Title: Black holes as mirrors

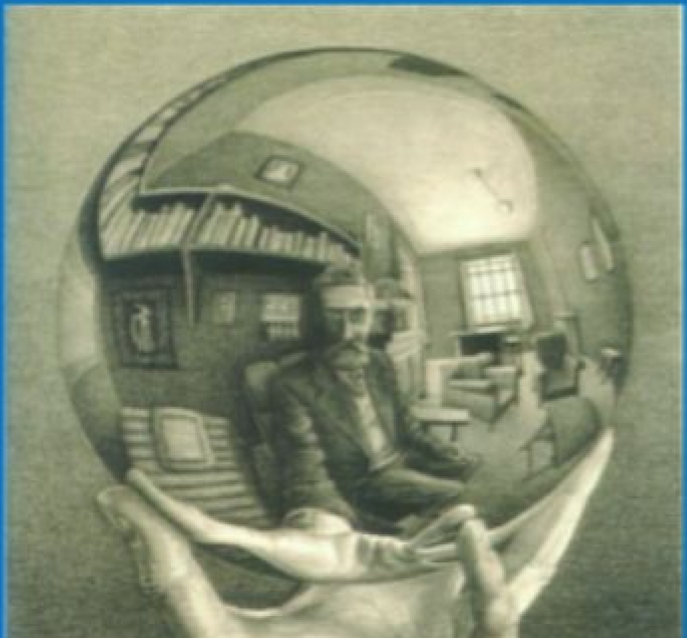
Date: Jan 24, 2009 02:30 PM

URL: http://pirsa.org/09010031

Abstract: I'll discuss information retrieval from evaporating black holes, assuming that the internal dynamics of a black hole is unitary and rapidly mixing, and assuming that the retriever has unlimited control over the emitted Hawking radiation. If the evaporation of the black hole has already proceeded past the 'half-way' point, where half of the initial entropy has been radiated away, then additional quantum information deposited in the black hole is revealed in the Hawking radiation very rapidly. Information deposited prior to the half-way point remains concealed until the half-way point, and then emerges quickly. These conclusions hold because typical local quantum circuits are efficient encoders for quantum error-correcting codes that nearly achieve the capacity of the quantum erasure channel. The resulting estimate of a black hole's information retention time, based on speculative dynamical assumptions, is just barely compatible with the black hole complementary hypothesis. (Joint work with John Preskill).

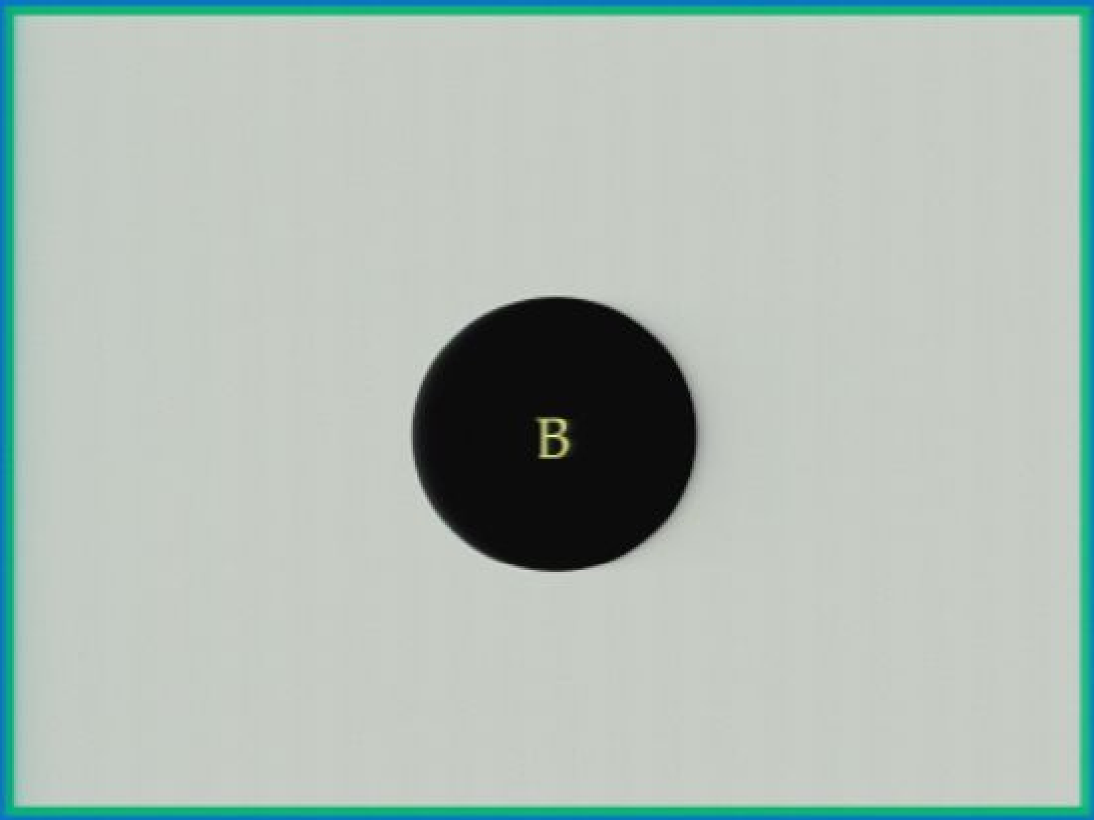
Black Holes as Mirrors

Patrick Hayden (McGill University)
John Preskill (Caltech)



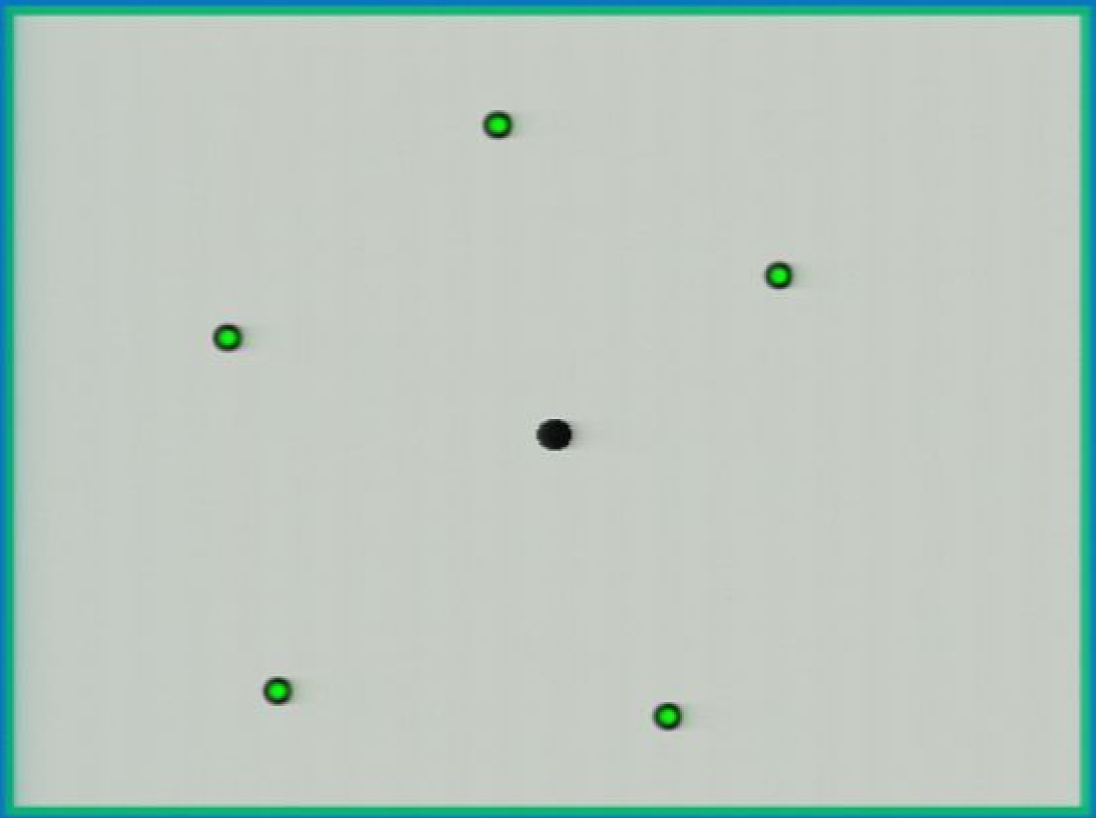
Black Holes and

Black Hole Evaporation



Pure state

Black Hole Evaporation



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Thermal Hawking radiation

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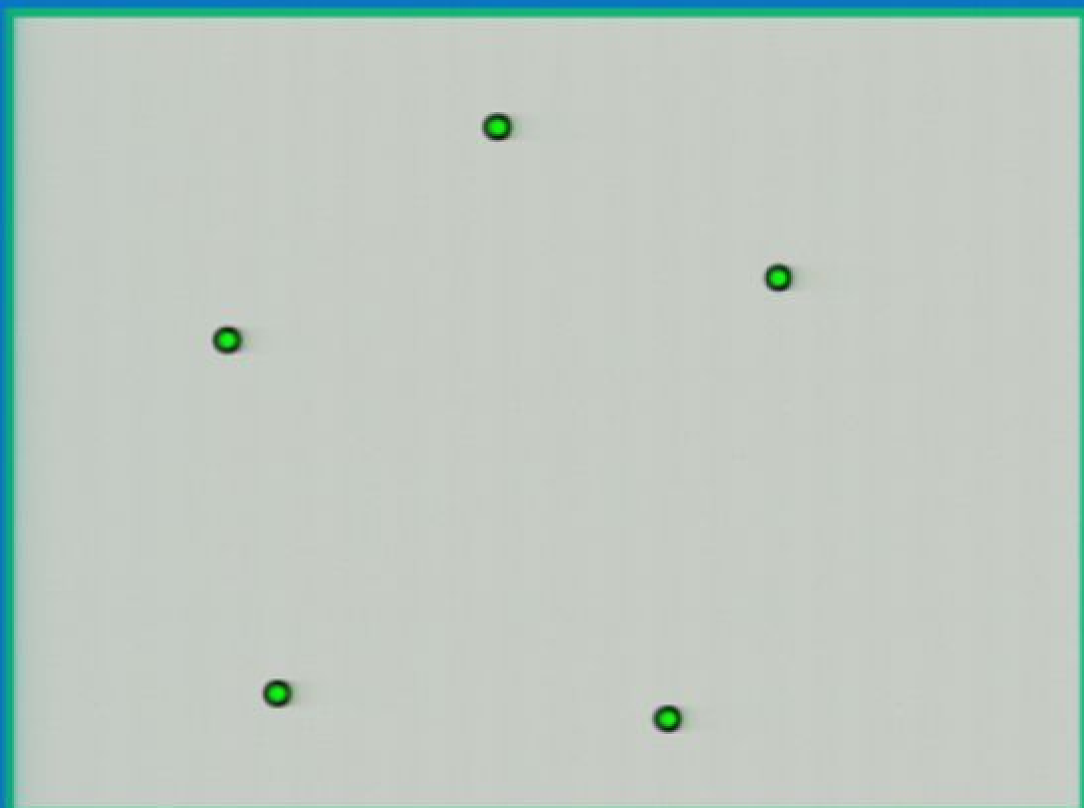

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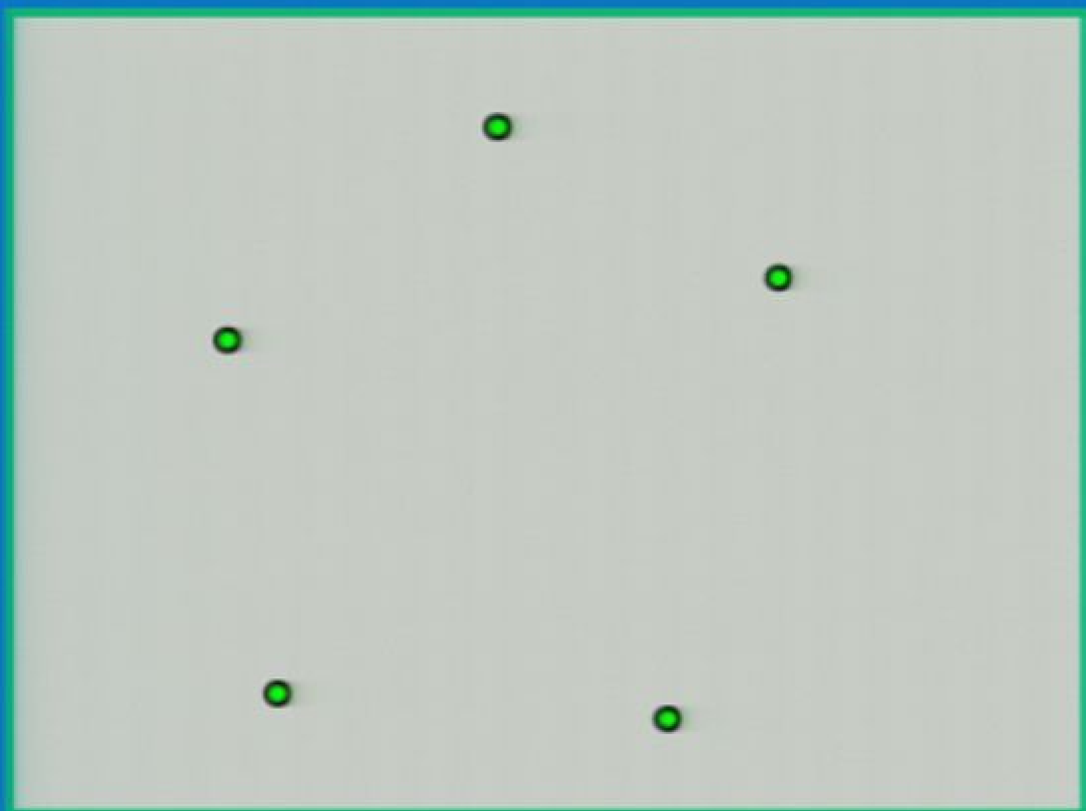
Thermal Hawking radiation

Radiation but no black hole

Black Hole Evaporation



Pure state

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Radiation but no black hole

Hawking's Question: Is the final state mixed or pure?

Between a Rock and a Hard Place

Finer Question: Does information dropped into a black hole ever come out?

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The Black Hole Complementarity Principle

Cloning is **unverifiable** by an experiment

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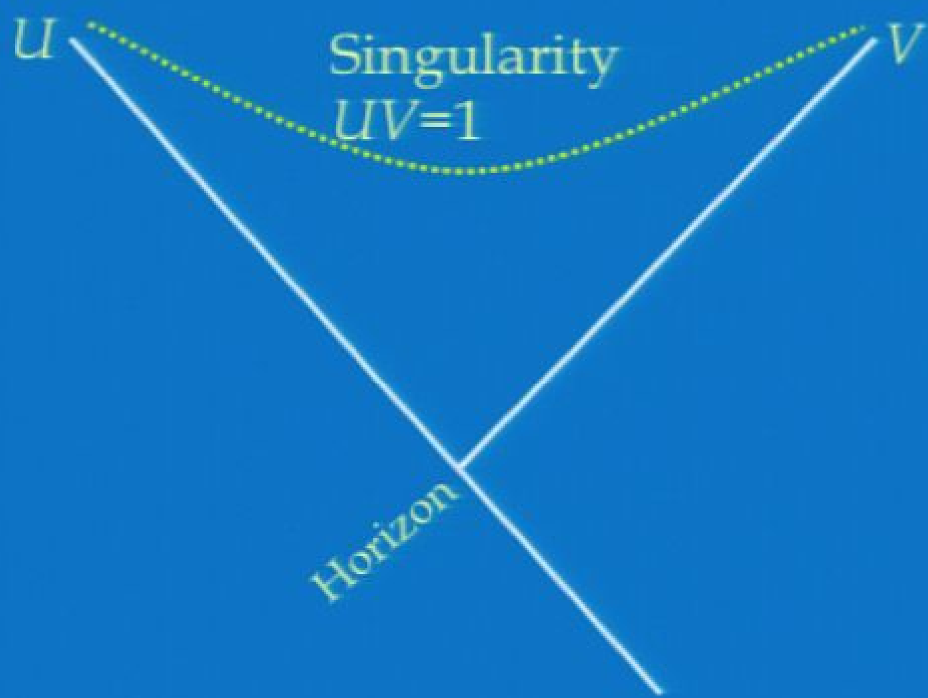

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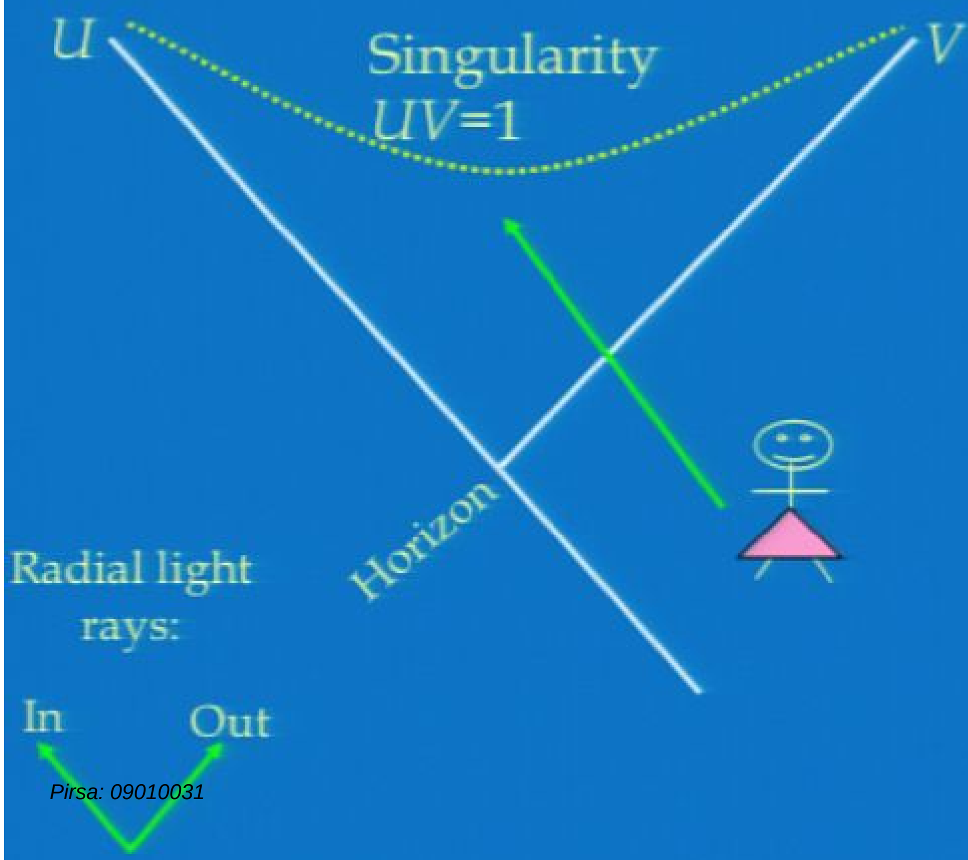

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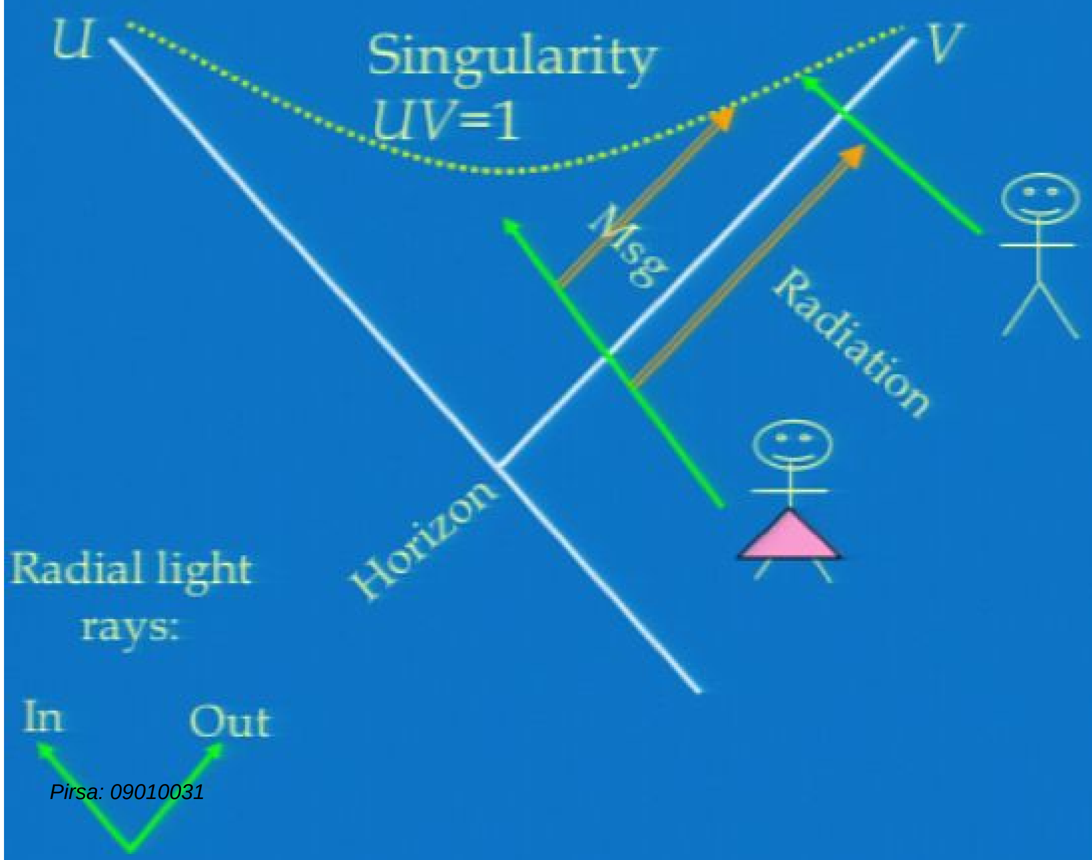

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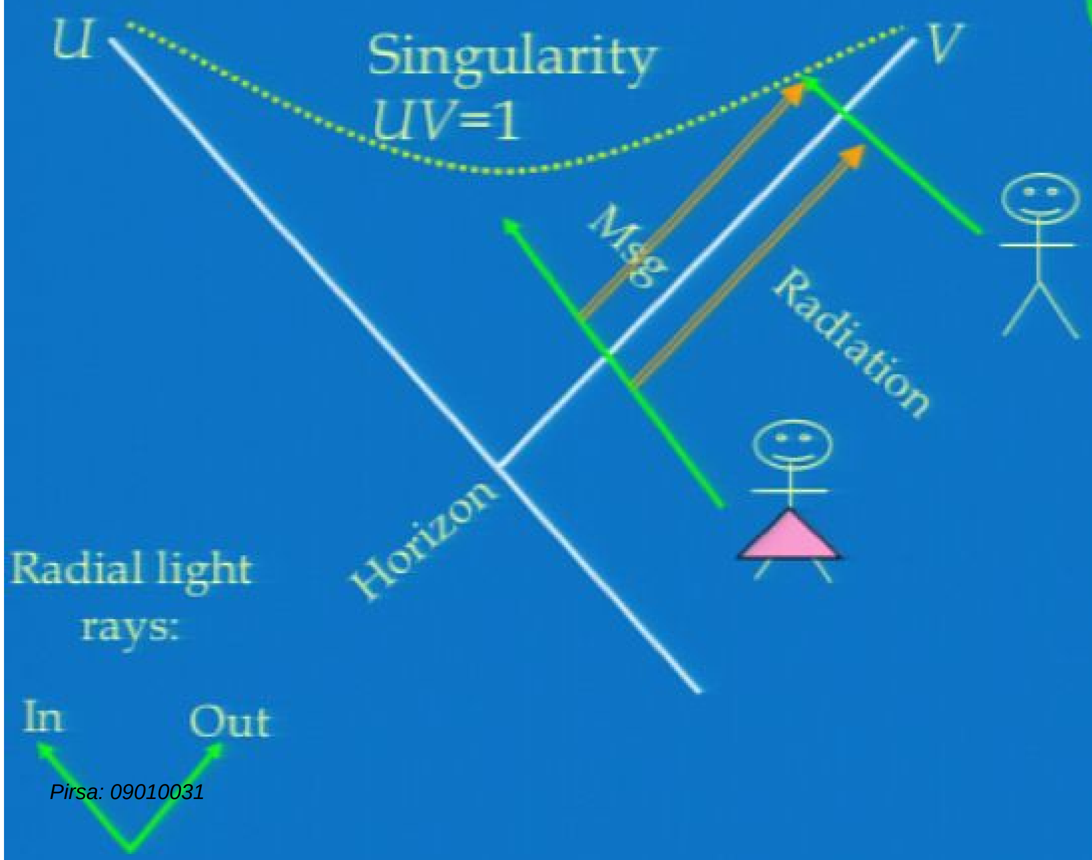

Alice proper time to release msg

Bob's delay (Sch. time)

$$\tau_{Al} = C r_s \exp\left(\frac{-\Delta t}{r_s}\right)$$

Schwarzschild radius

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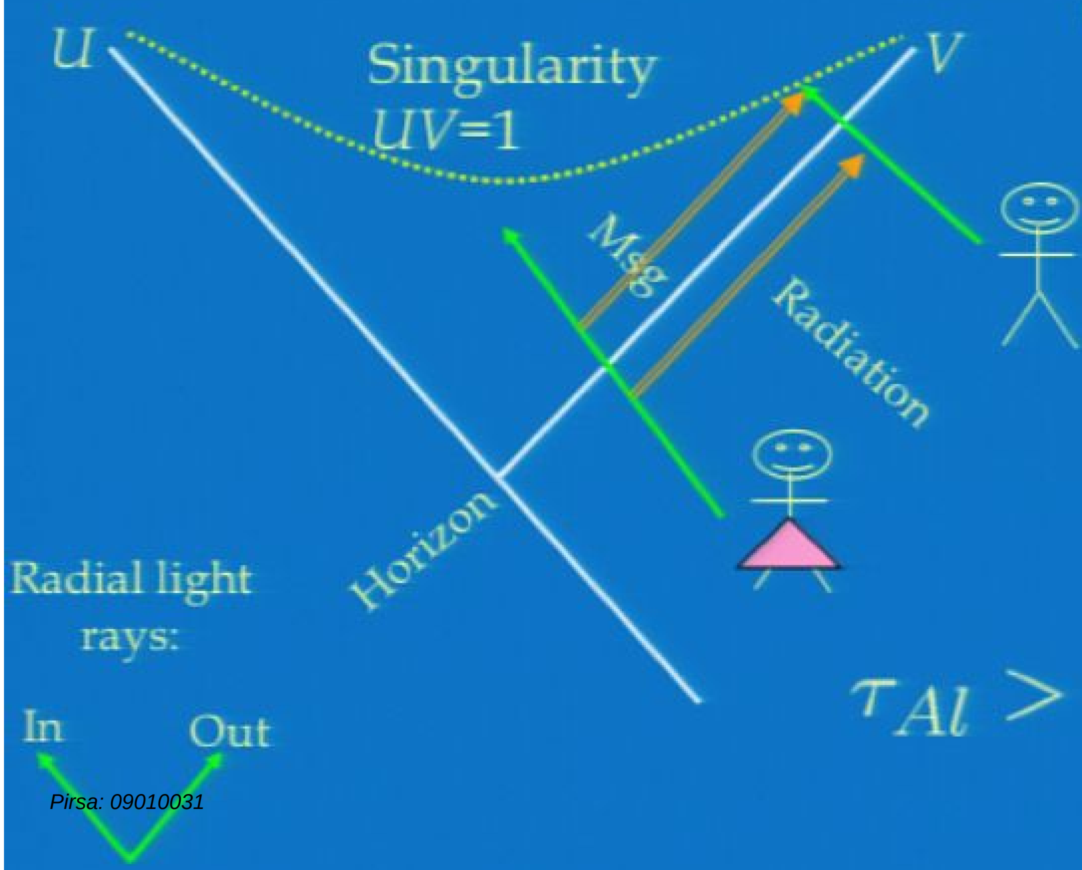

