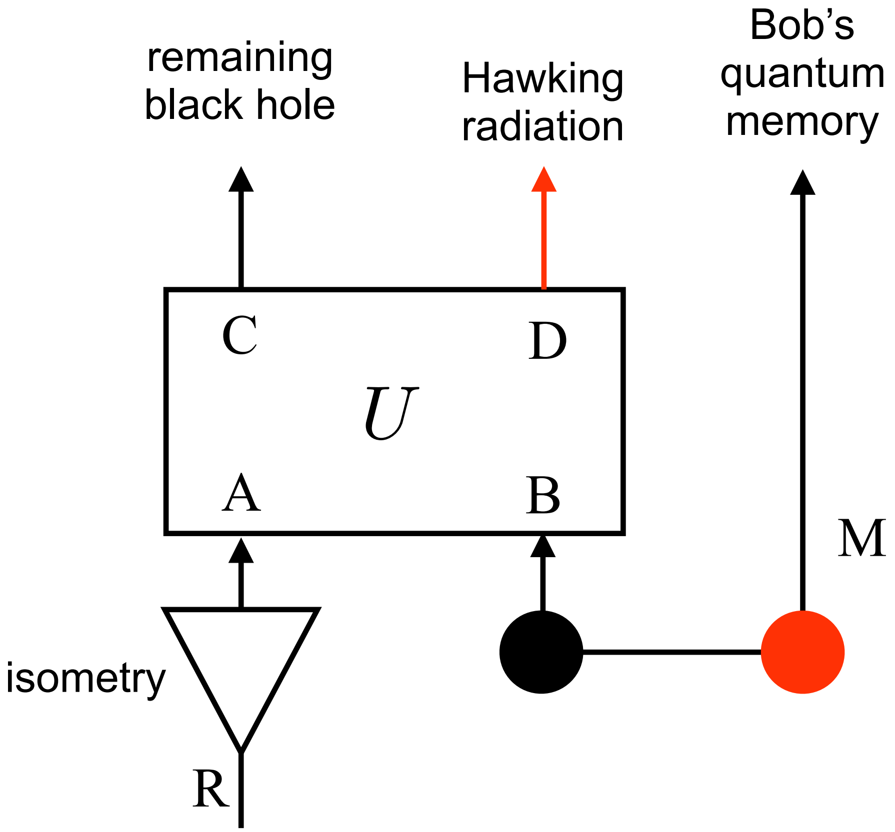
Black hole

decoding

- We can probe the black hole interior !?

Coarse-grained entropy

- A particle with energy E, carrying R qubits information, falls into a black hole at temperature T.



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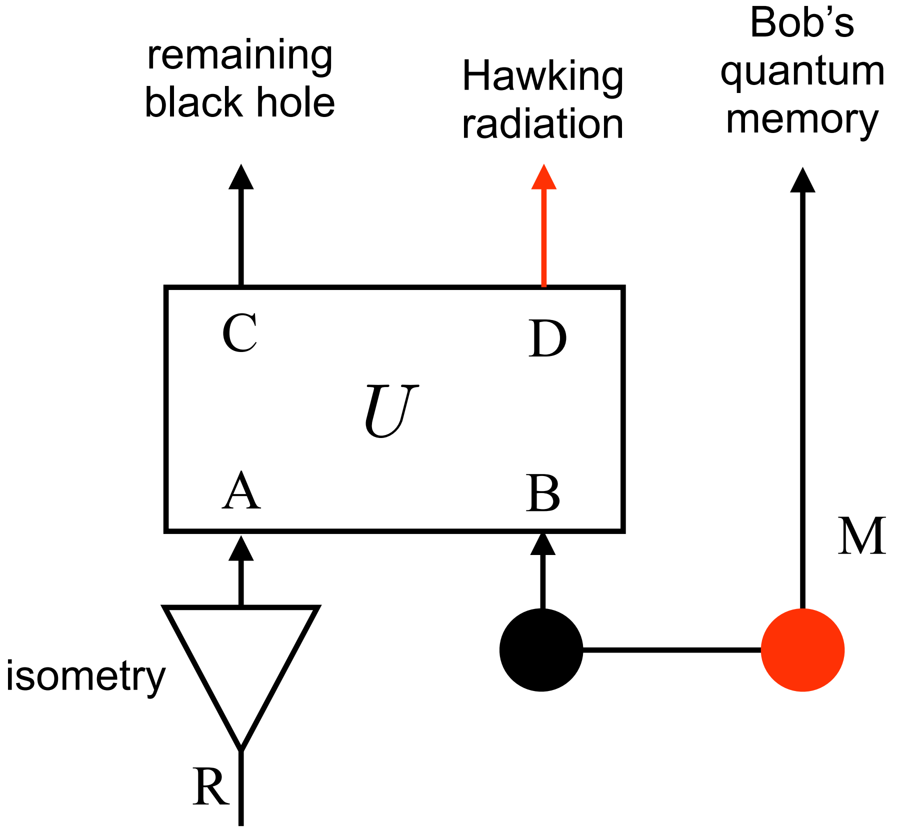