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$$\tau_{Al} = C r_s \exp\left(\frac{-\Delta t}{r_s}\right)$$

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Require expt using sub-Planck energy:

$$\tau_{Al} > 1$$

$$\Delta t < C' r_s \log r_s$$

Black Hole Complementarity Consistency Condition

$$t_{info} > C' r_s \log r_s$$

t_{info} via Page ansatz

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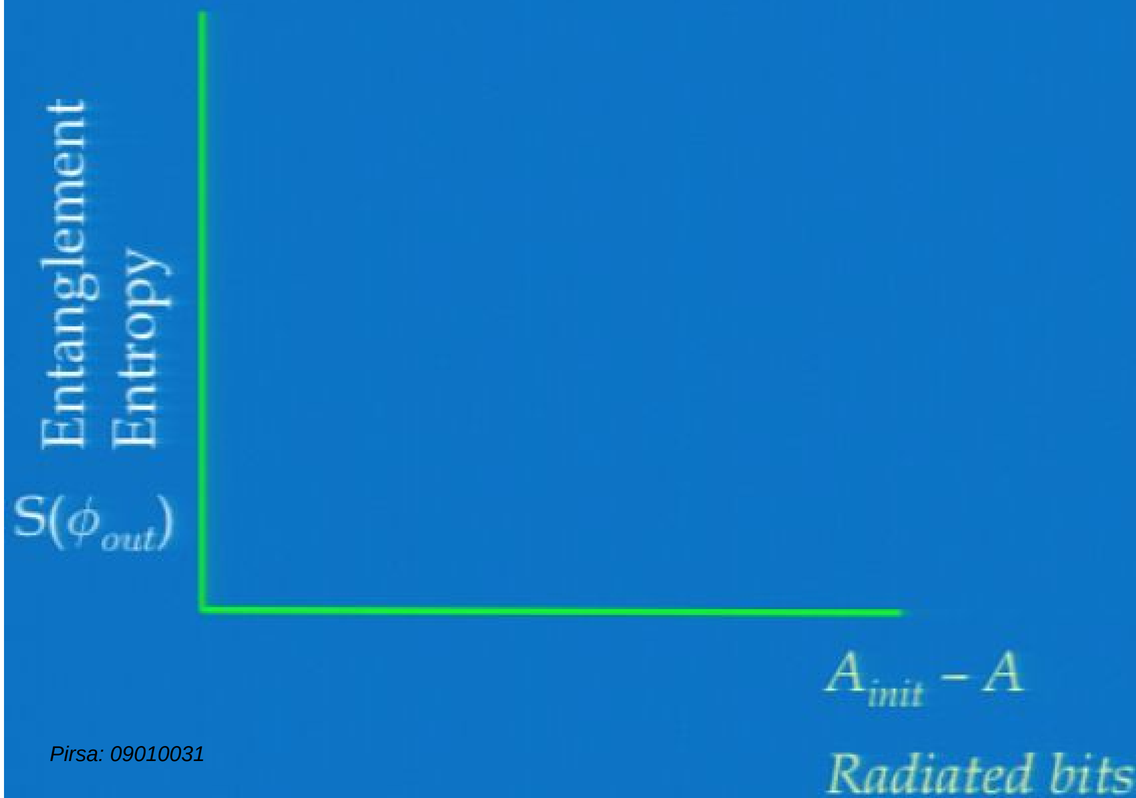

t_{info} via Page ansatz

Random $|\phi\rangle \in \mathcal{H}_{in} \otimes \mathcal{H}_{out} \cong \mathbb{C}^{d^2}$

Area $A \sim \log \dim \mathcal{H}_{in}$

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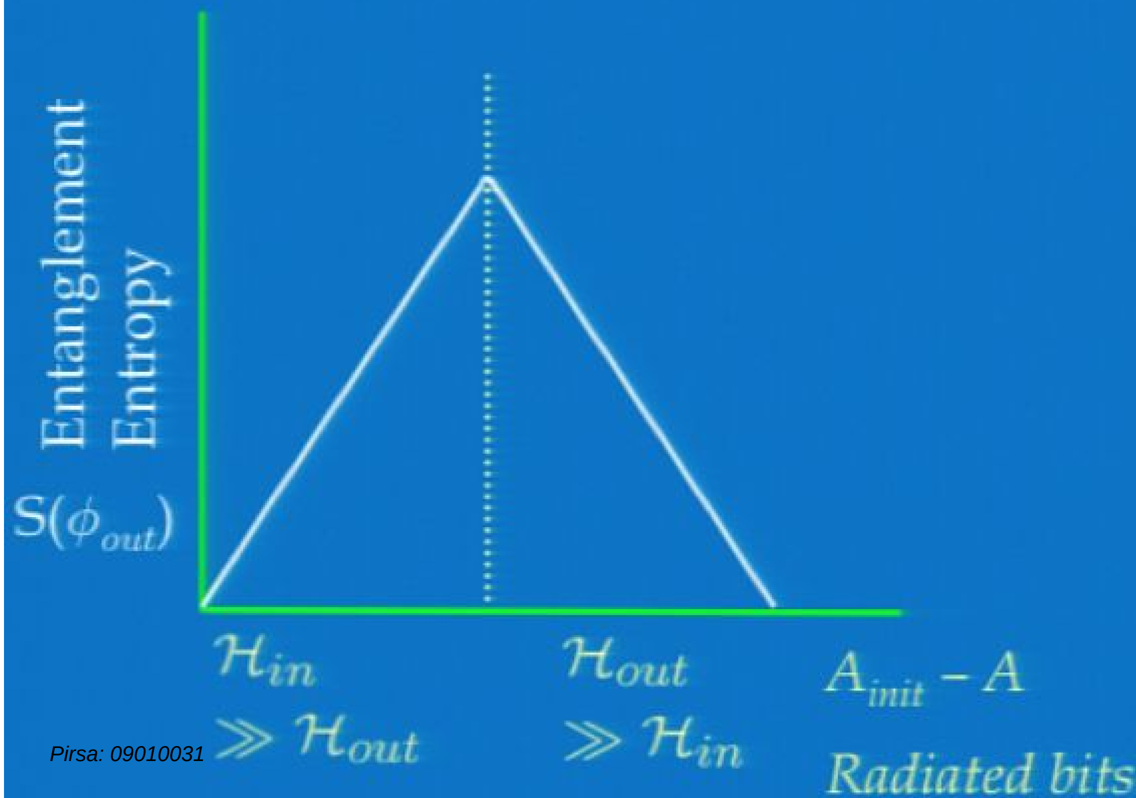

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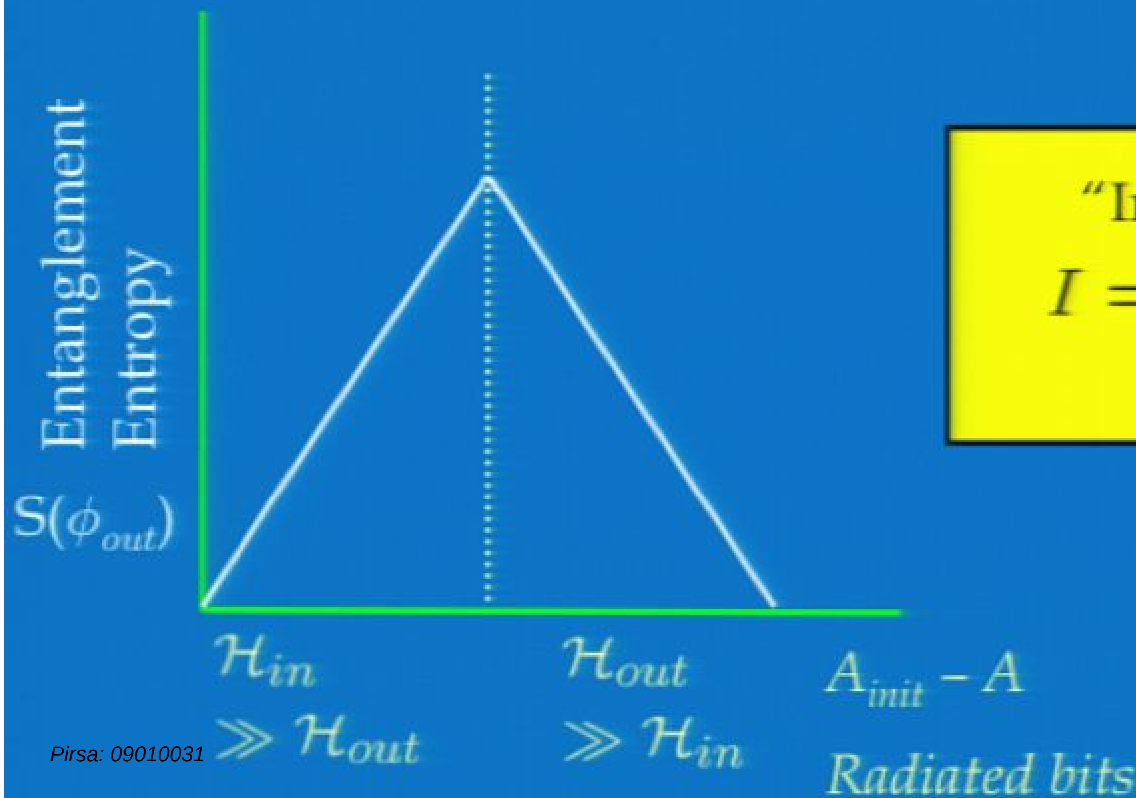

"Information" in the radiation:

$$I = \log \dim \mathcal{H}_{out} - S(\phi_{out})$$

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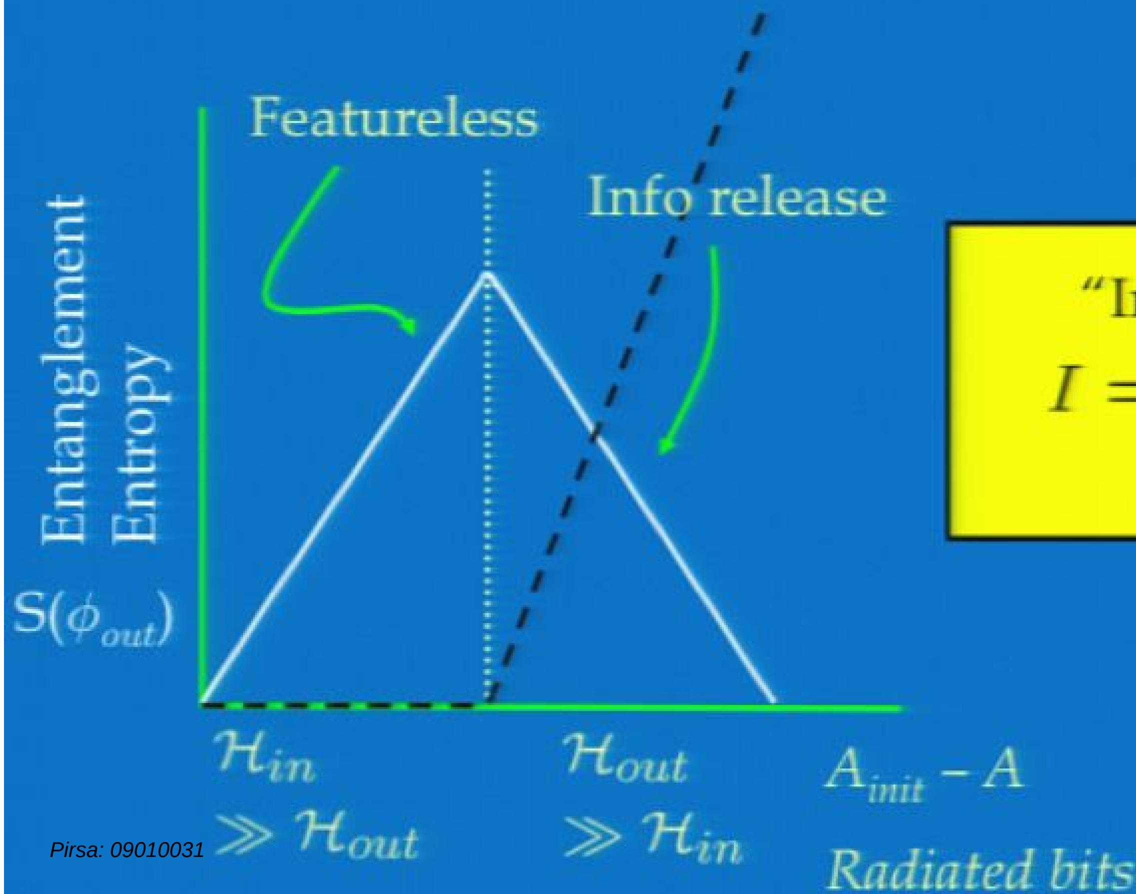

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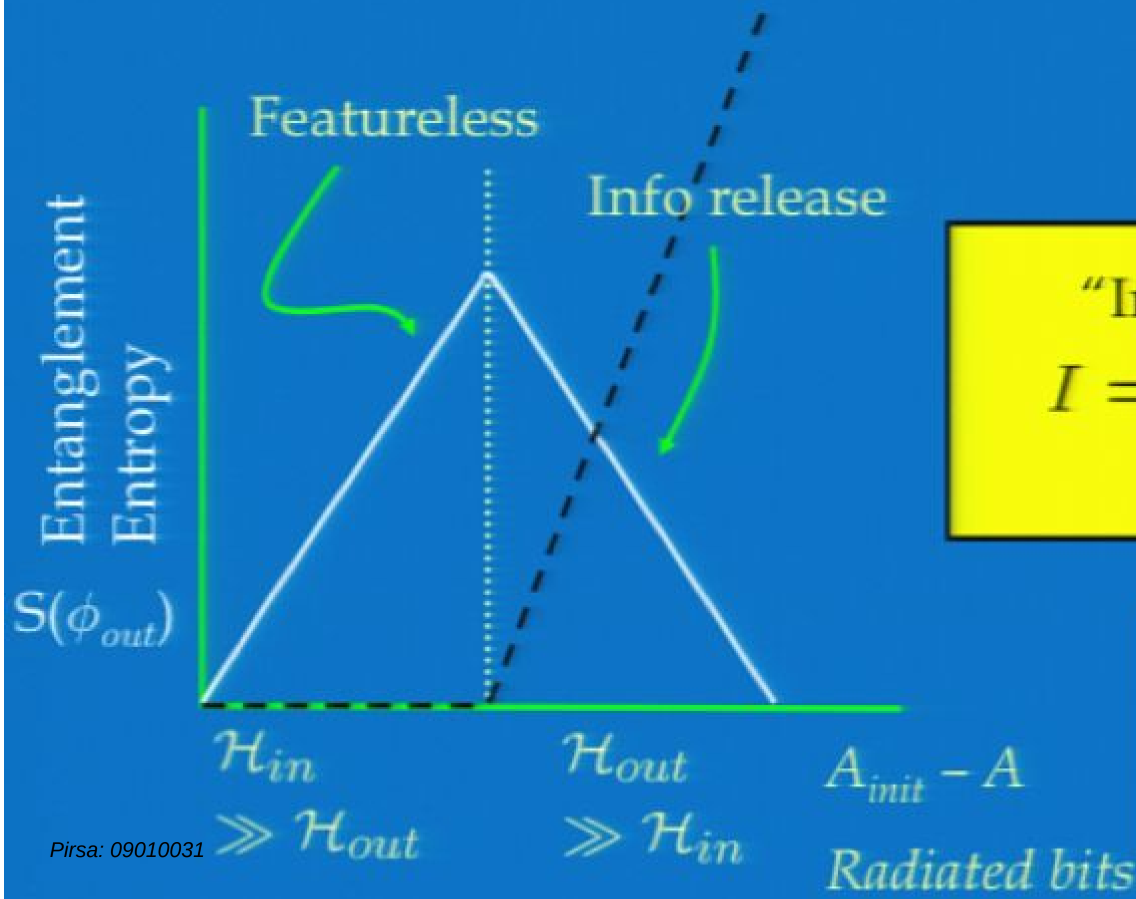

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$$t_{info} \sim \text{BH lifetime} \sim r_s^3$$

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$M_\odot$

Milliseconds vs 10^{70} years

Needle in a Haystack?

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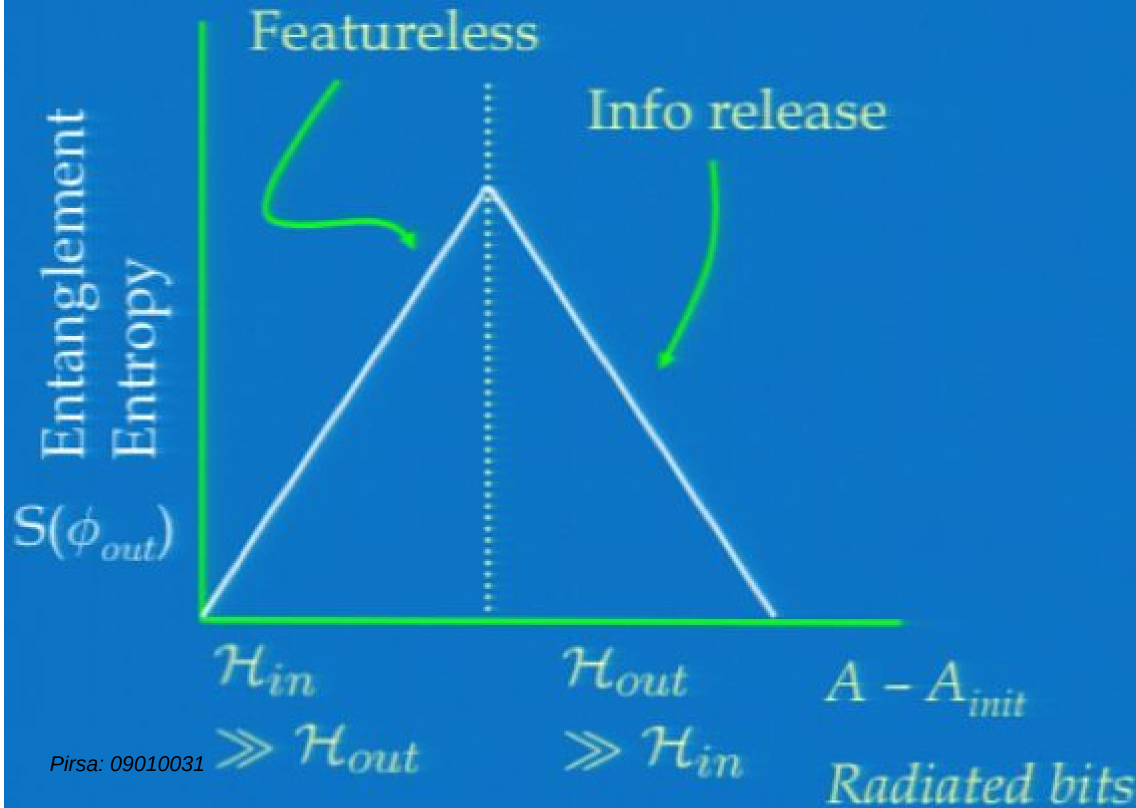

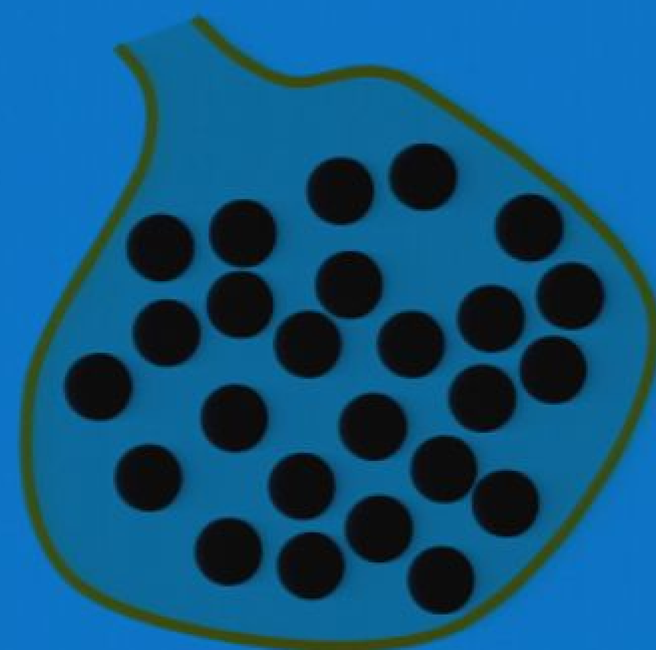

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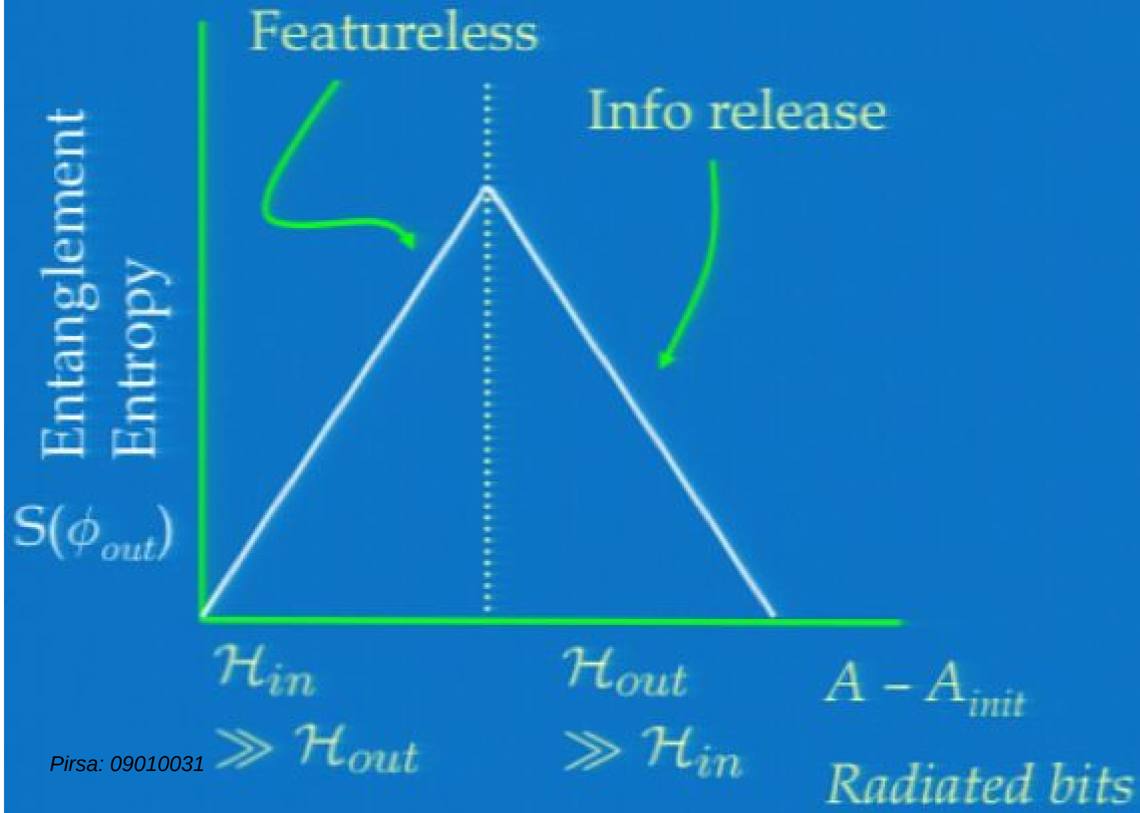

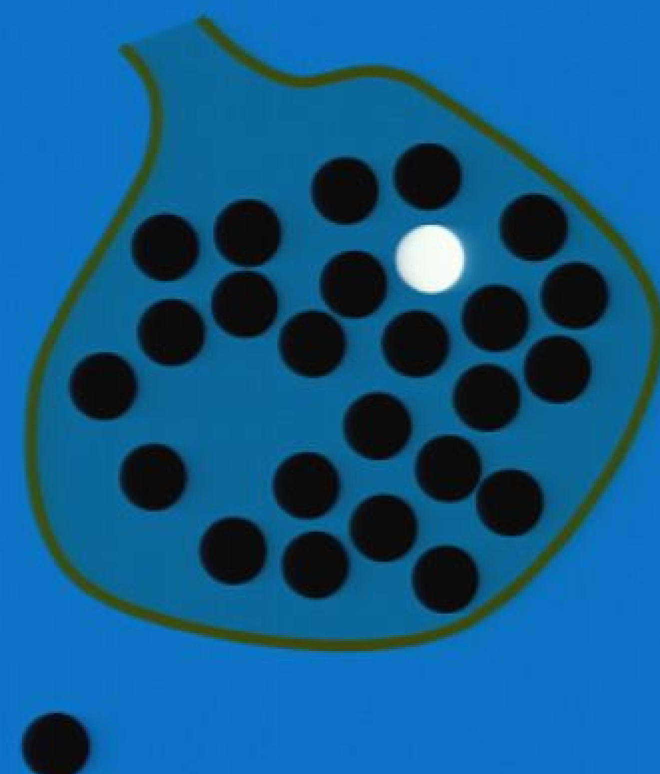

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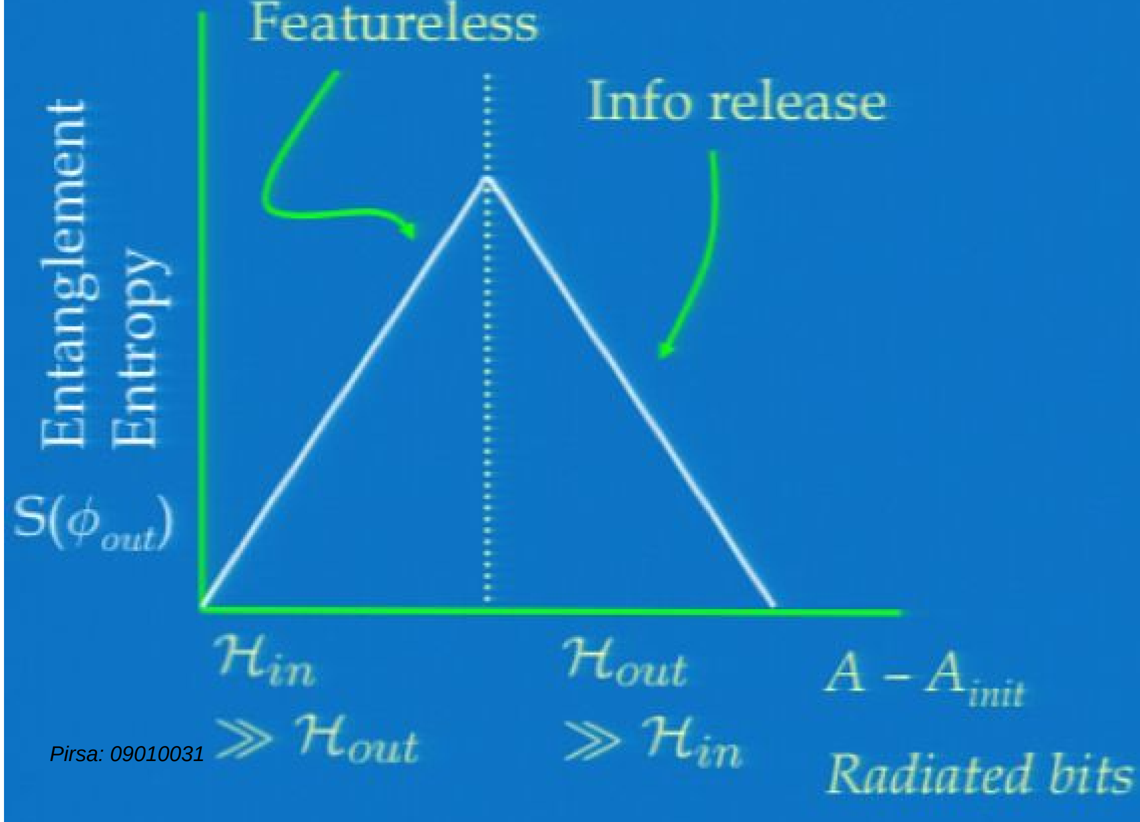