Coarse-grained entropy

$$\boxed{\Delta S \approx \frac{E}{T} \gg |R|}$$

volume of A

entropy of a particle

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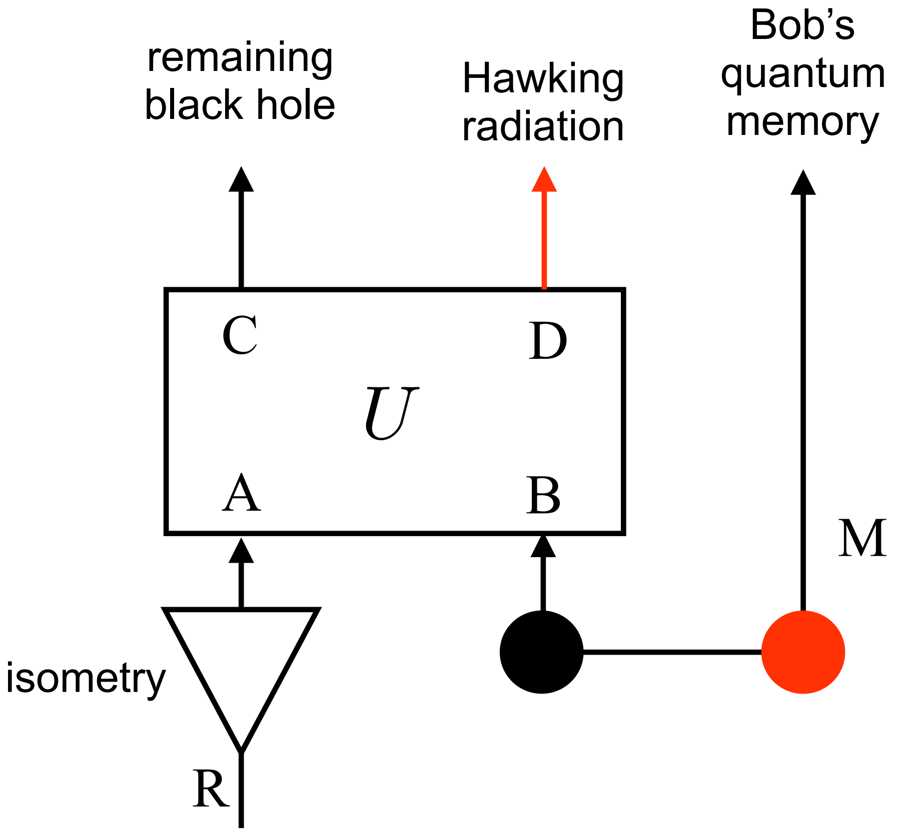