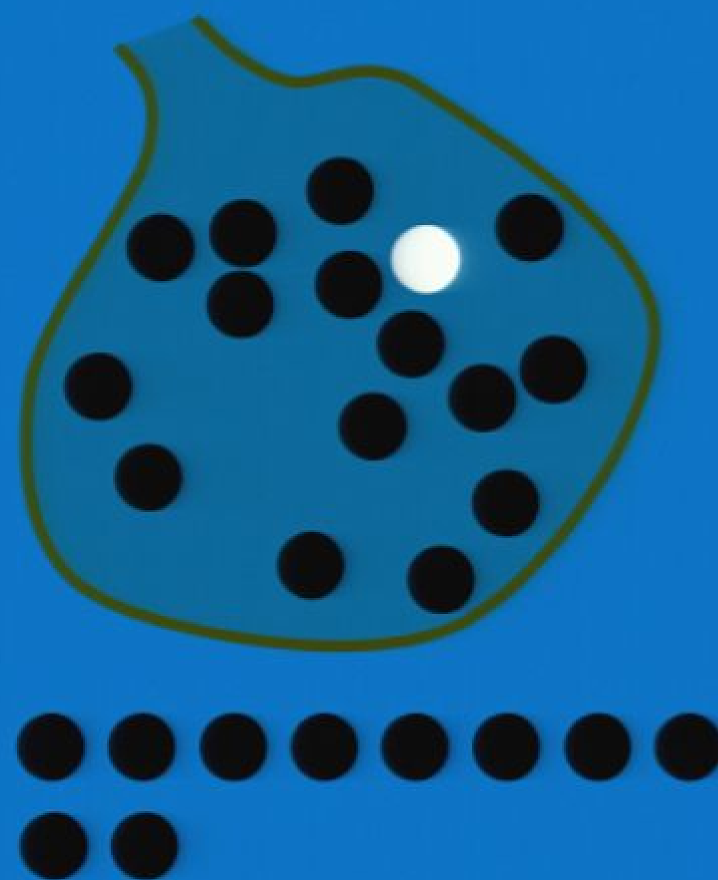

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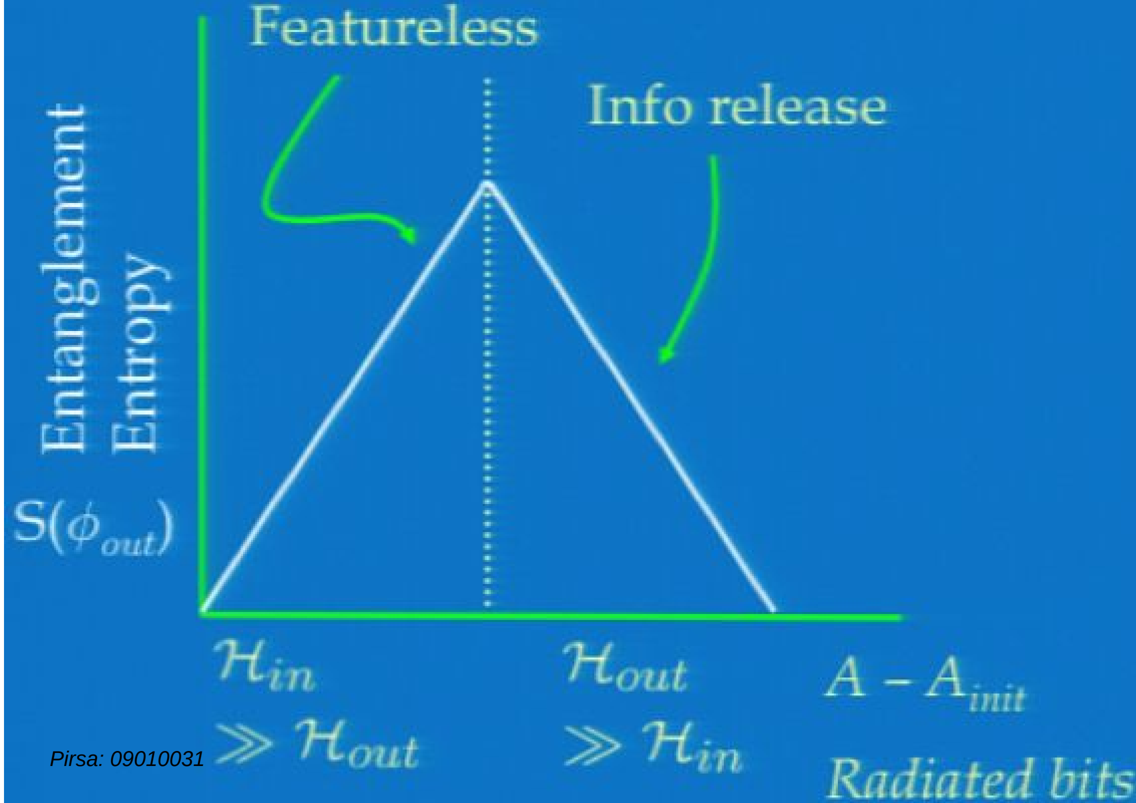

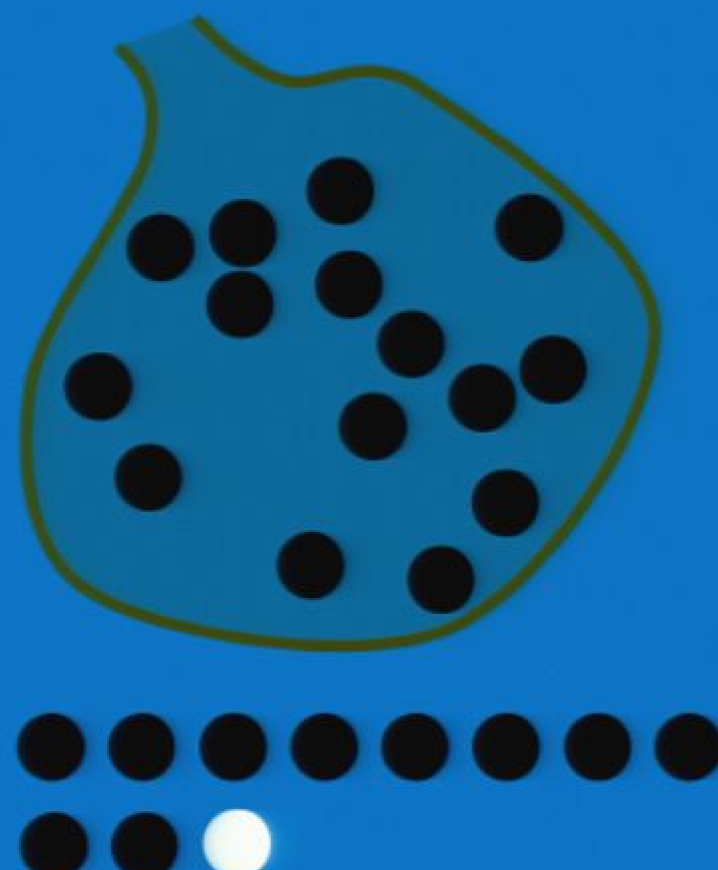

Classical Model

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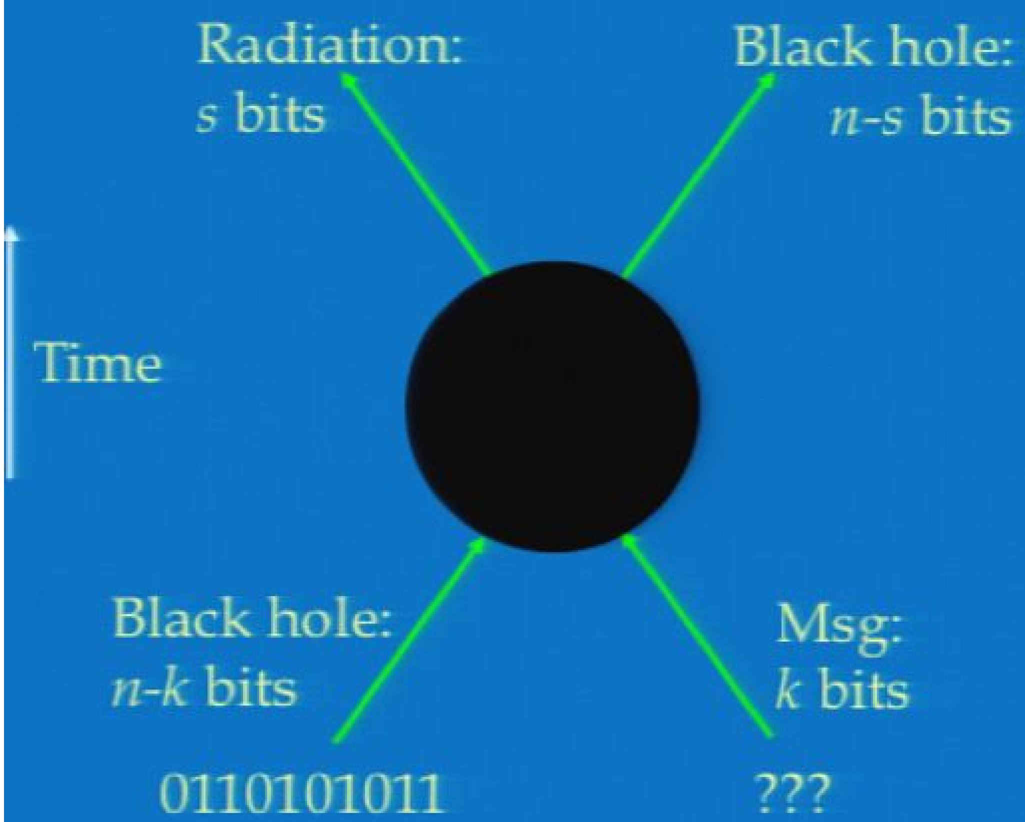
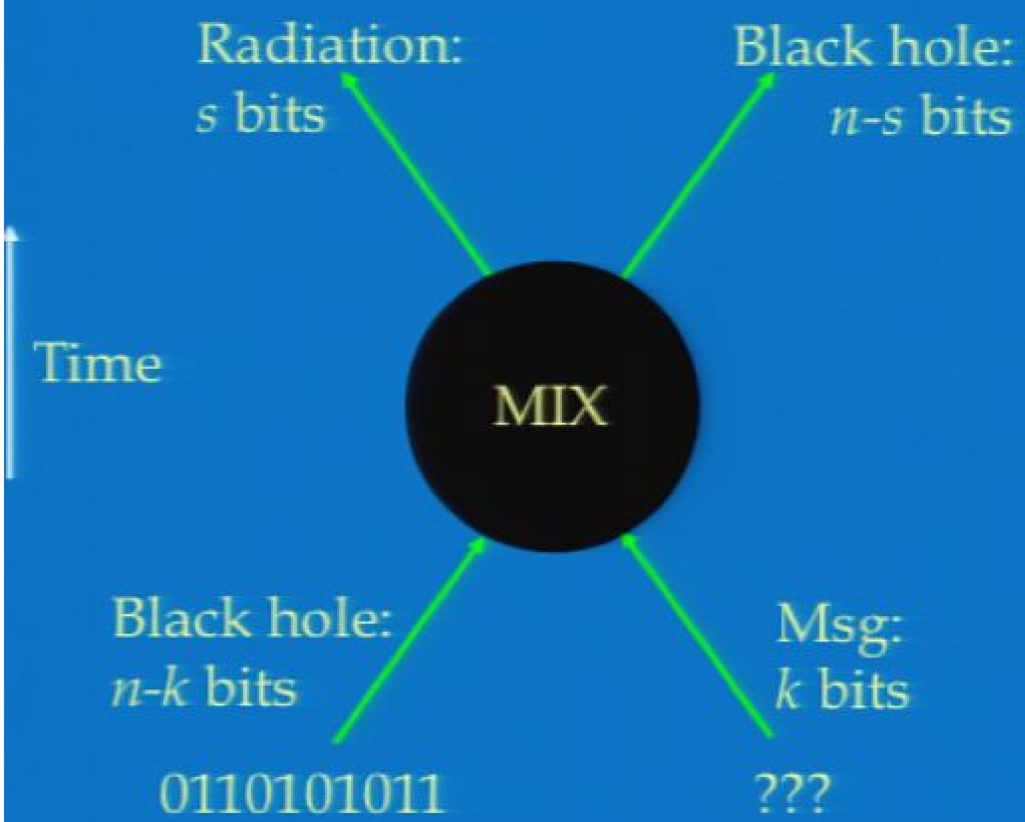


Classical Model

Assume MIX is a *random* permutation on 2^n bit strings.



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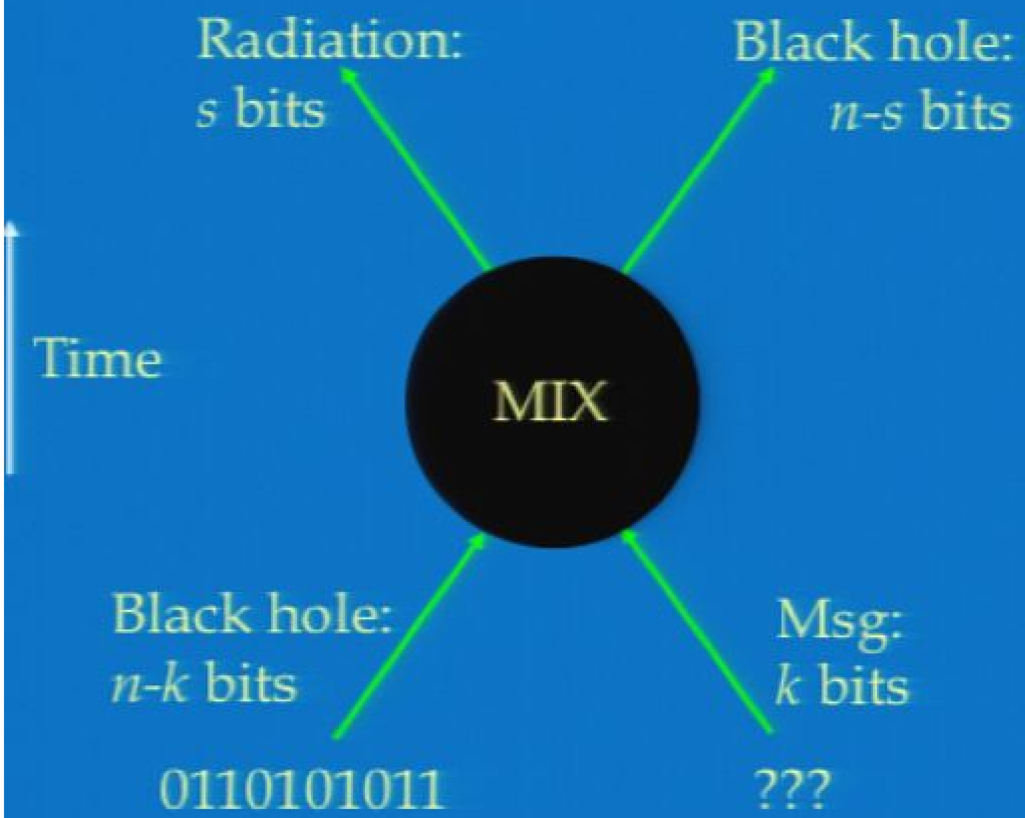

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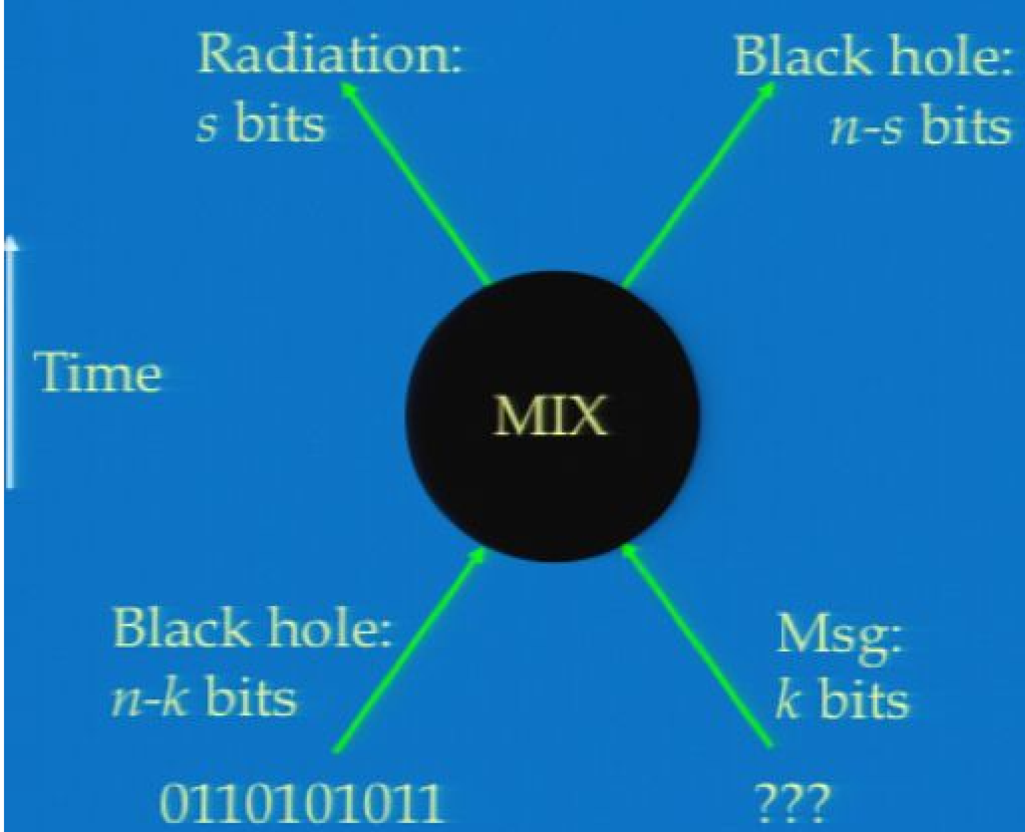
Example: s=k=1

Msg: 0 → 011010110
1 → 101001101

Message bit i	Radiation bit r(i)			
0				
1				

Classical Model



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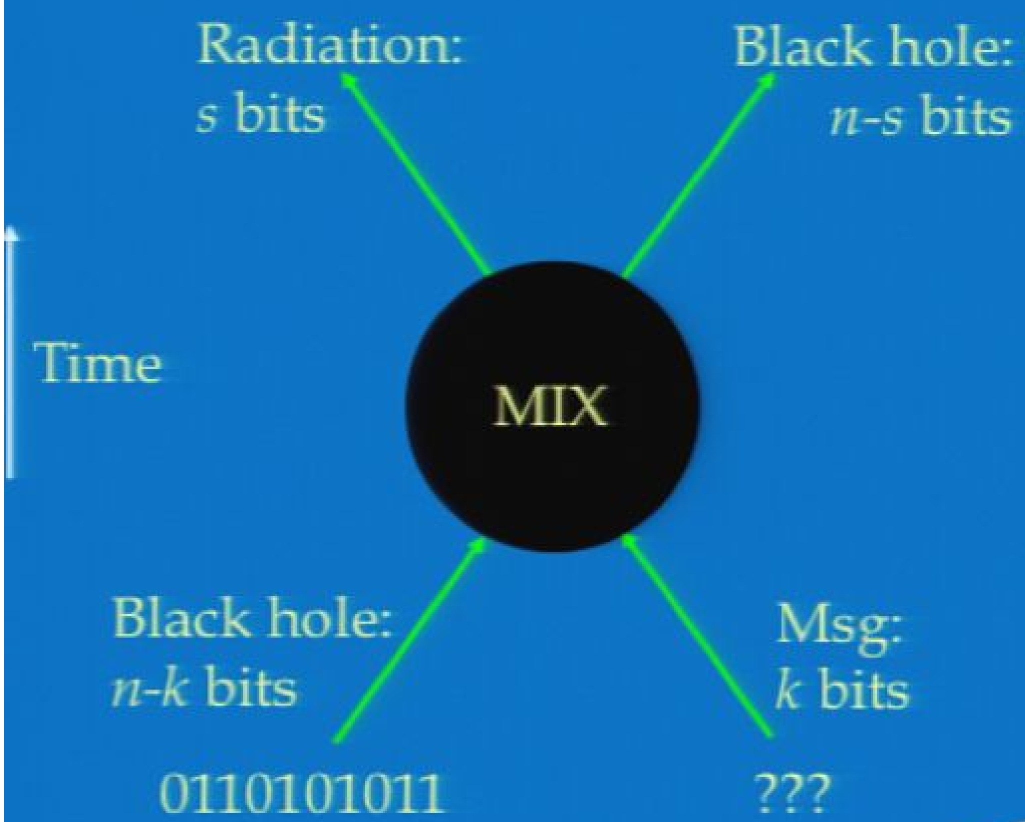

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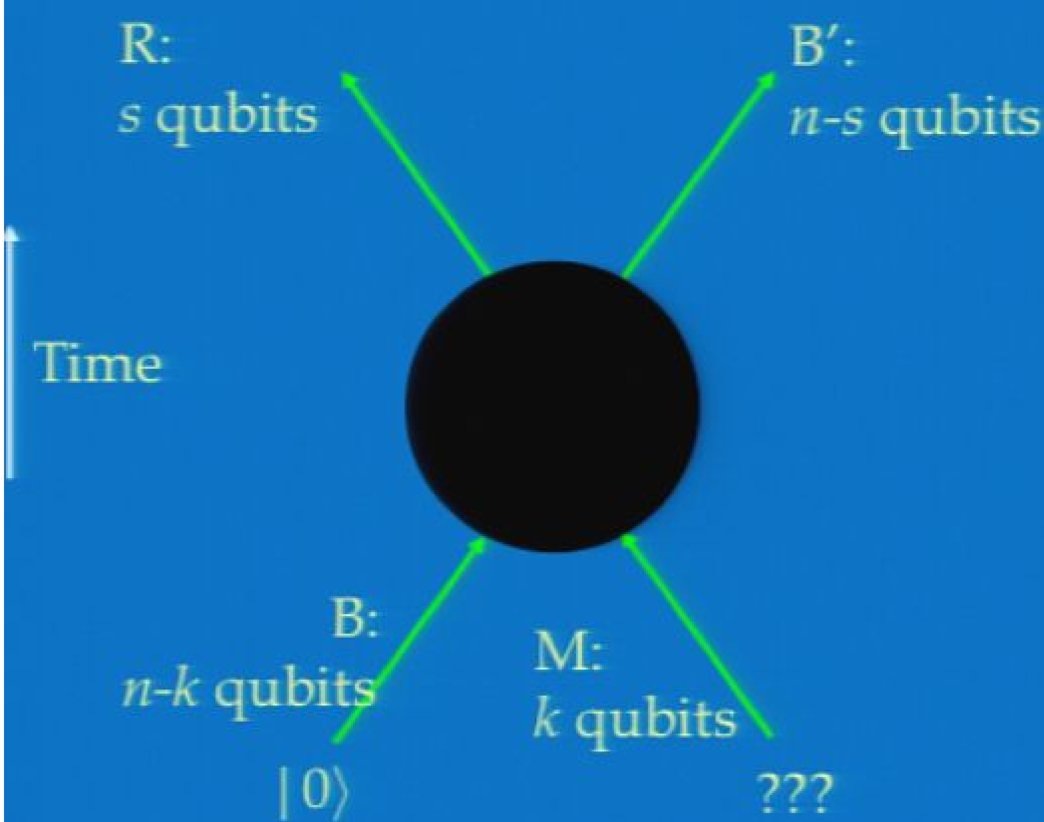
Mirror effect!