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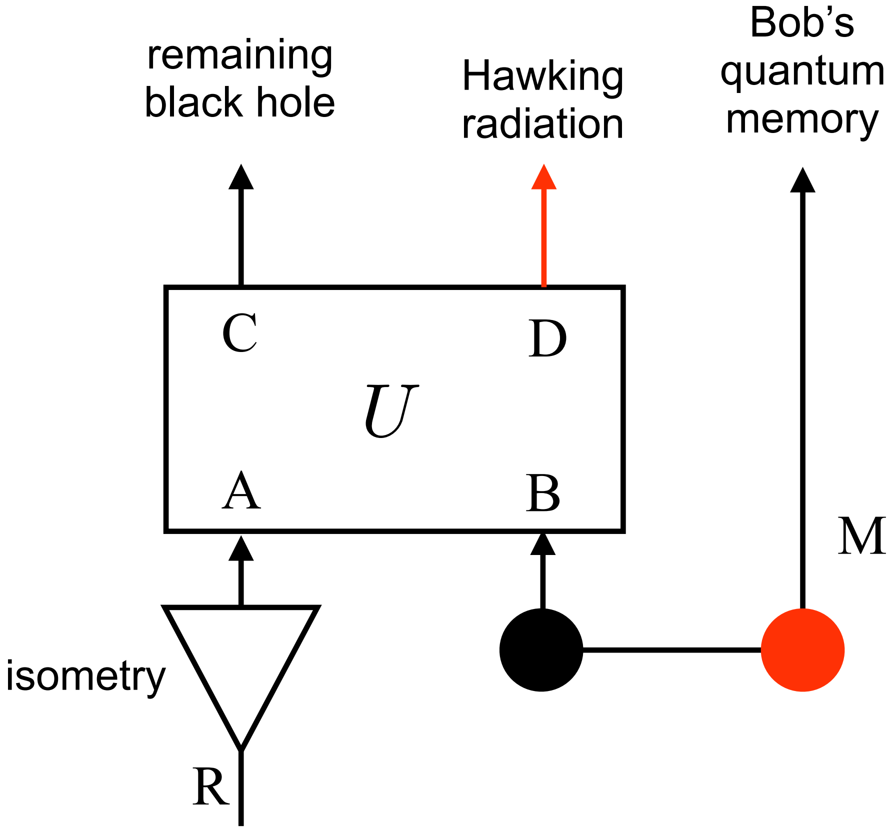
- A closely related idea was used to resolve the firewall paradox (Verlinde-Verlinde)



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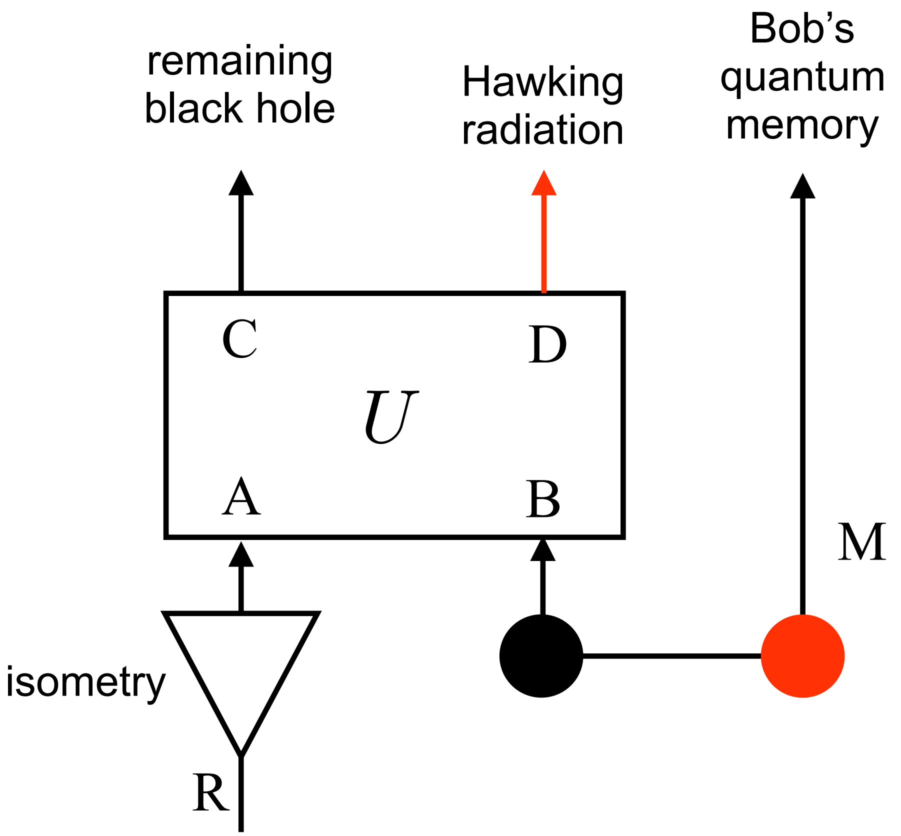
- In QI literature, a similar idea has been recently proposed. “alpha-bits” (Hayden-Pennington)