Quantum Model (v1)



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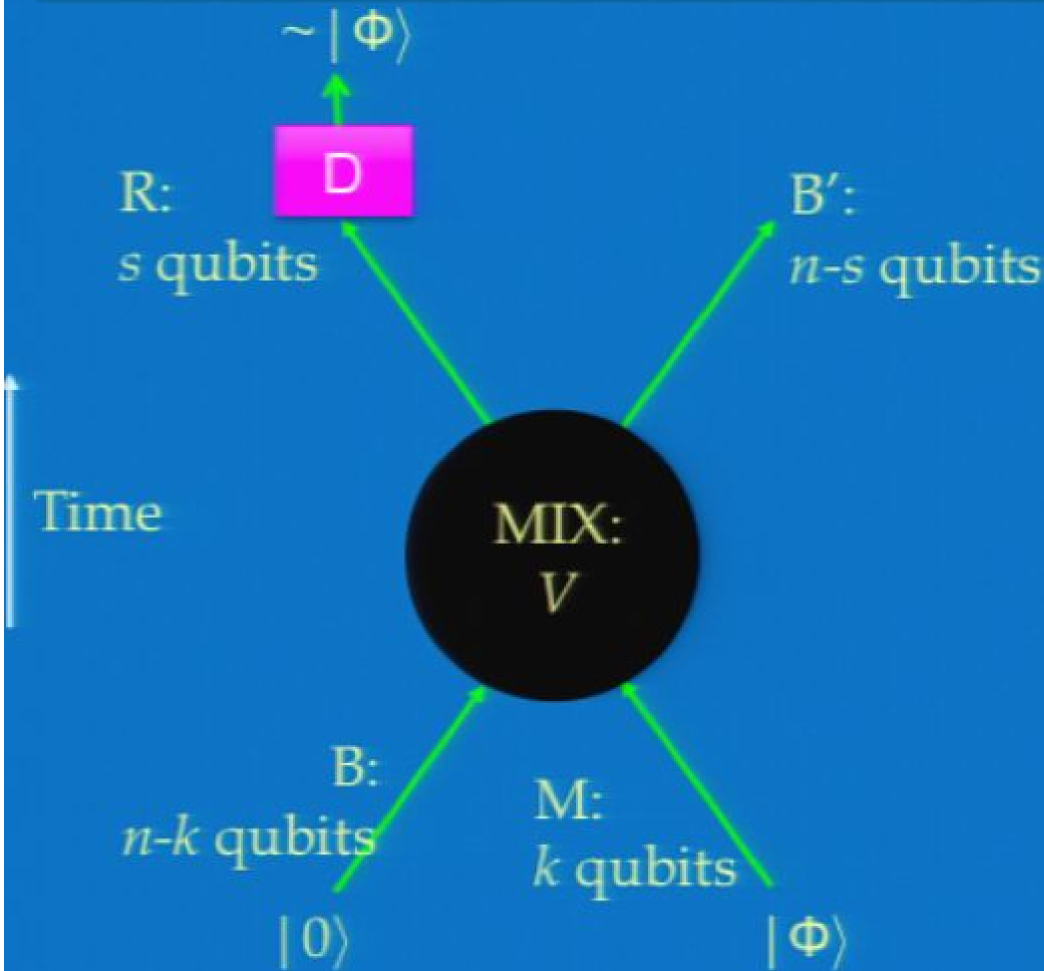

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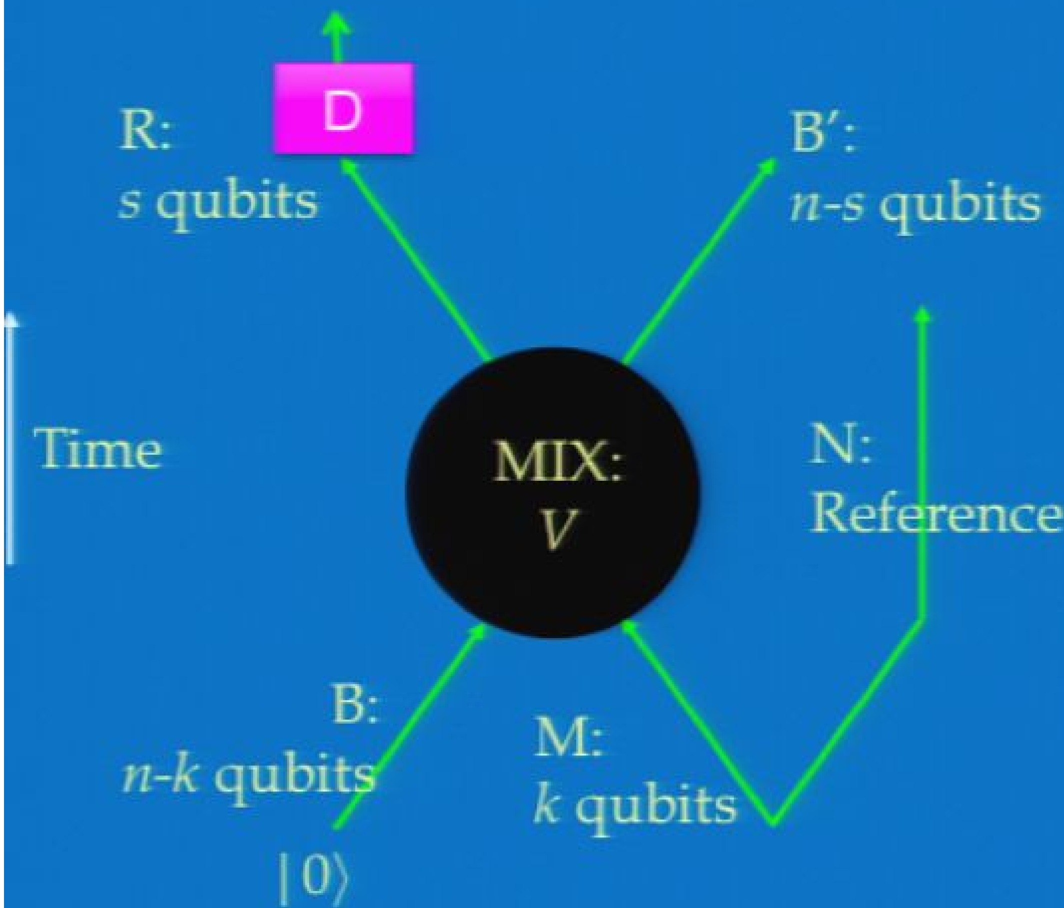

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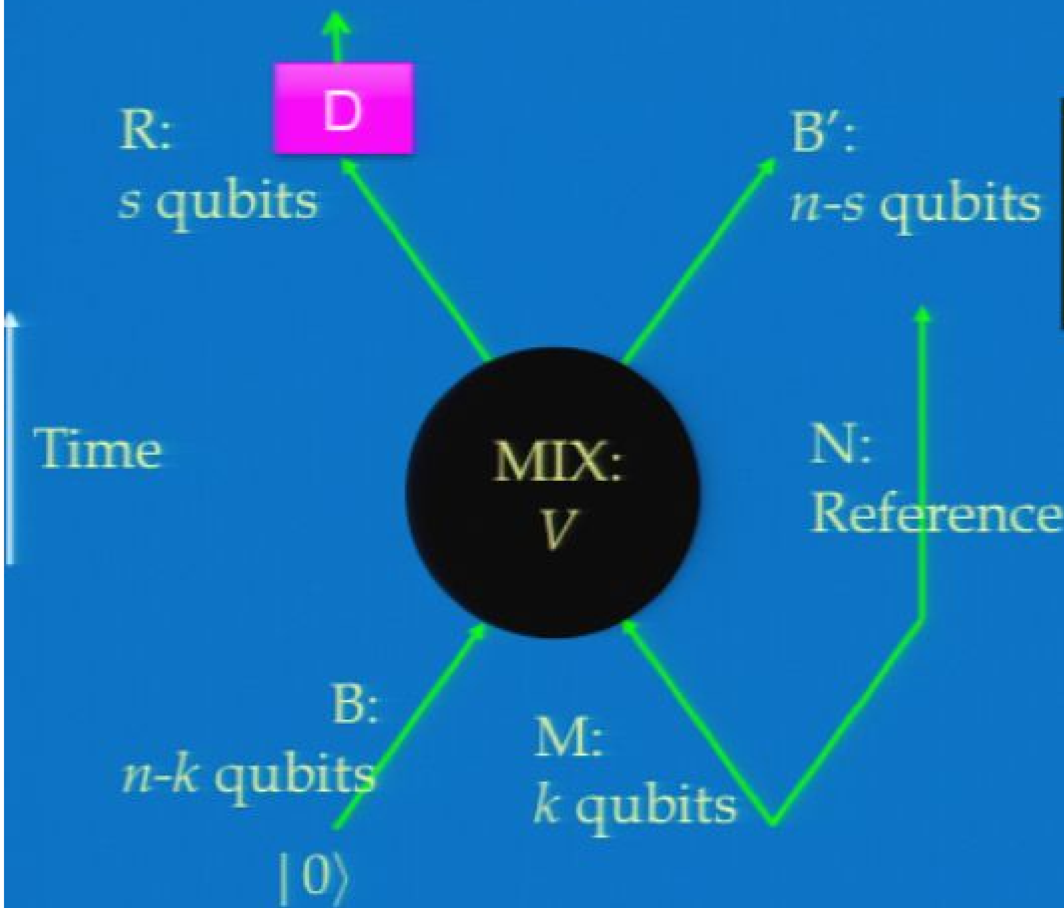

Sending arbitrary states from M to R is *equivalent* to establishing entanglement between N and R

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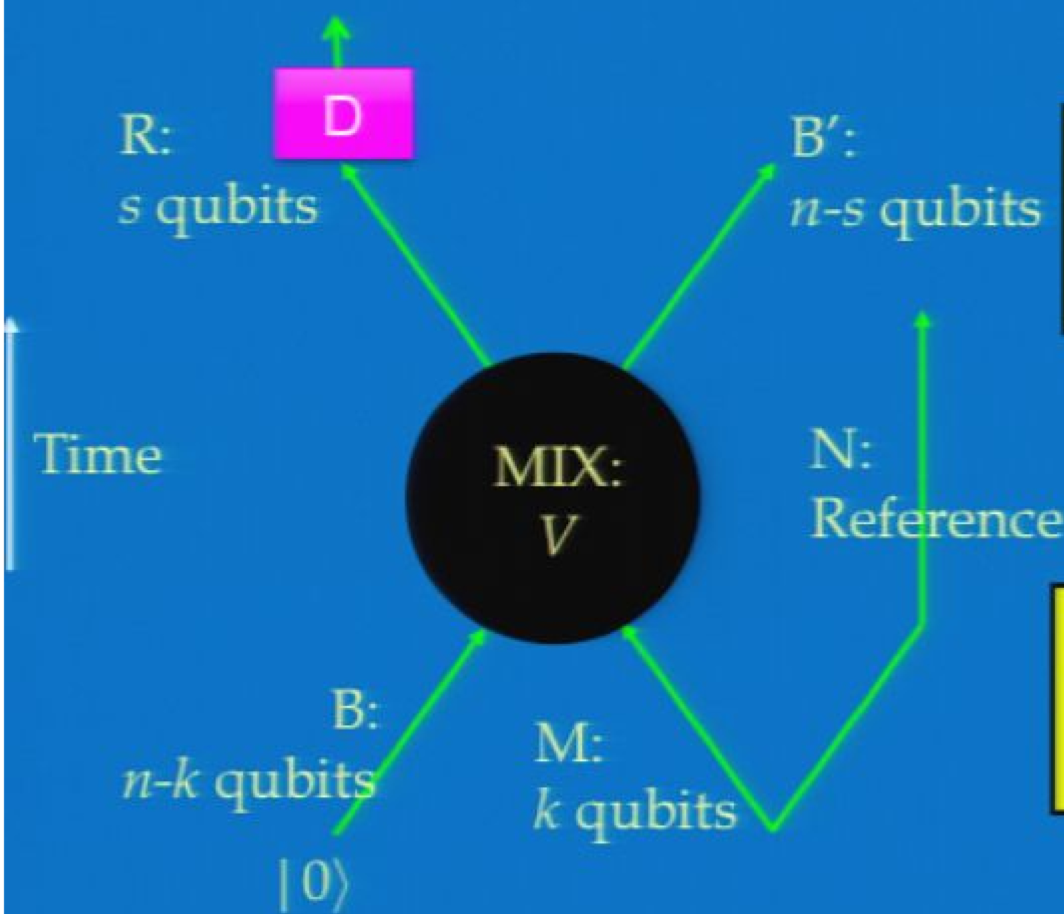


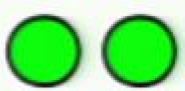
Sending arbitrary states from M to R is *equivalent* to establishing entanglement between N and R

Establishing entanglement between N and R is *equivalent* to eliminating all correlations between N and B′

Church of the Larger Hilbert Space

Purification: $|\Psi\rangle_{XY}$ is a *purification* of ρ_X if $\mathrm{tr}_Y\, |\psi\rangle\langle\psi| = \rho_X$.

Purifications are essentially *unique*.
(Up to local unitaries on the purifying space.)



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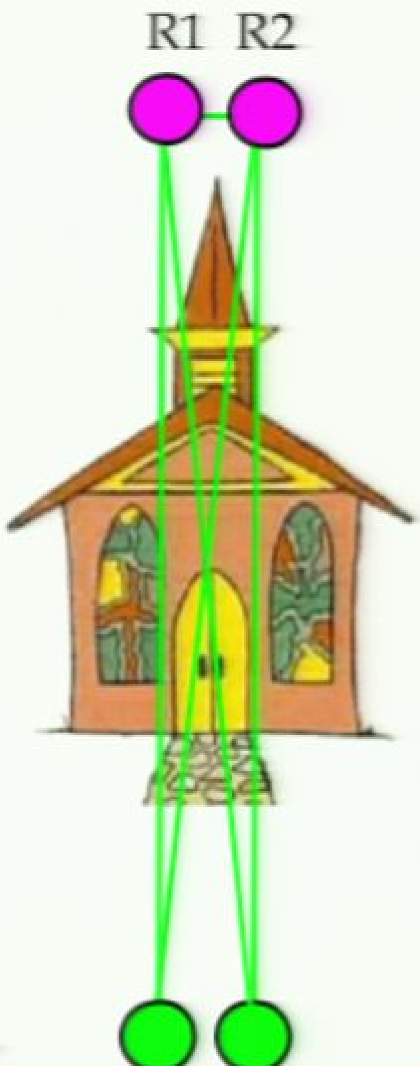

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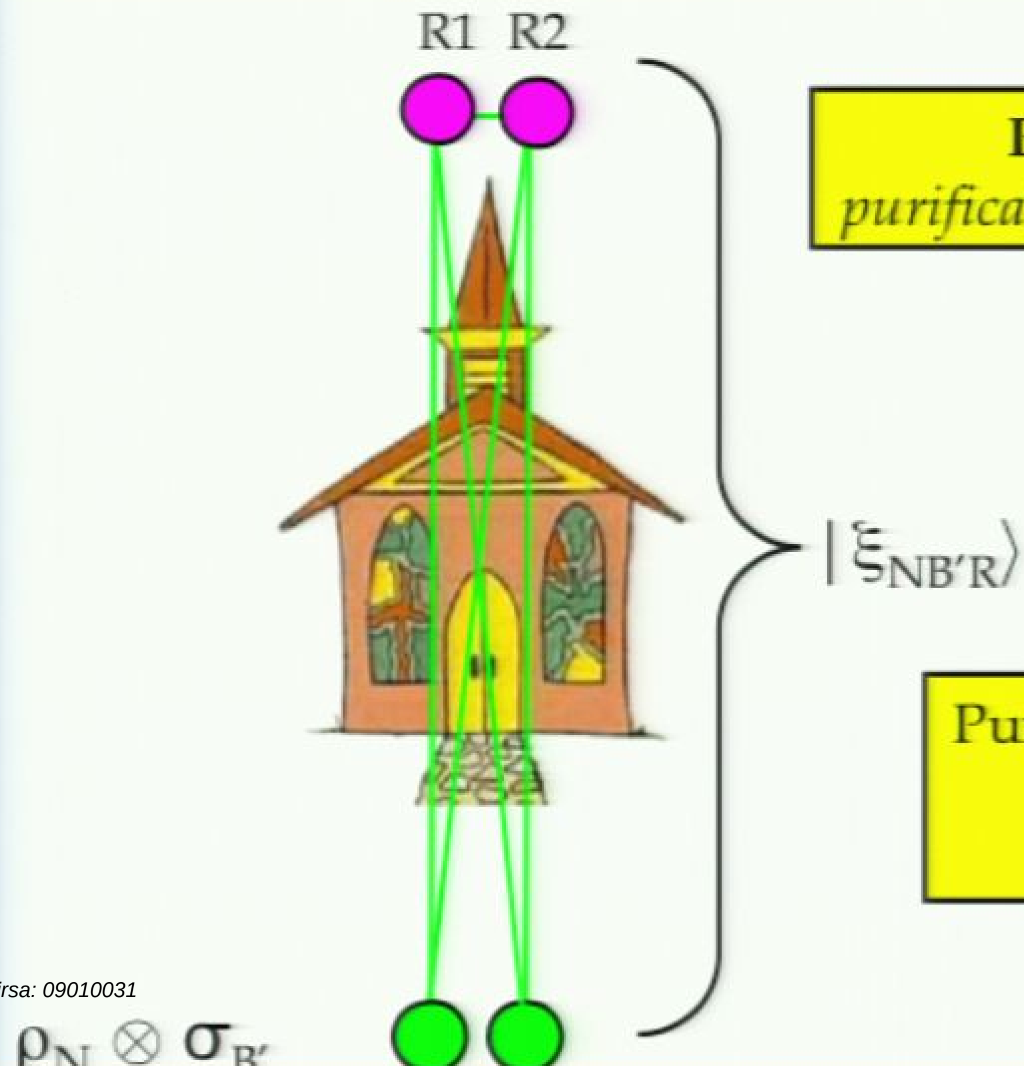

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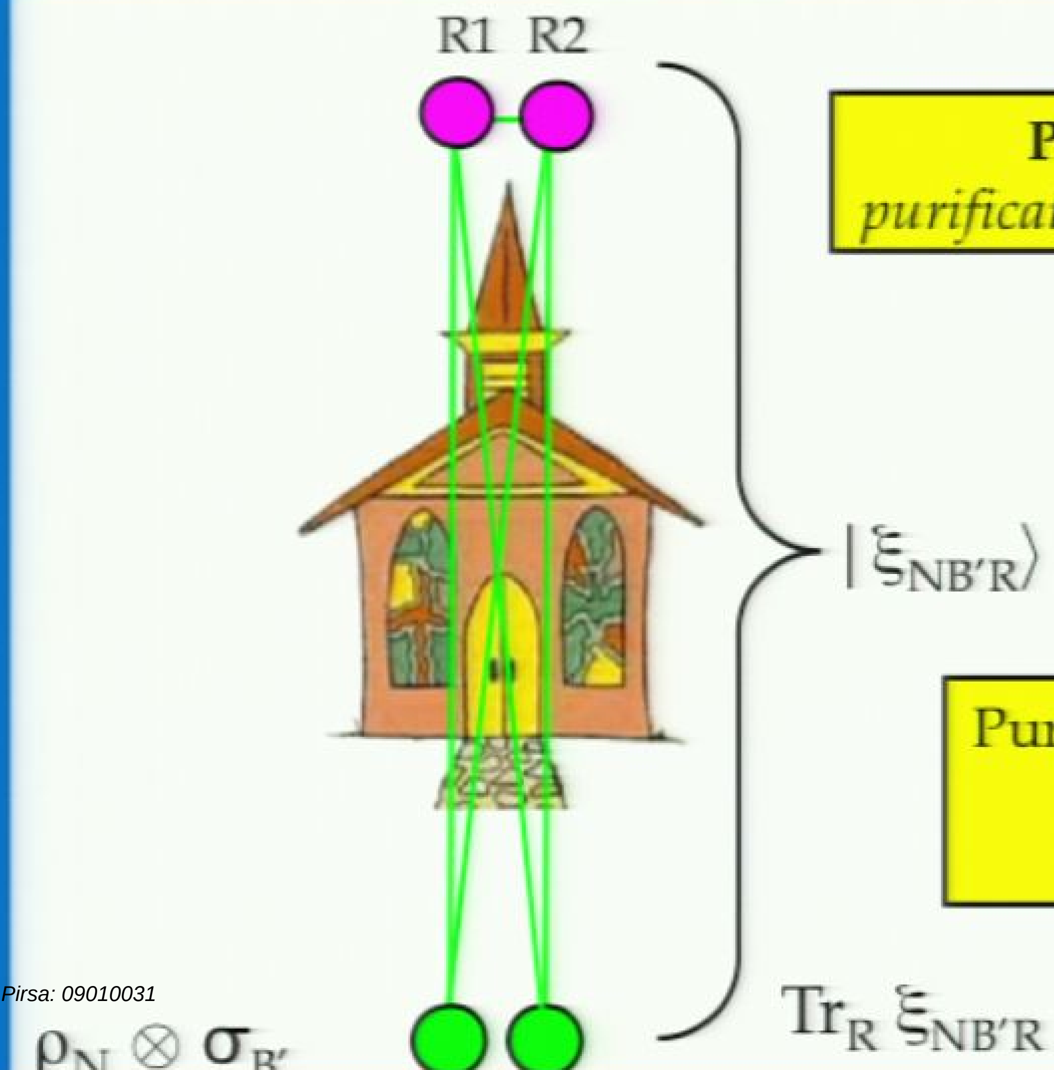

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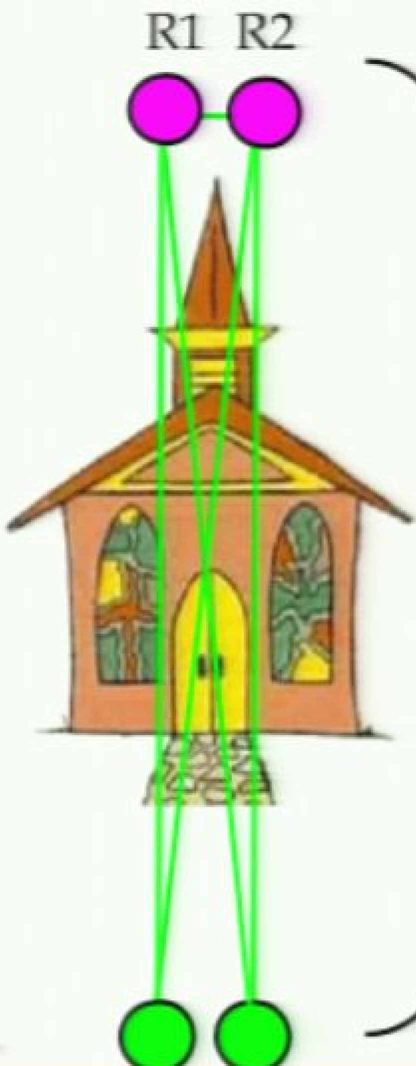
$$\mathrm{Tr}_R\,\xi_{NB'R} = \rho_N \otimes \sigma_{B'}$$

Church of the Larger Hilbert Space



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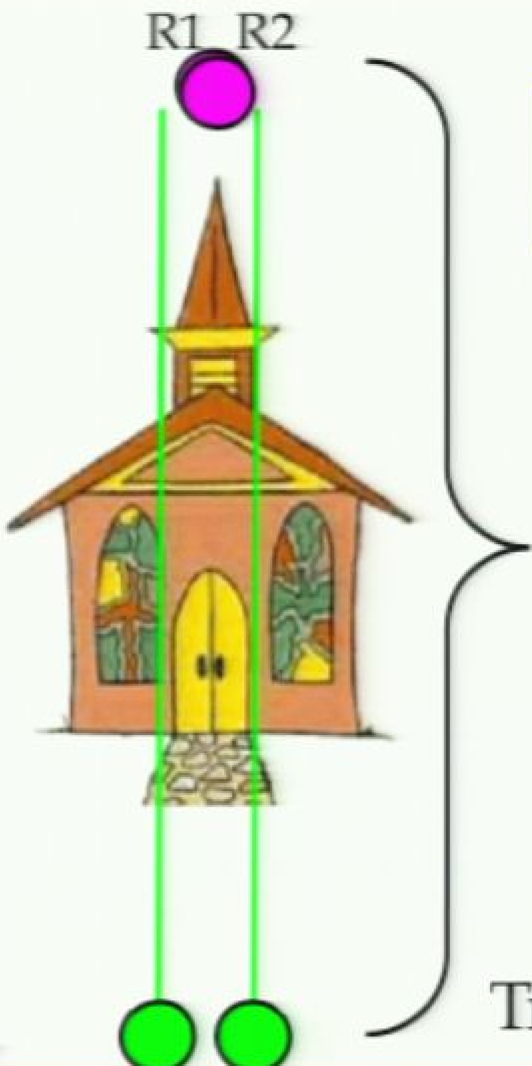

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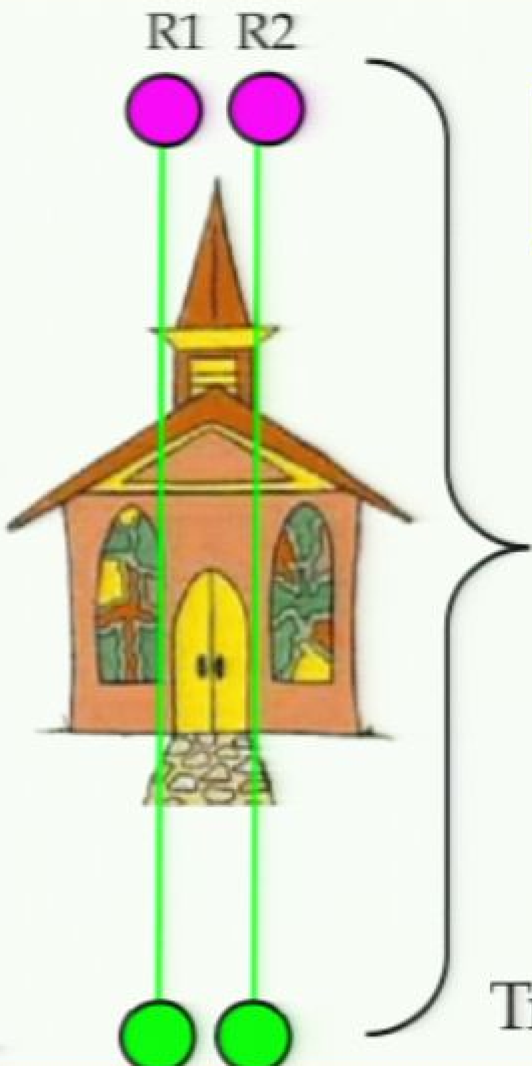

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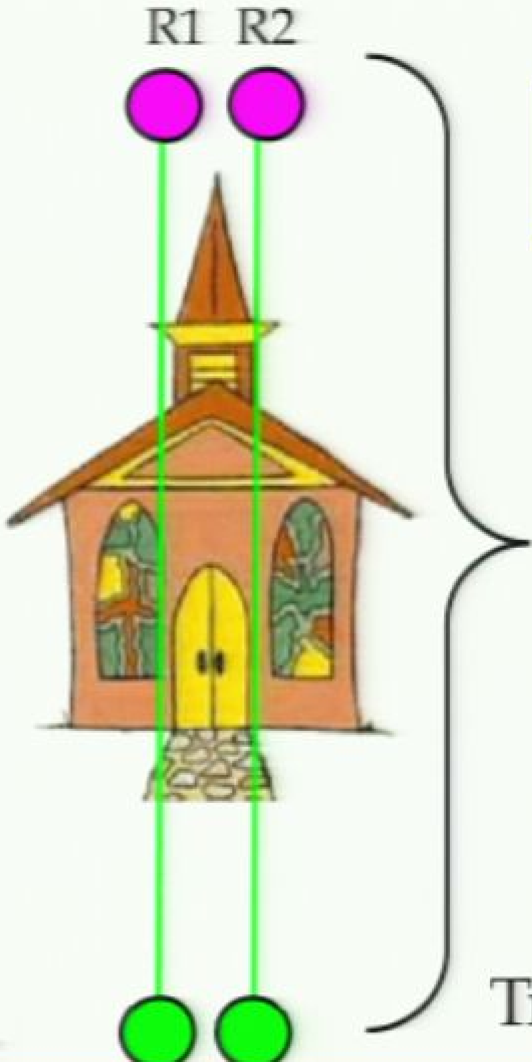

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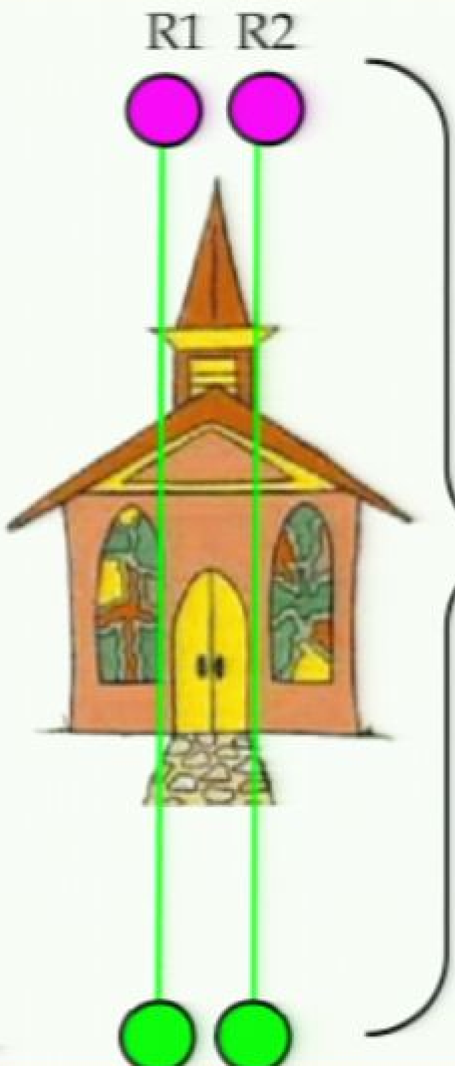

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$$|\phi_{NR1}\rangle |\psi_{B'R2}\rangle = (\mathrm{id}_{NB'} \otimes U_R^{-1}) |\xi_{NB'R}\rangle$$

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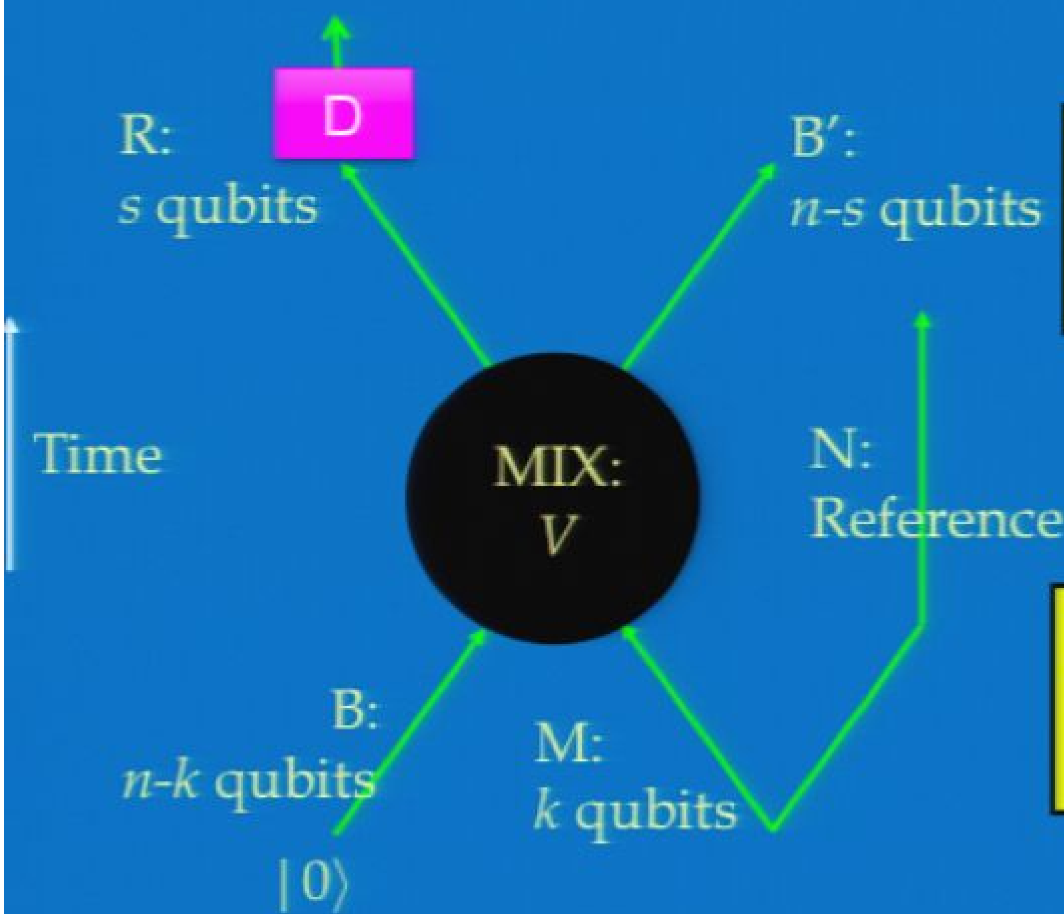
$\rho_N \otimes \sigma_{B'}$

Quantum Model (v1)



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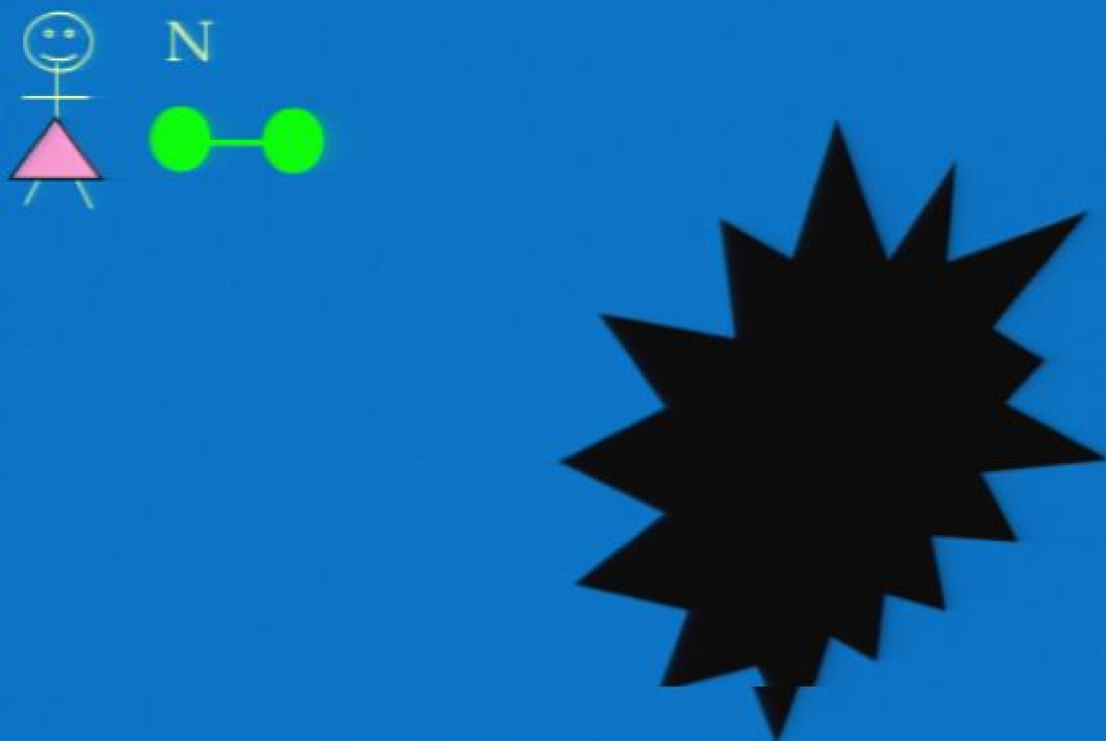

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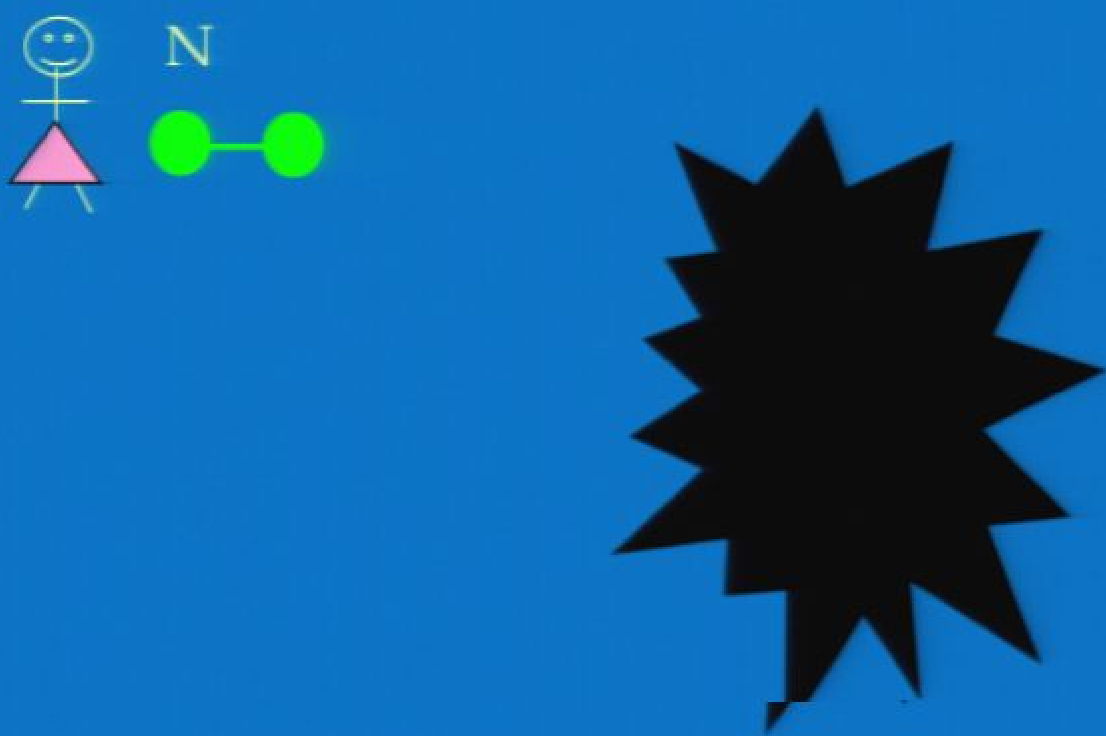

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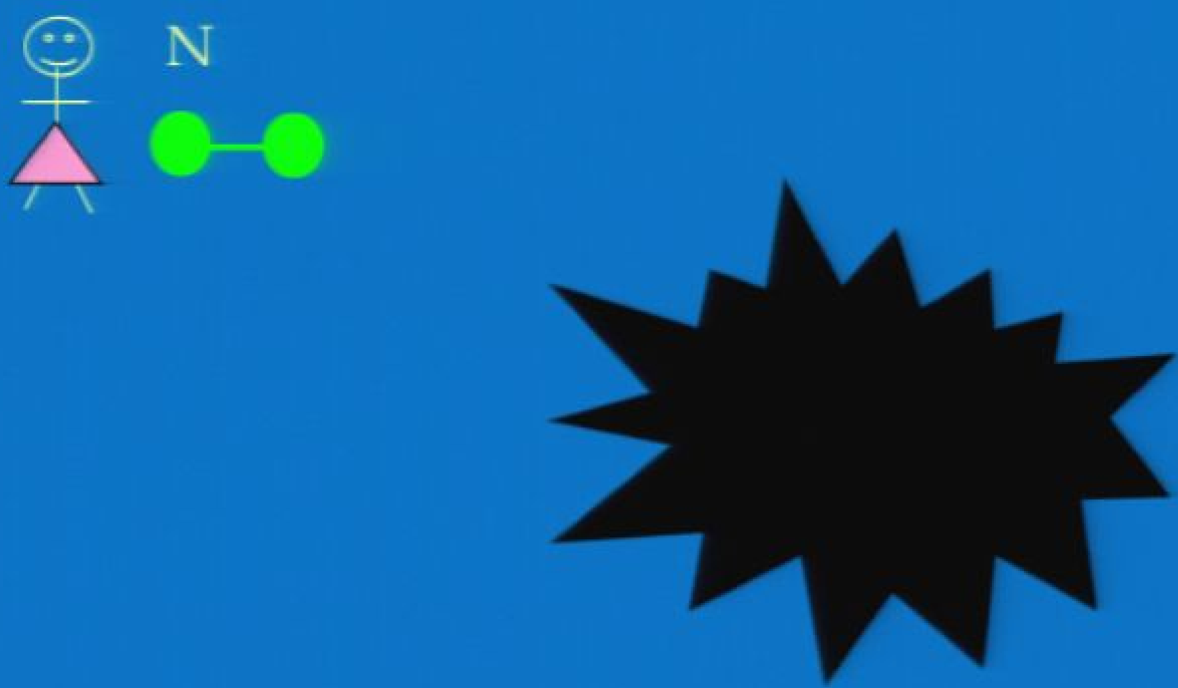

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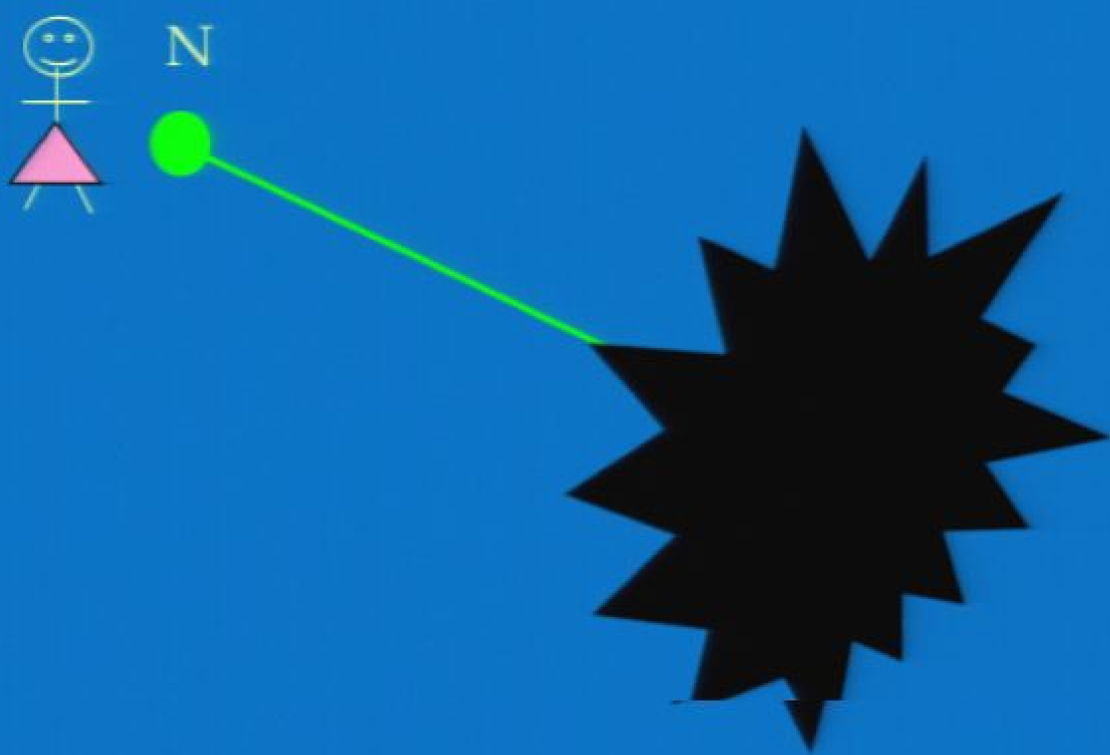

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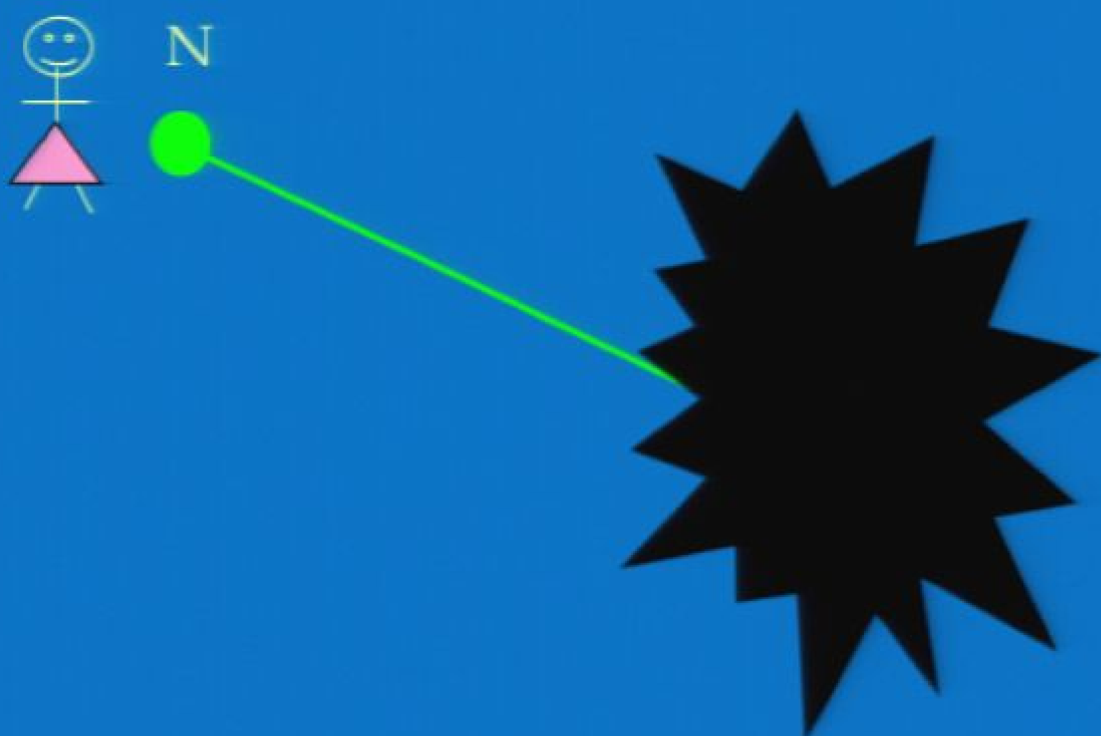

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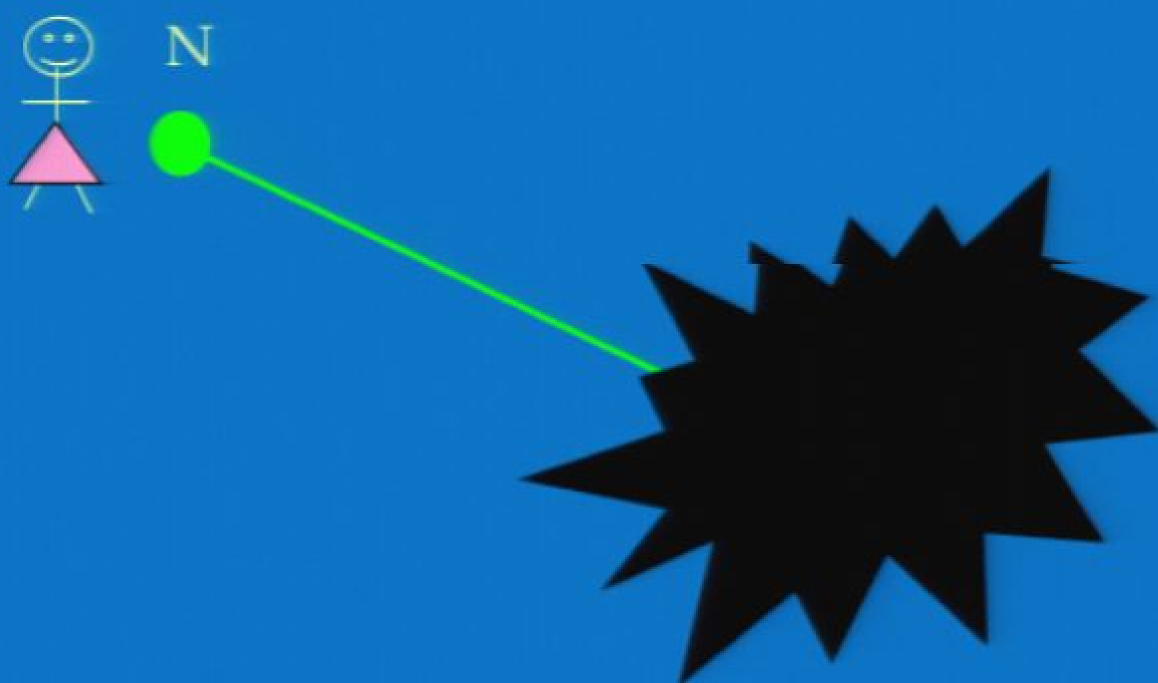

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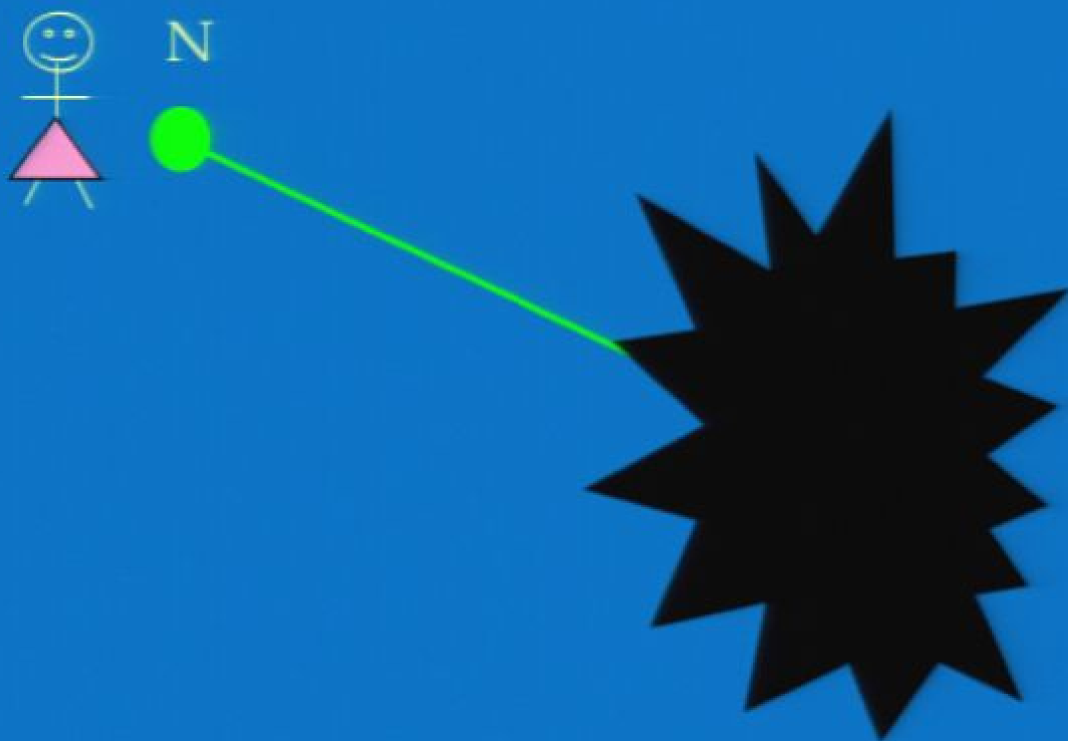

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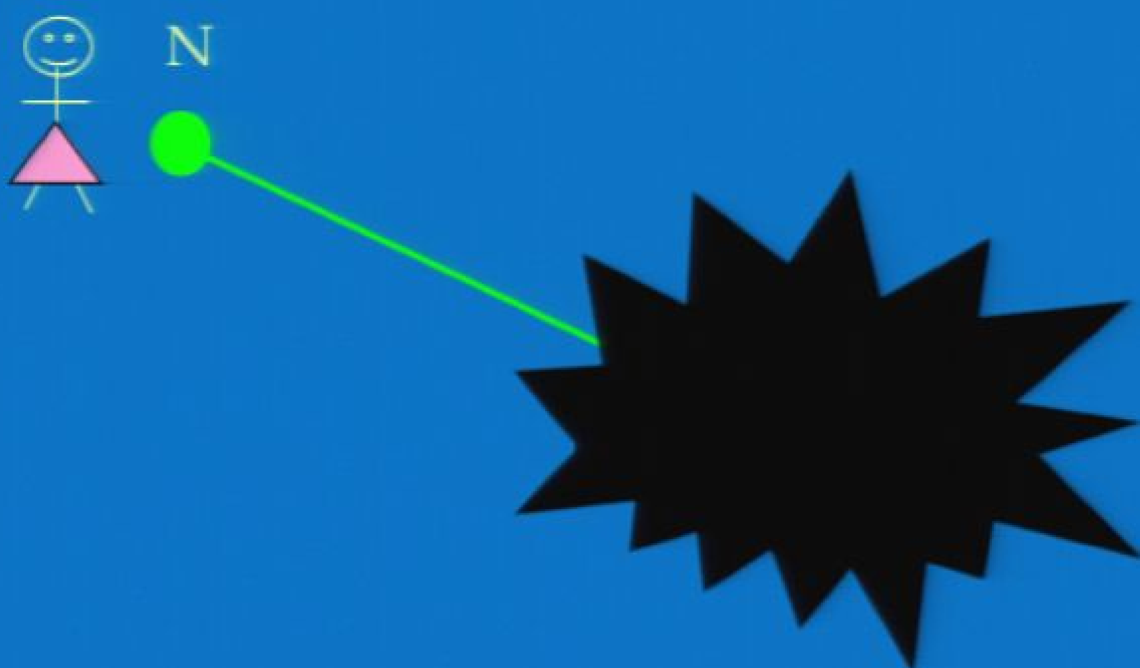

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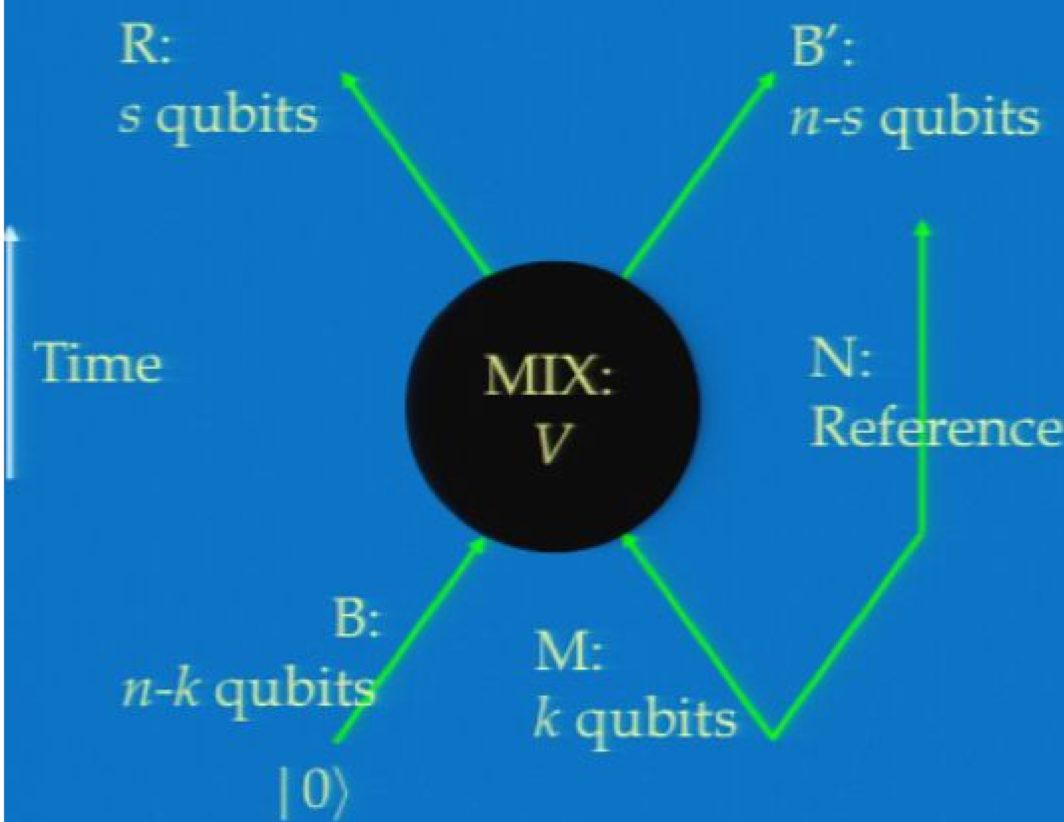