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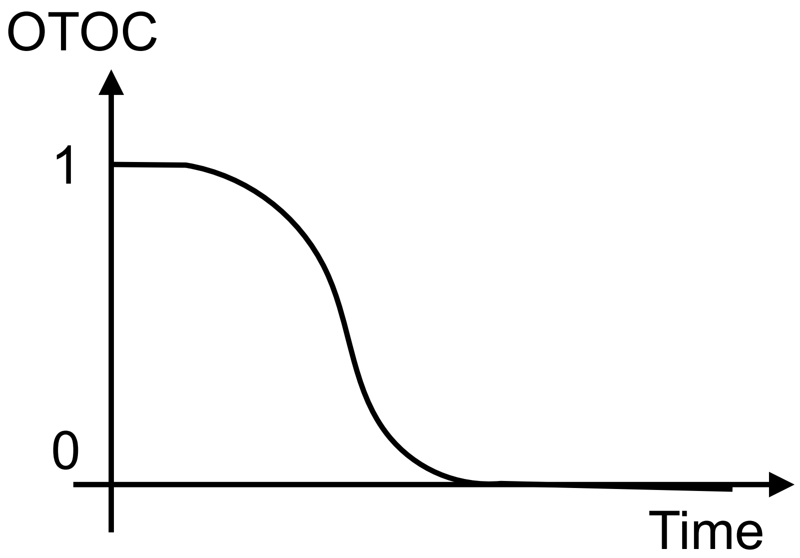
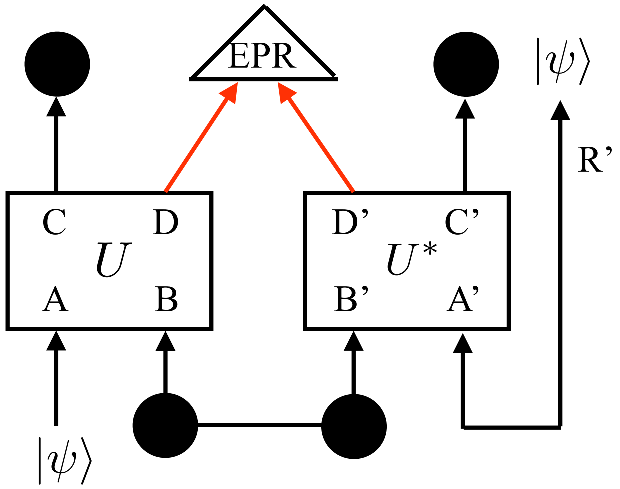
Experimental characterization of scrambling