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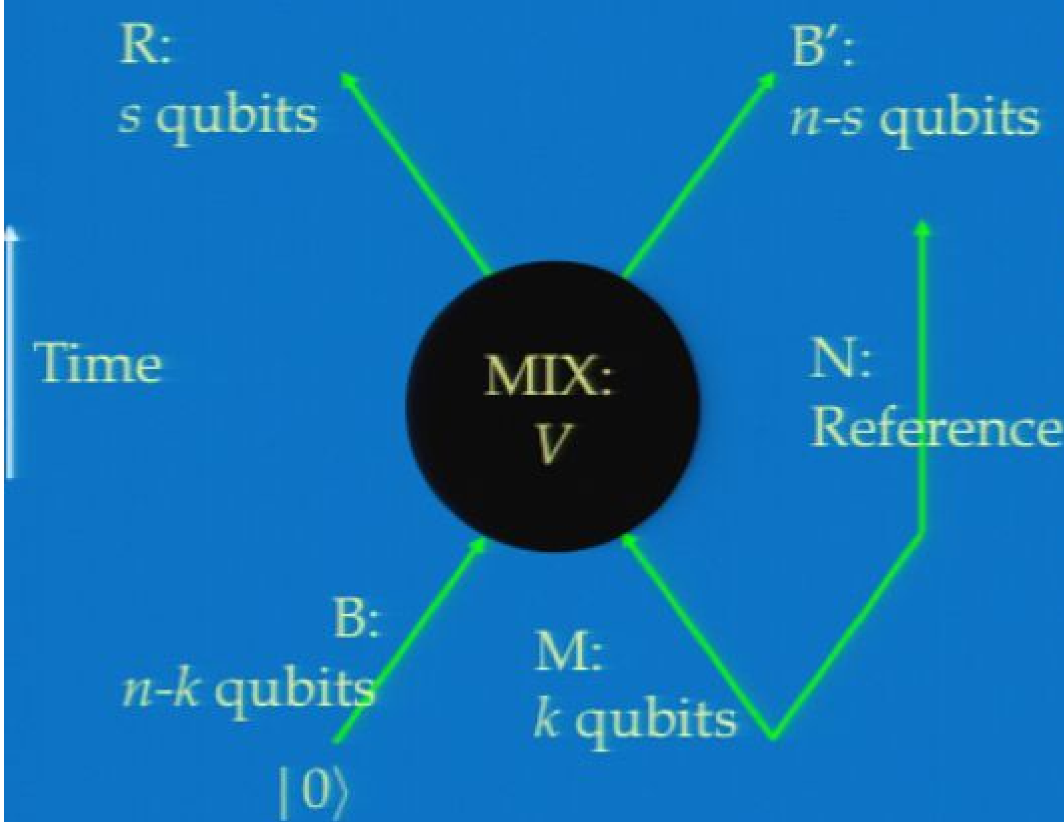

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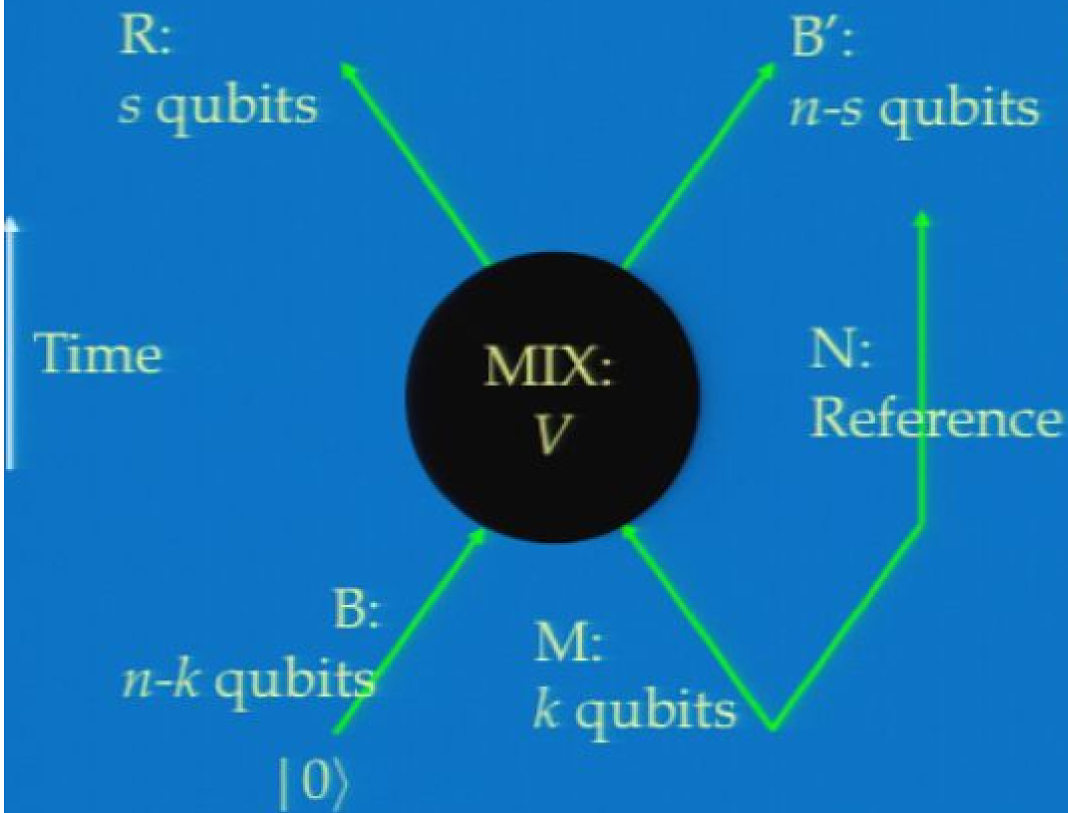

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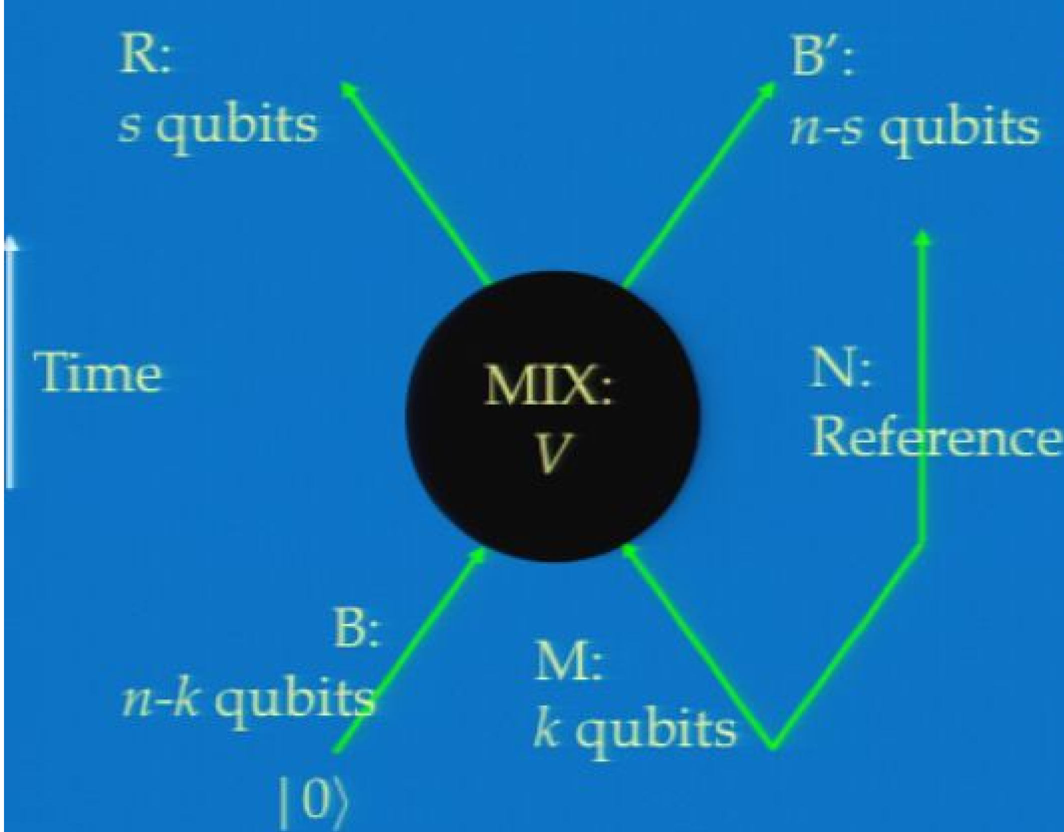

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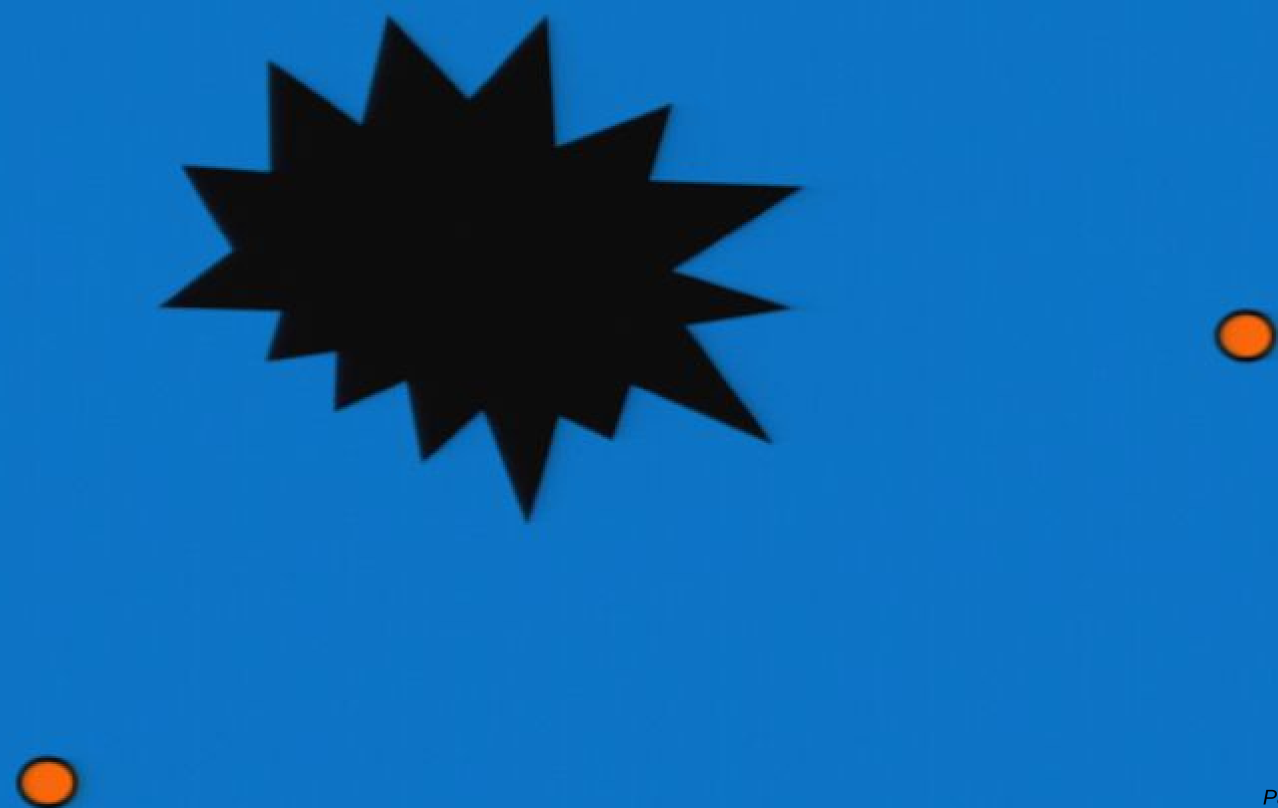

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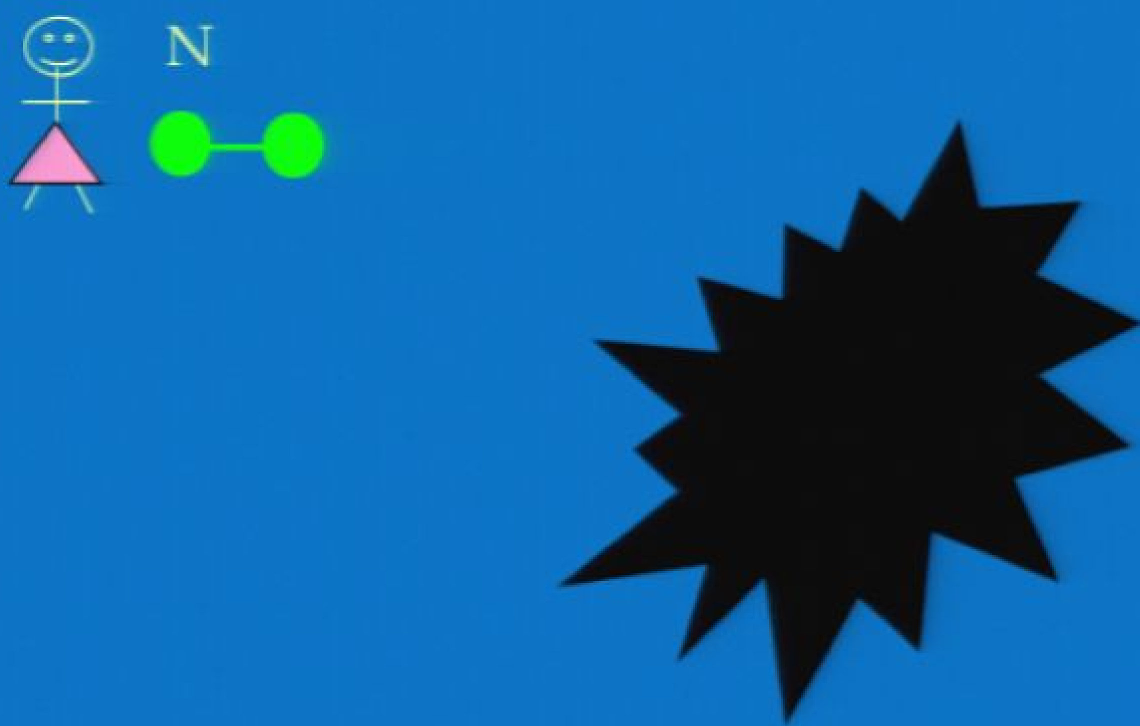

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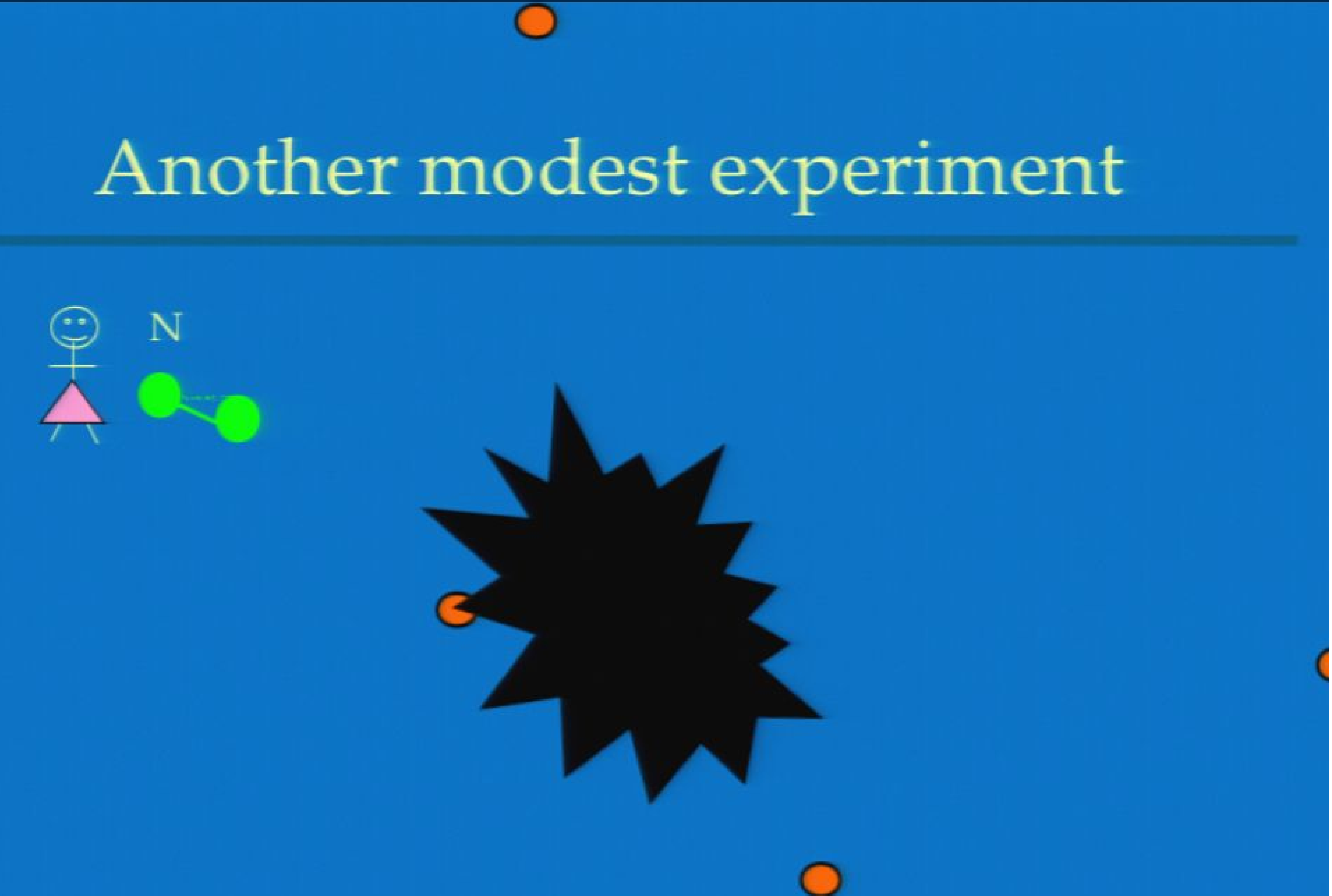

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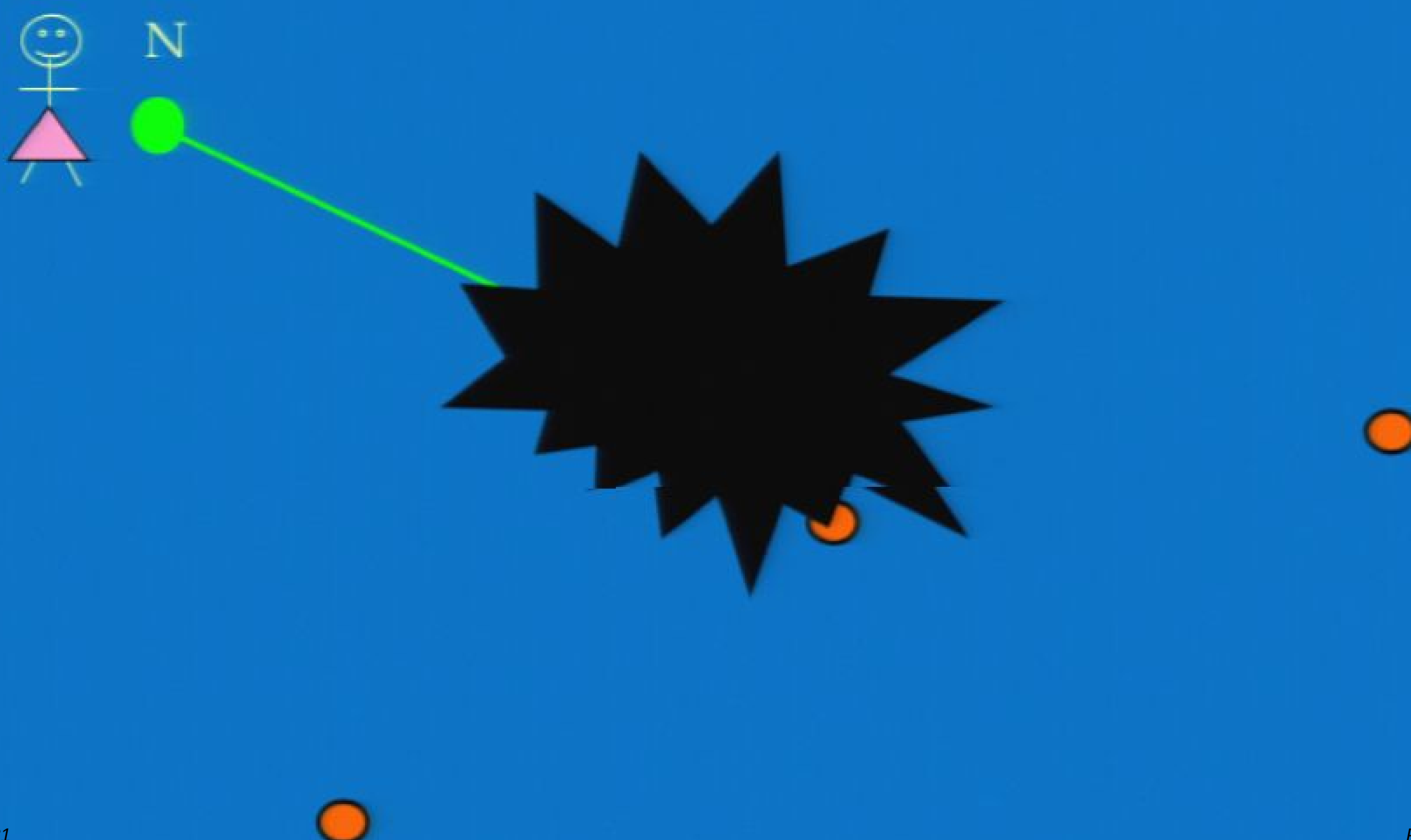

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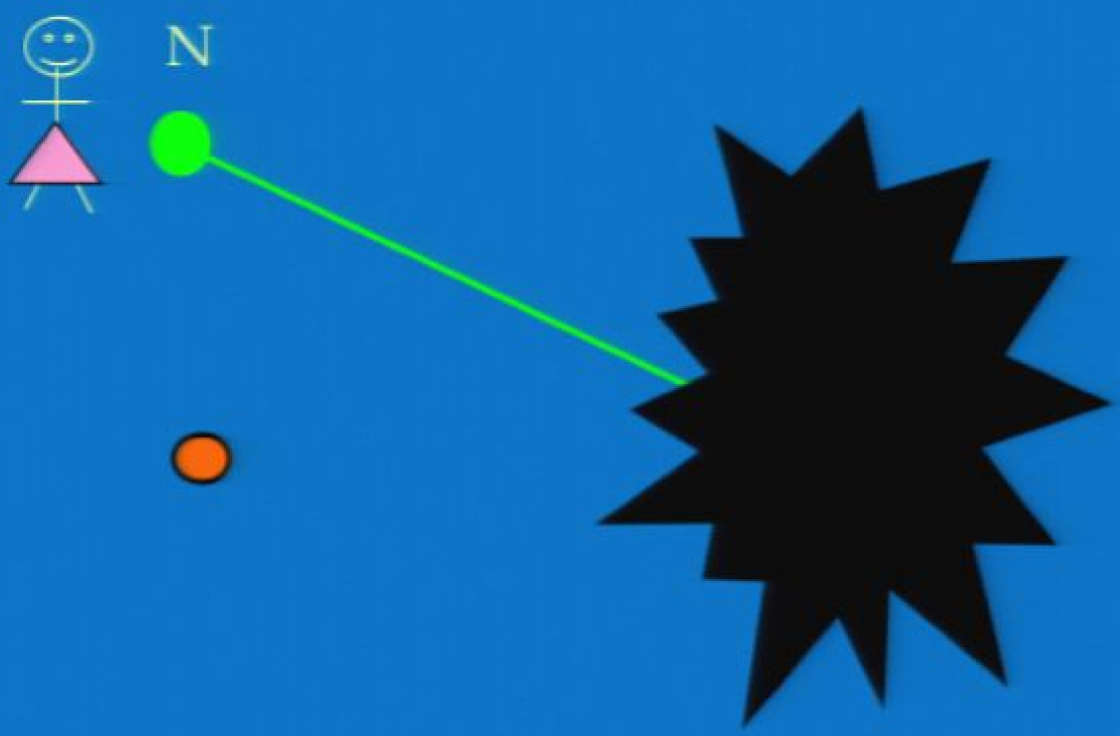

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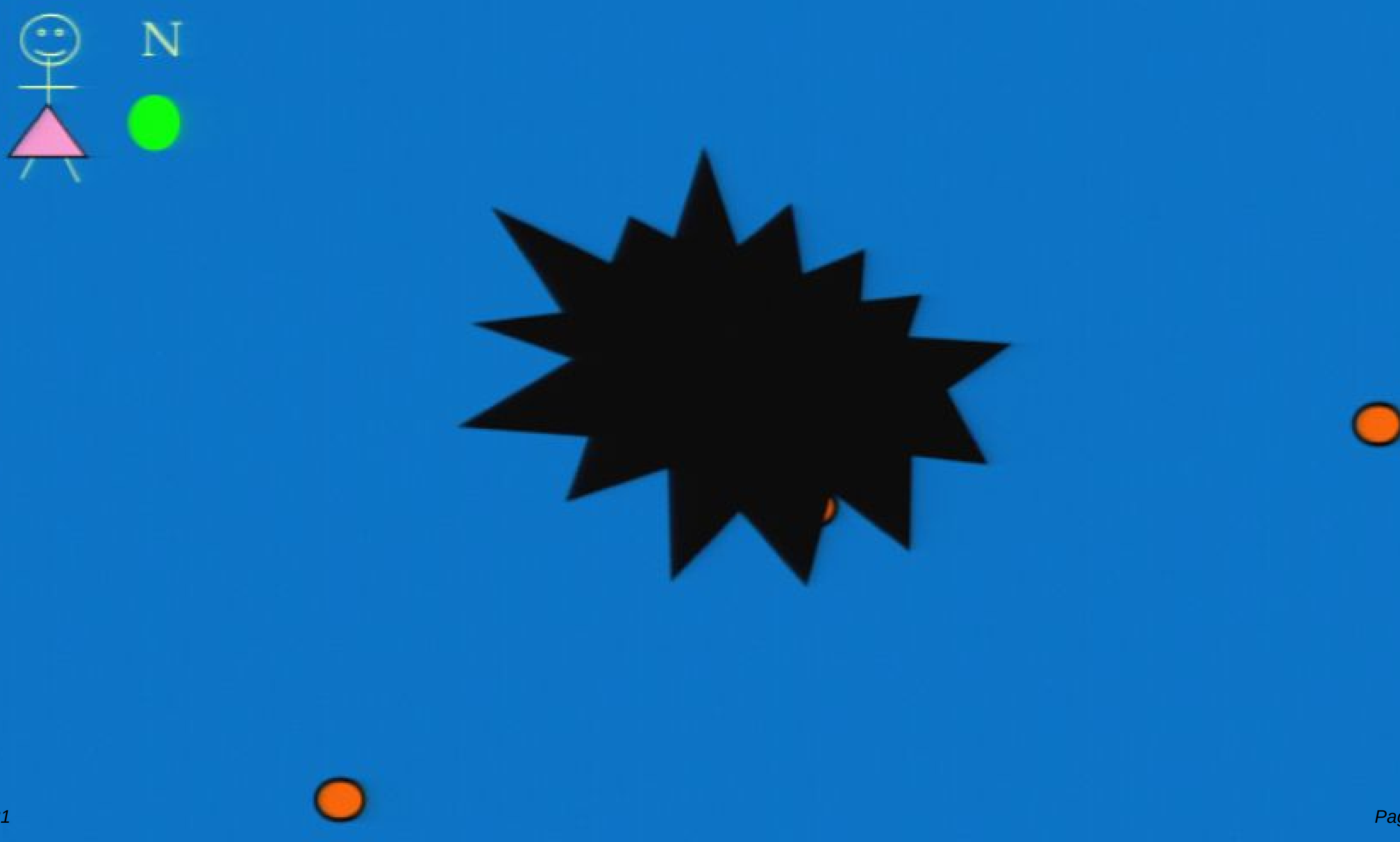