- OTOC decay due to decoherence…





Experimental characterization of scrambling

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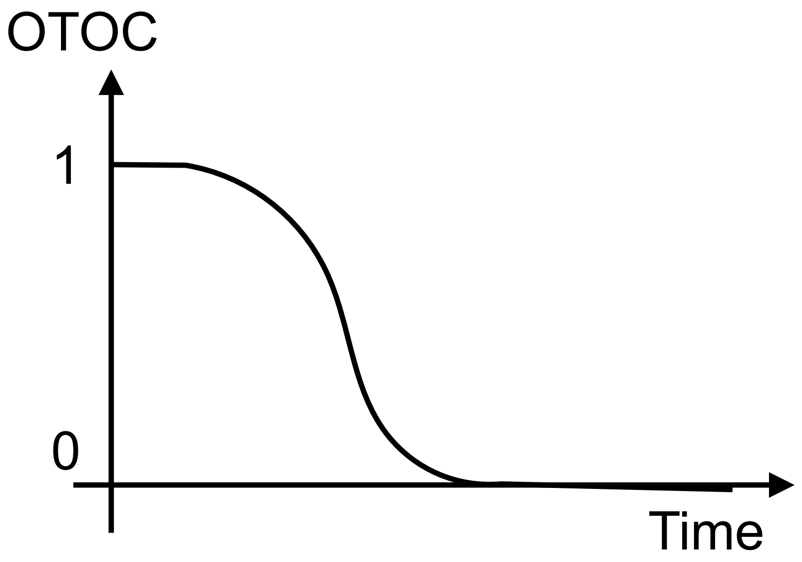
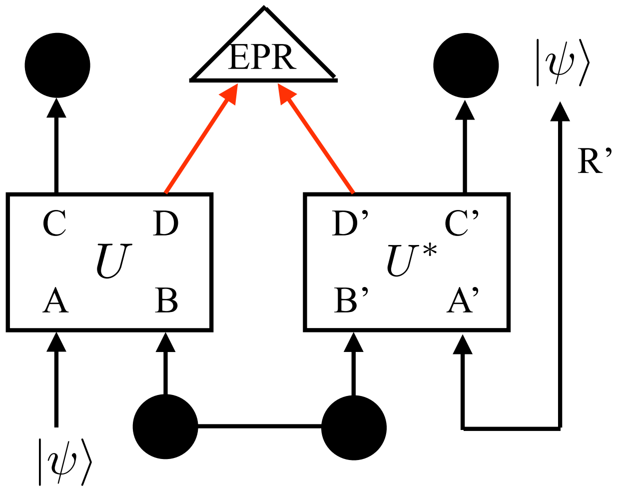


- Decoding protocol distinguishes unitary scrambling from decoherence !



If U = unitary + decoherence, …

- EPR projection

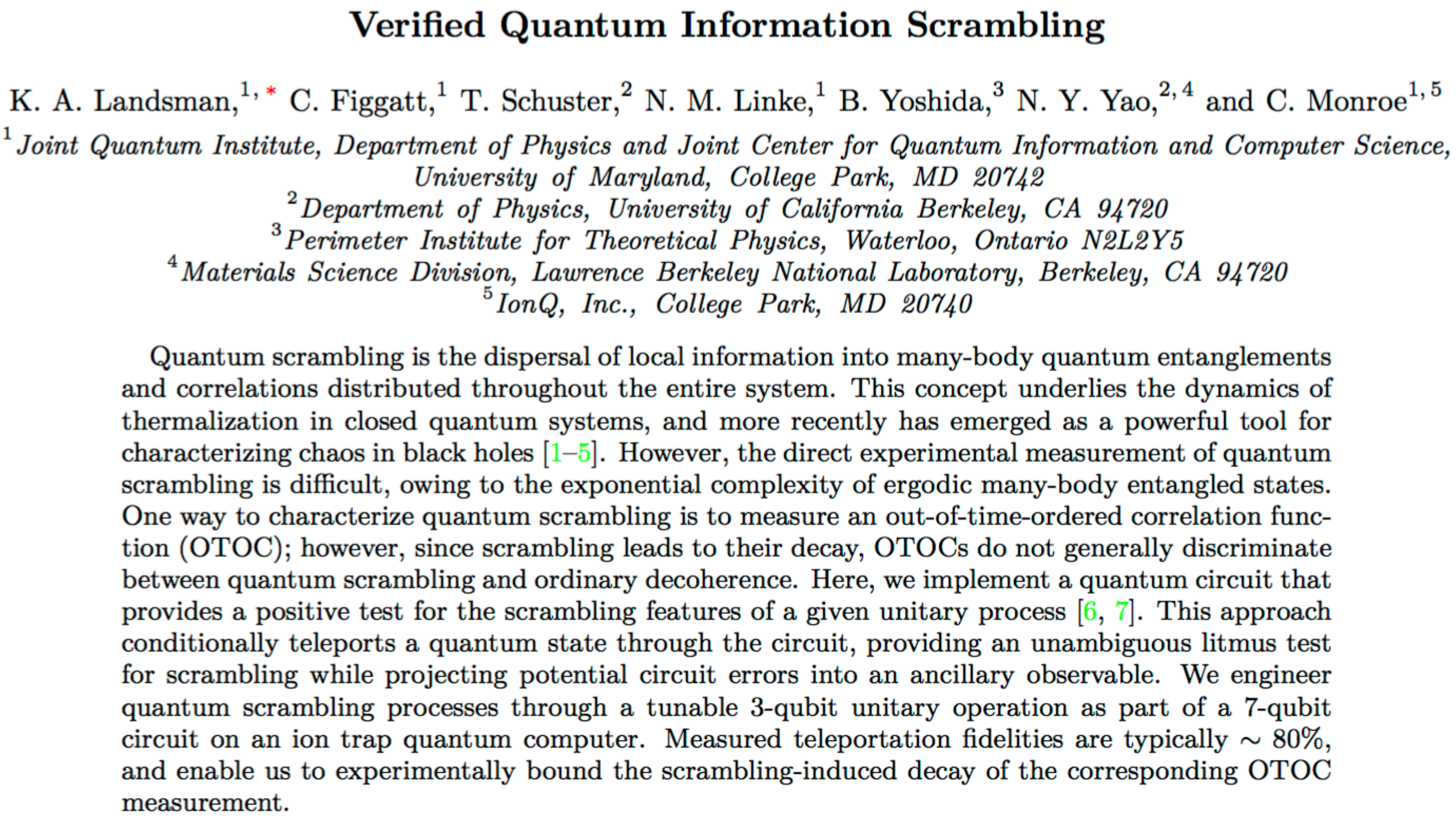
  PEPR : OTOC decay with scrambling and decoherence

- Decoding fidelity

  FEPR : OTOCs with scrambling only

With Chris Monroe group at U Maryland

arXiv:1806.02807



Verified Quantum Information Scrambling

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[1]*Joint Quantum Institute, Department of Physics and Joint Center for Quantum Information and Computer Science, University of Maryland, College Park, MD 20742*
[2]*Department of Physics, University of California Berkeley, CA 94720*
[3]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario N2L2Y5*
[4]*Materials Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720*
[5]*IonQ, Inc., College Park, MD 20740*

Quantum scrambling is the dispersal of local information into many-body quantum entanglements and correlations distributed throughout the entire system. This concept underlies the dynamics of thermalization in closed quantum systems, and more recently has emerged as a powerful tool for characterizing chaos in black holes [1–5]. 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, since 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 [6, 7]. This approach conditionally teleports a quantum state through the circuit, providing an unambiguous litmus test for scrambling while projecting potential circuit errors into an ancillary observable. We engineer quantum scrambling processes through a tunable 3-qubit unitary operation as part of a 7-qubit circuit on an ion trap quantum computer. Measured teleportation fidelities are typically ∼ 80%, and enable us to experimentally bound the scrambling-induced decay of the corresponding OTOC measurement.

Decoding a black hole;

from scrambling to information loss

Beni Yoshida (Perimeter Institute)

August 2018 @ Tokyo