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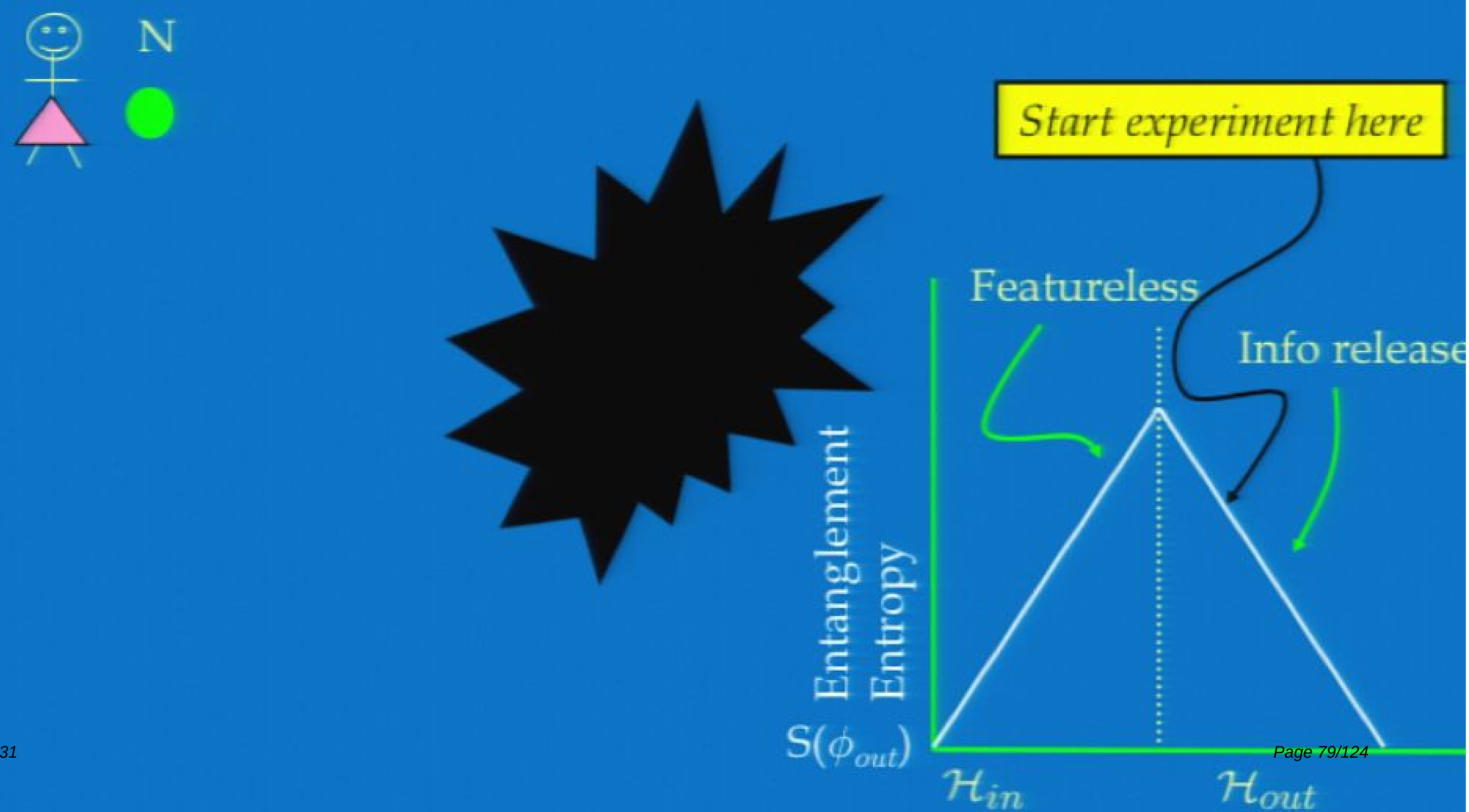

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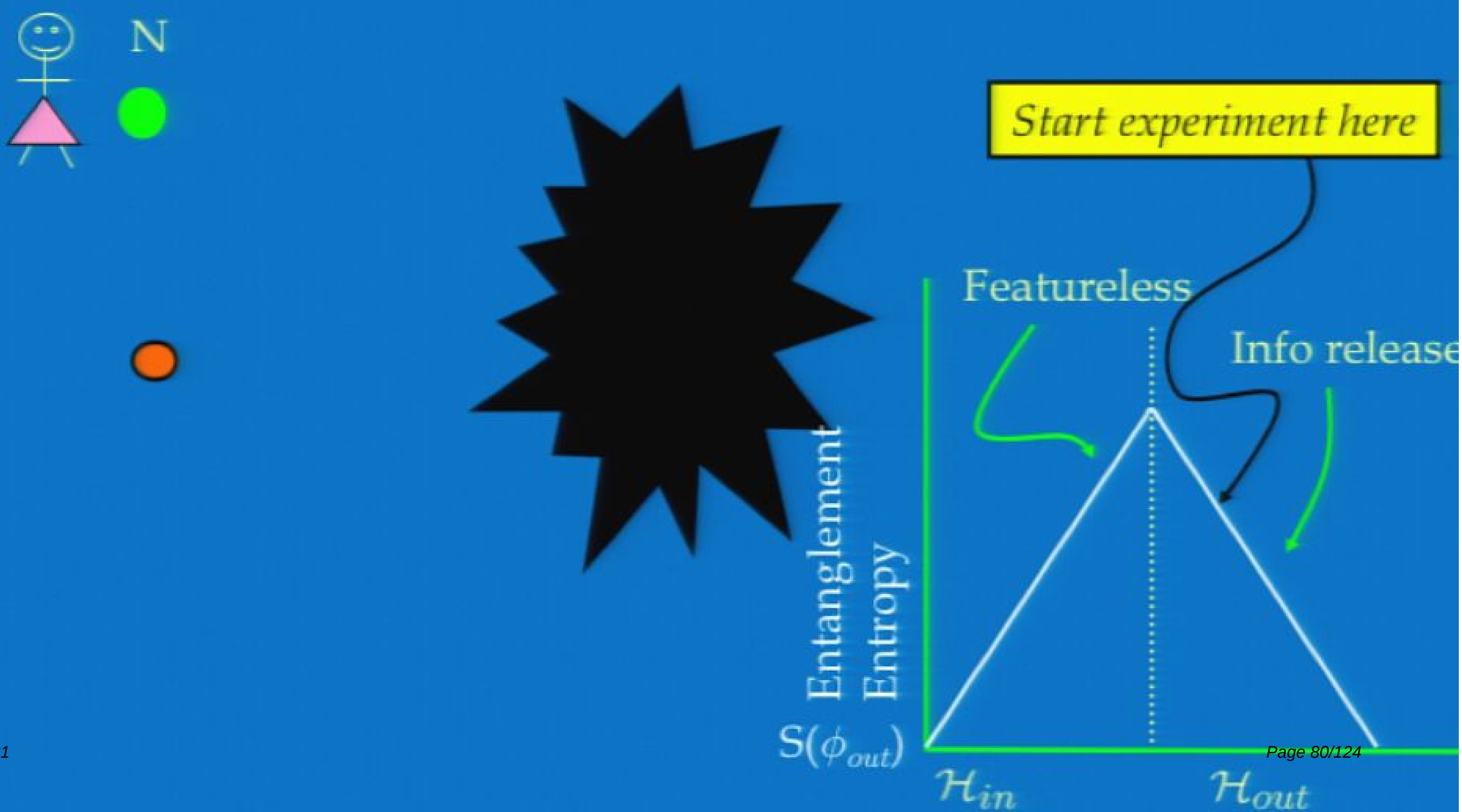

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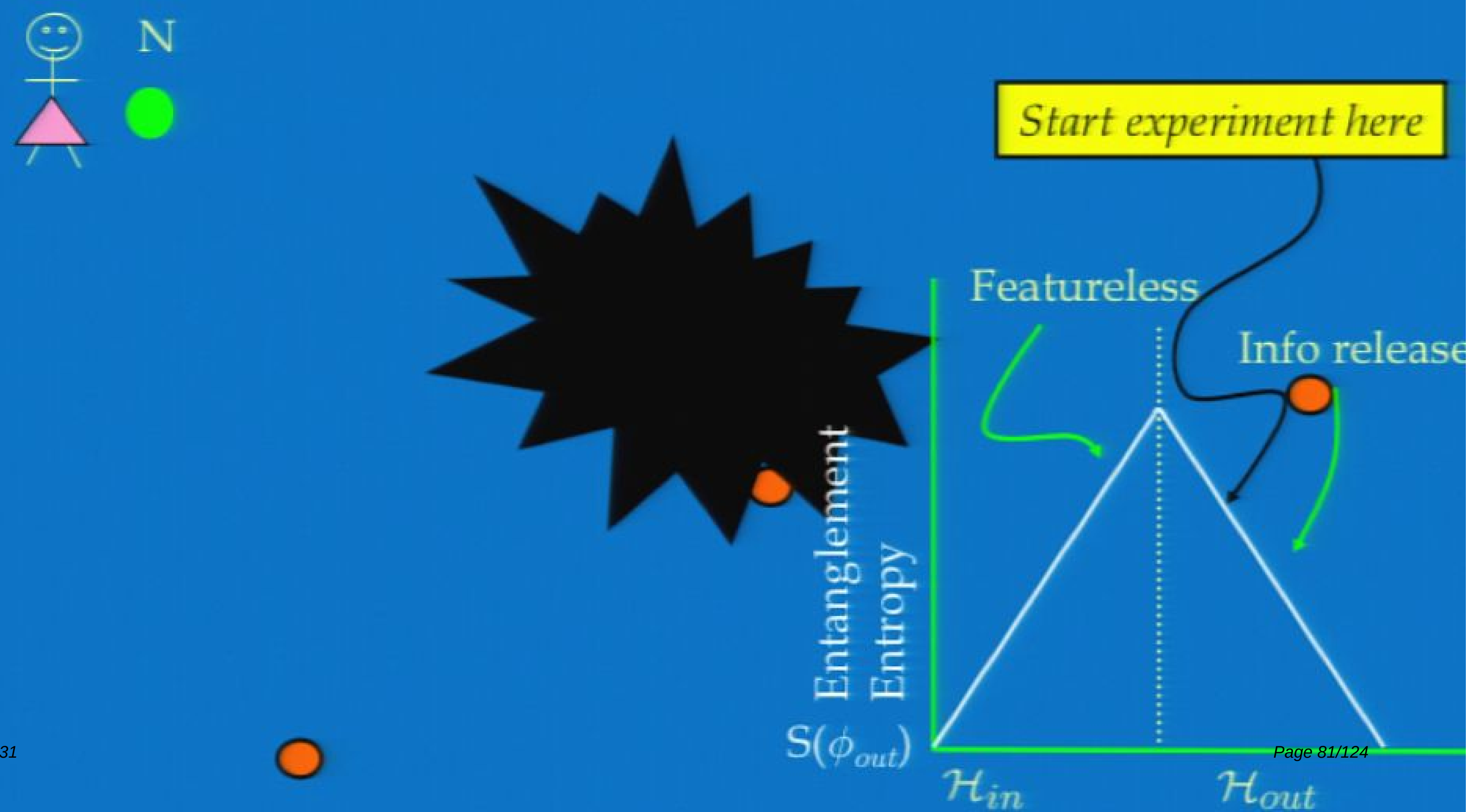

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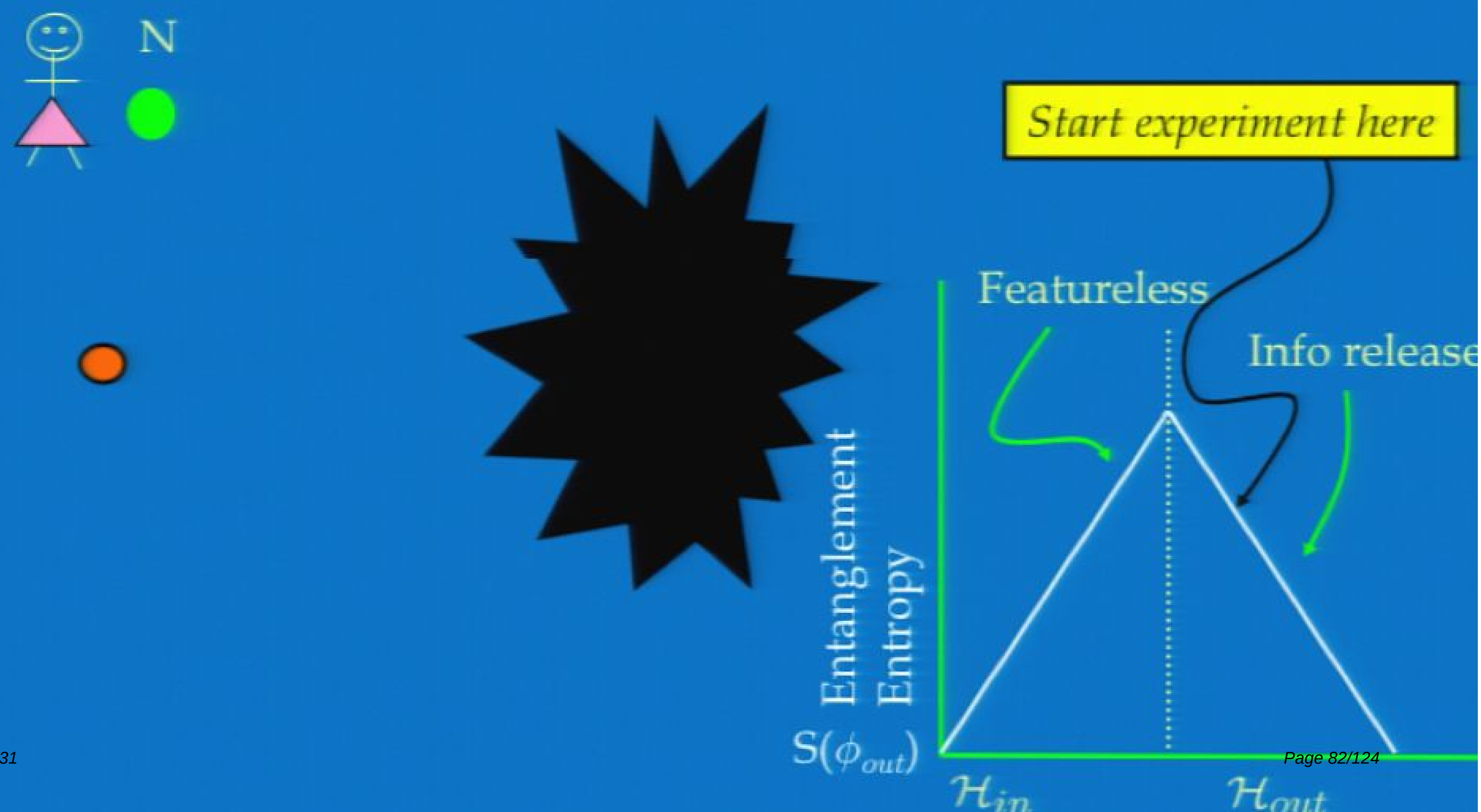

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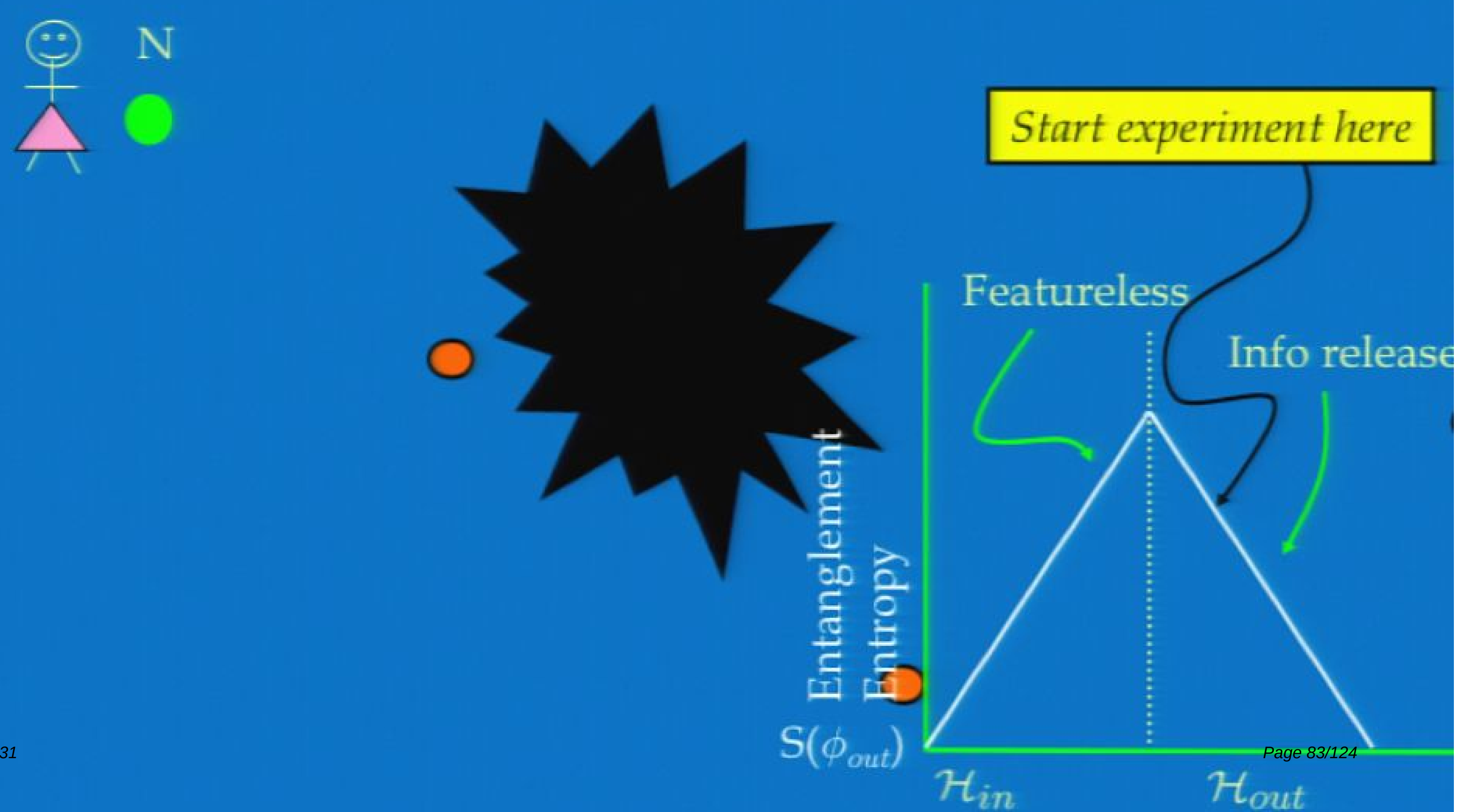

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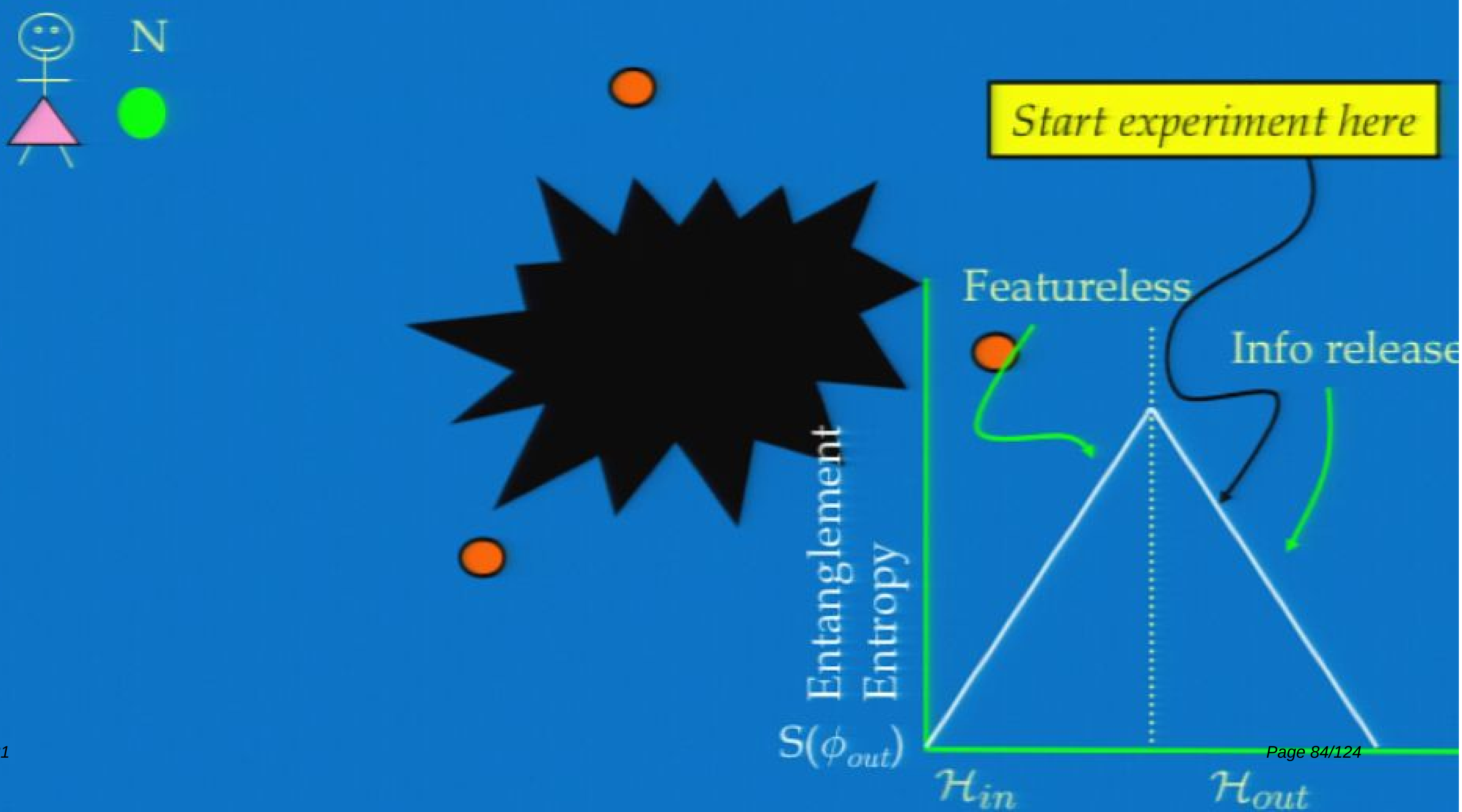

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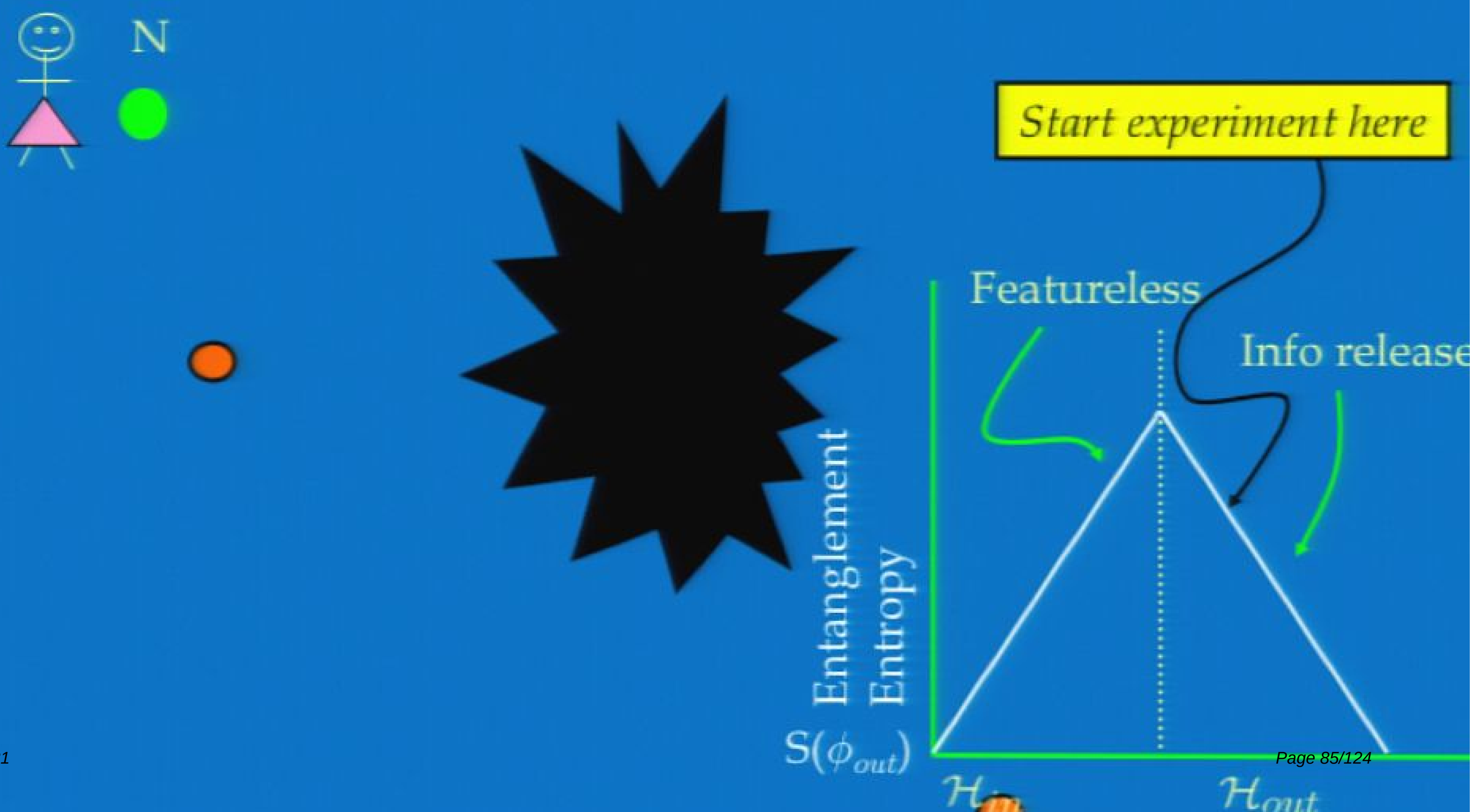

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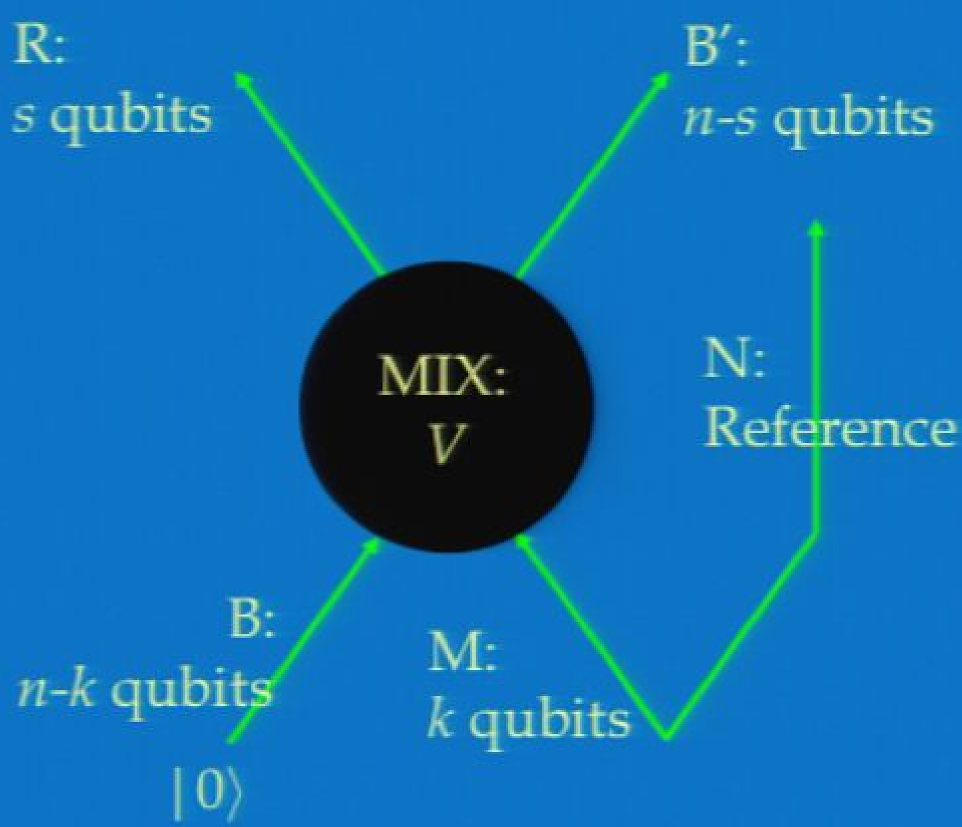

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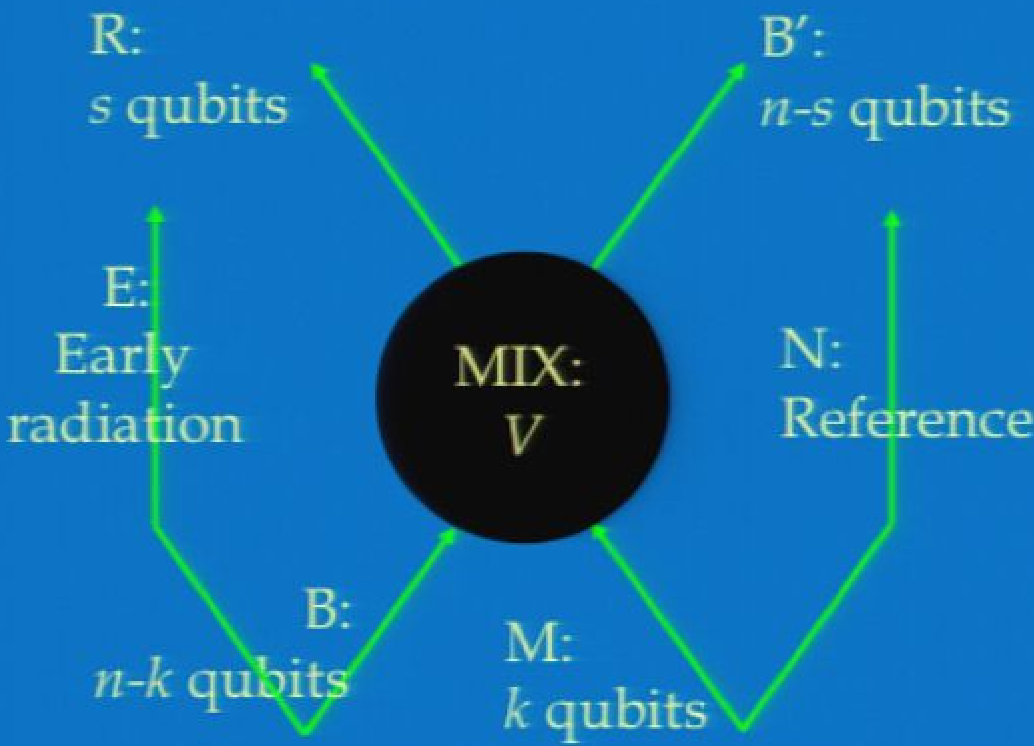

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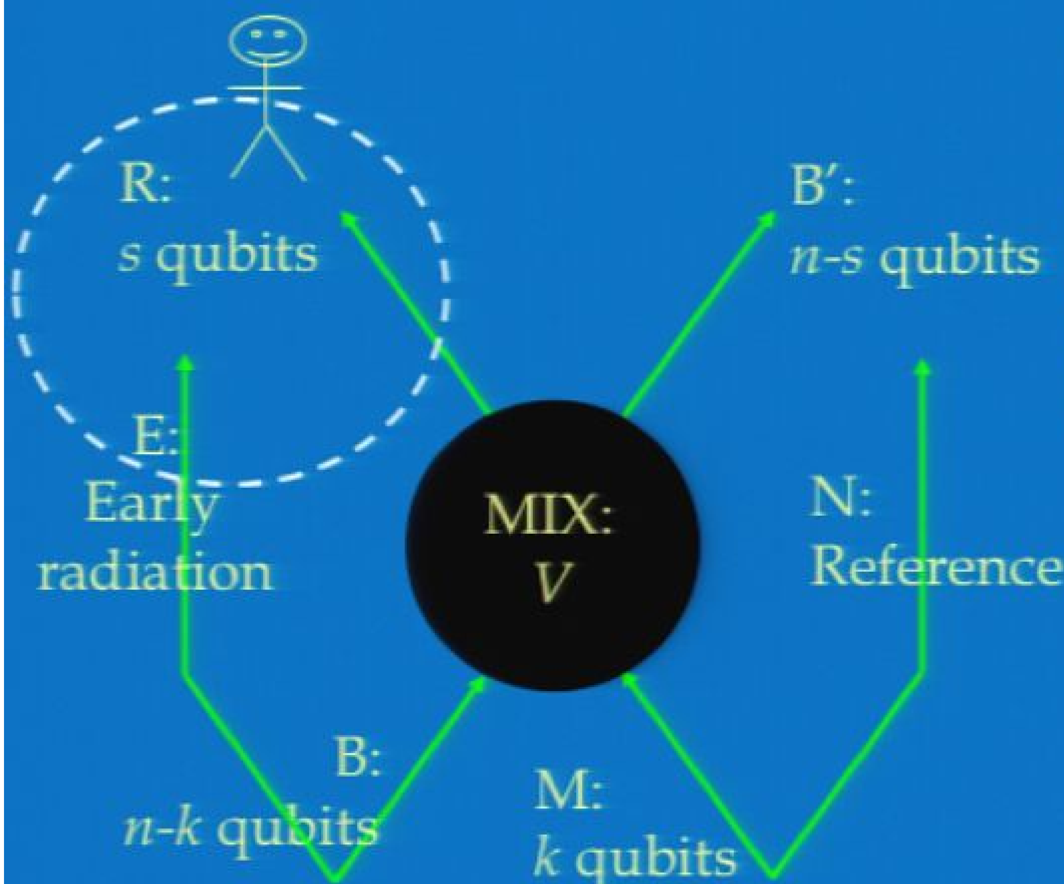

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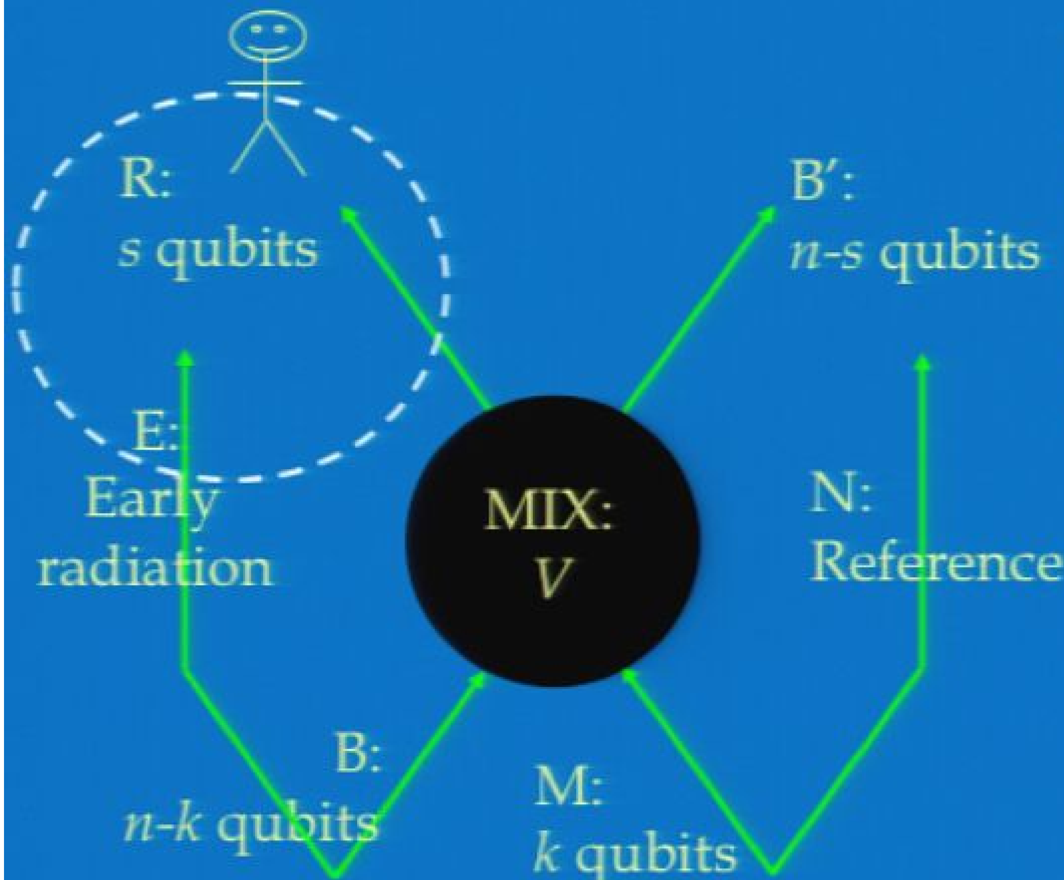

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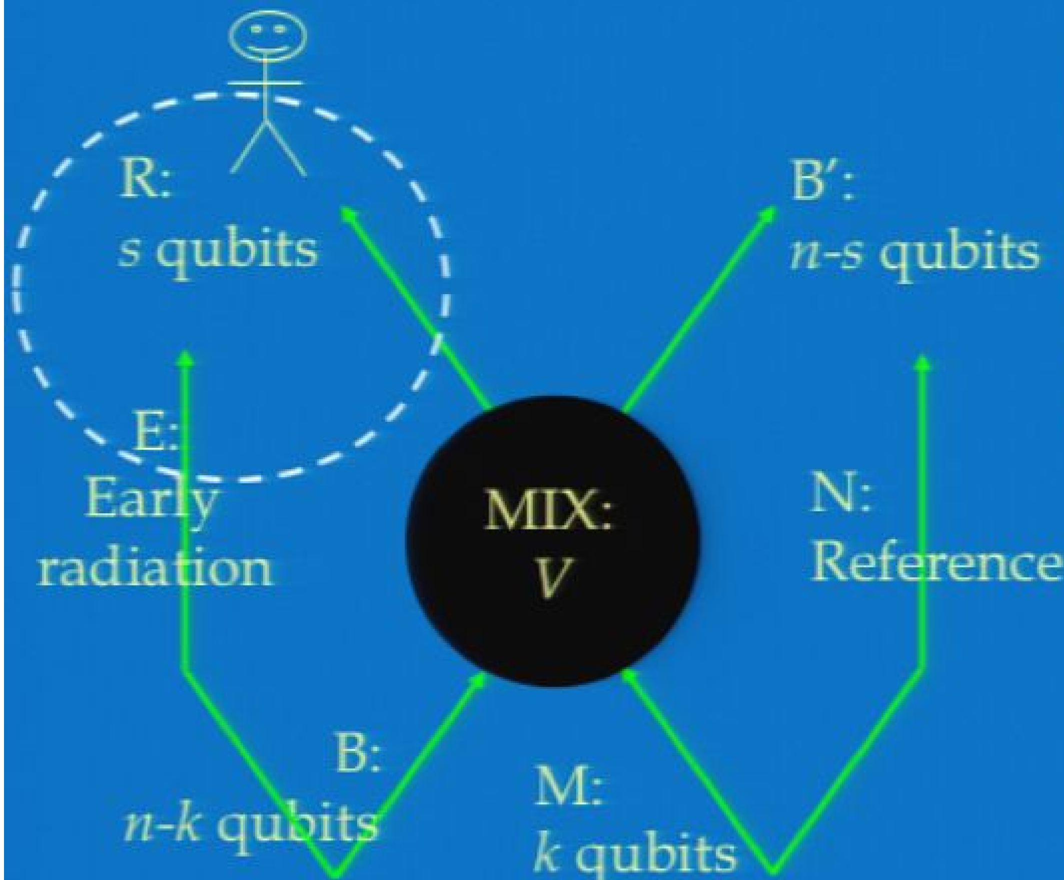

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Suggestive, but our question is more demanding:

$$\int \|\sigma_{NB'}(V) - \sigma_N \otimes \sigma_{B'}(V)\|_1 \, dV \quad \leq 2^{k-s}$$

ϵ-approximate unitary 2-designs to the rescue!

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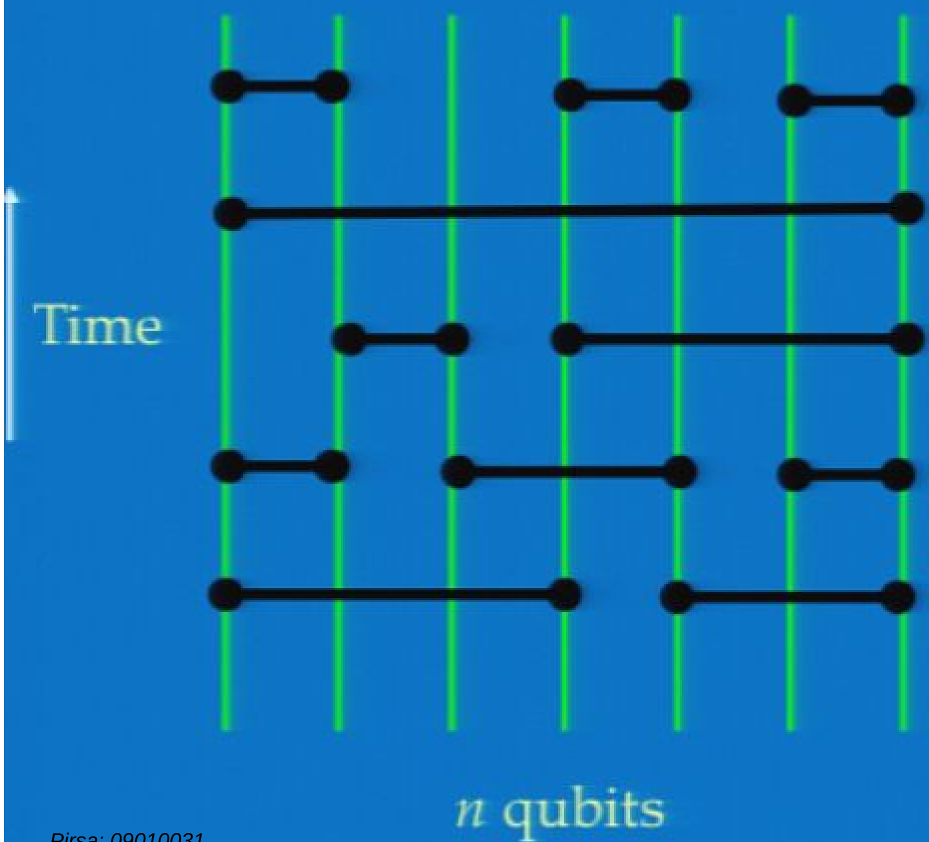

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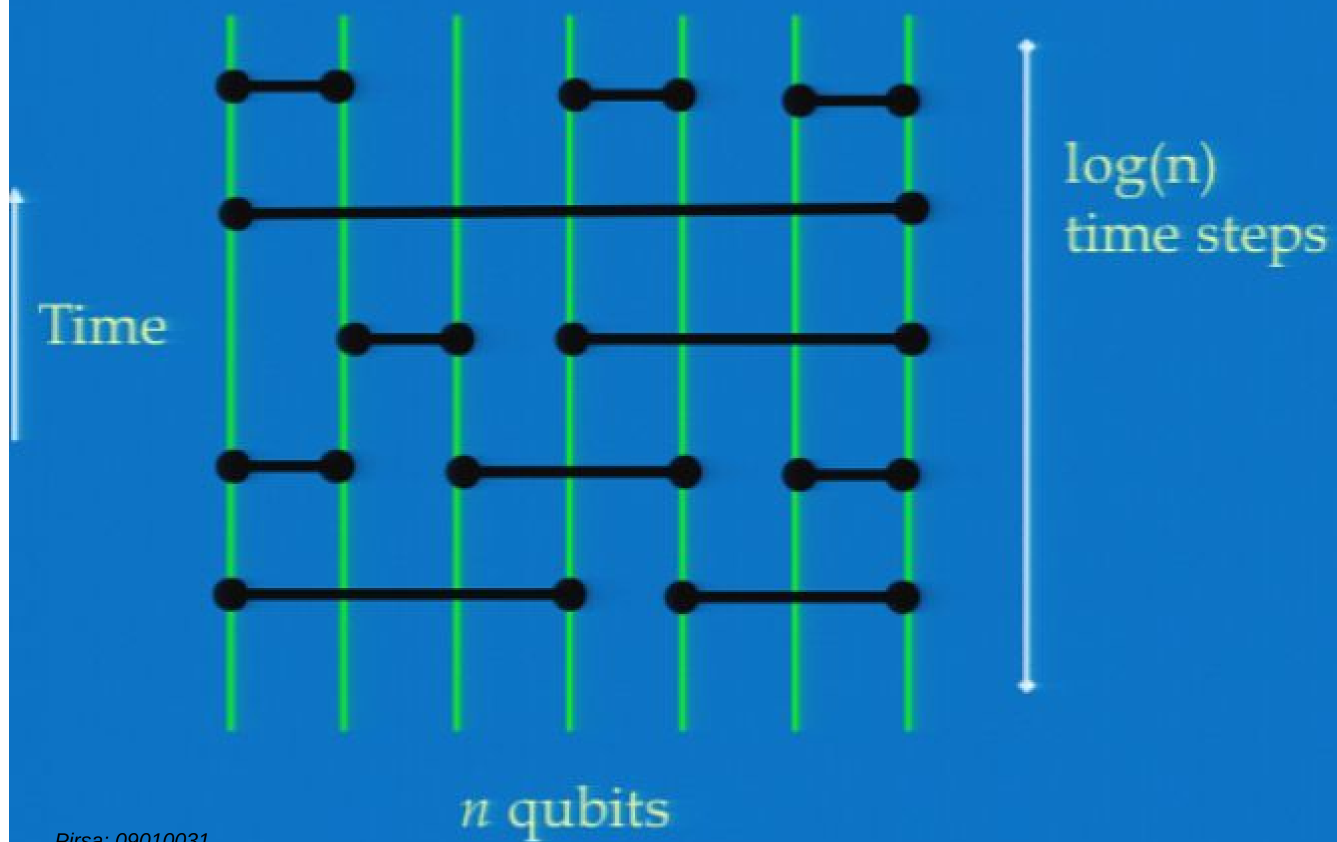

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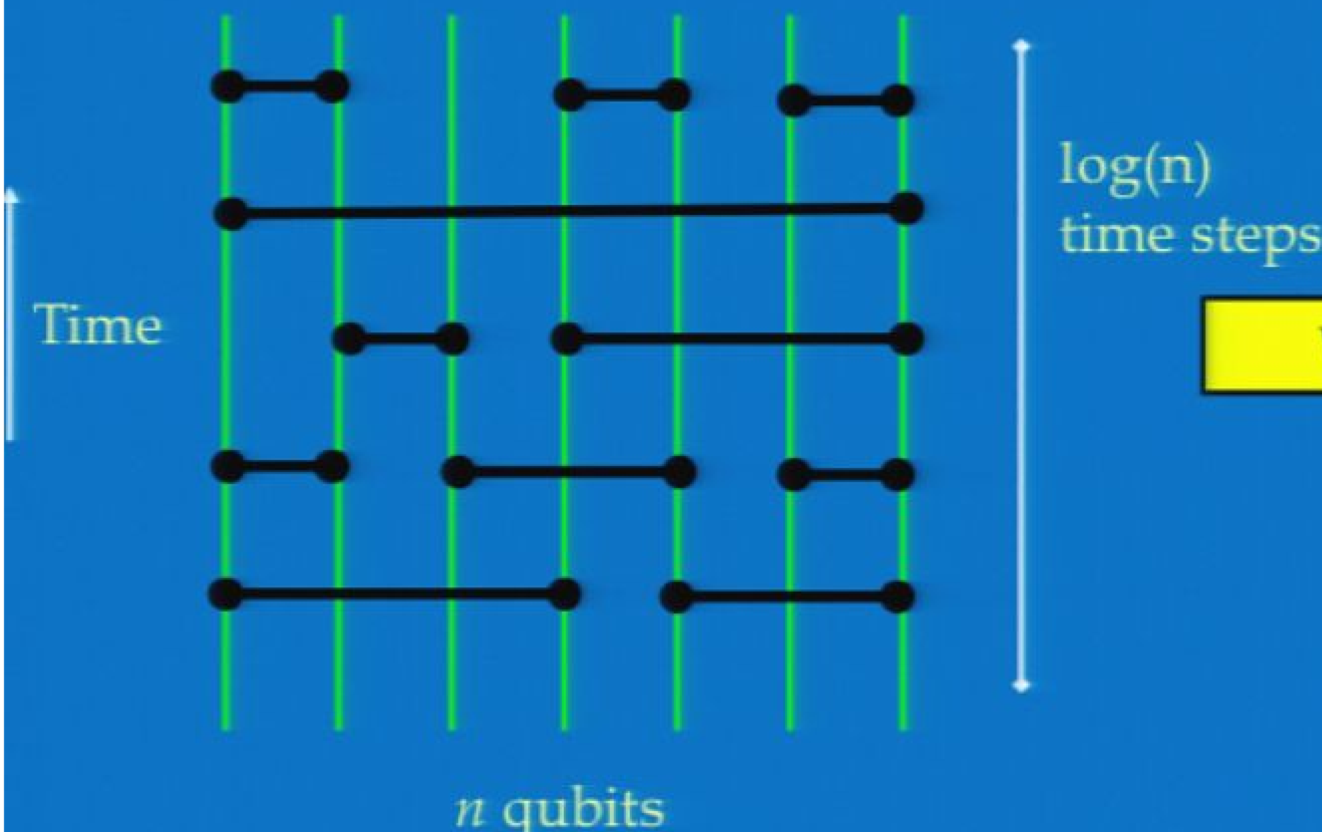

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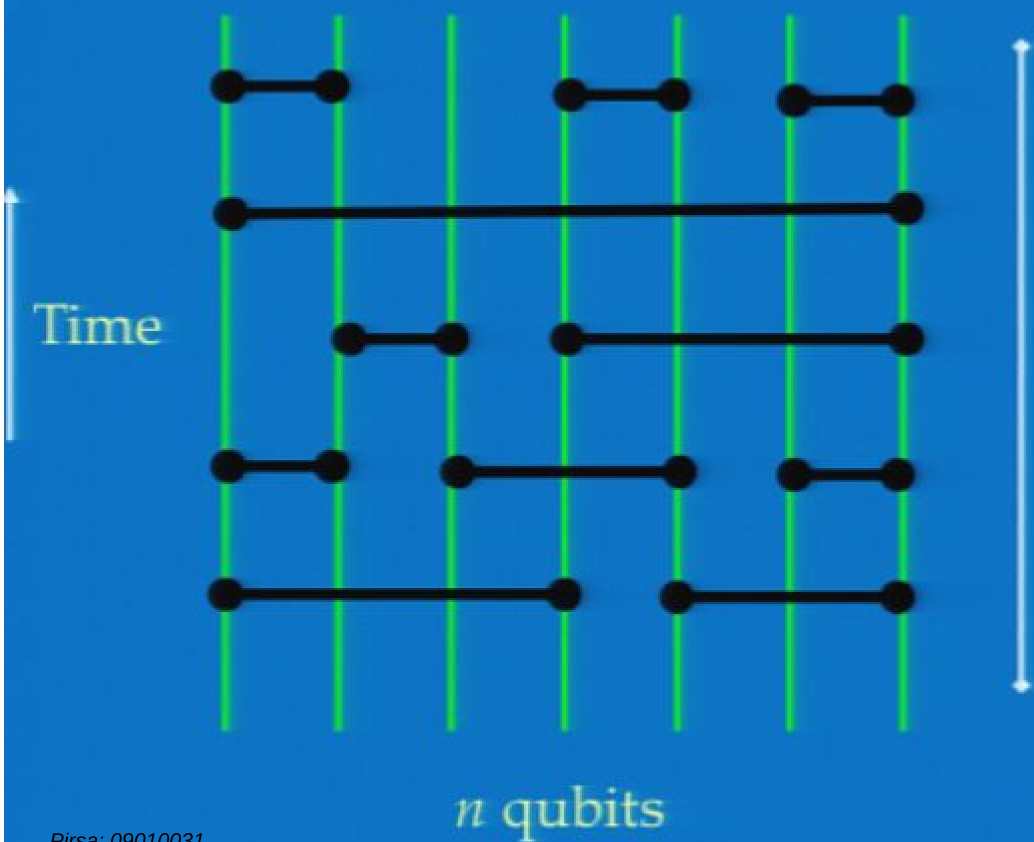

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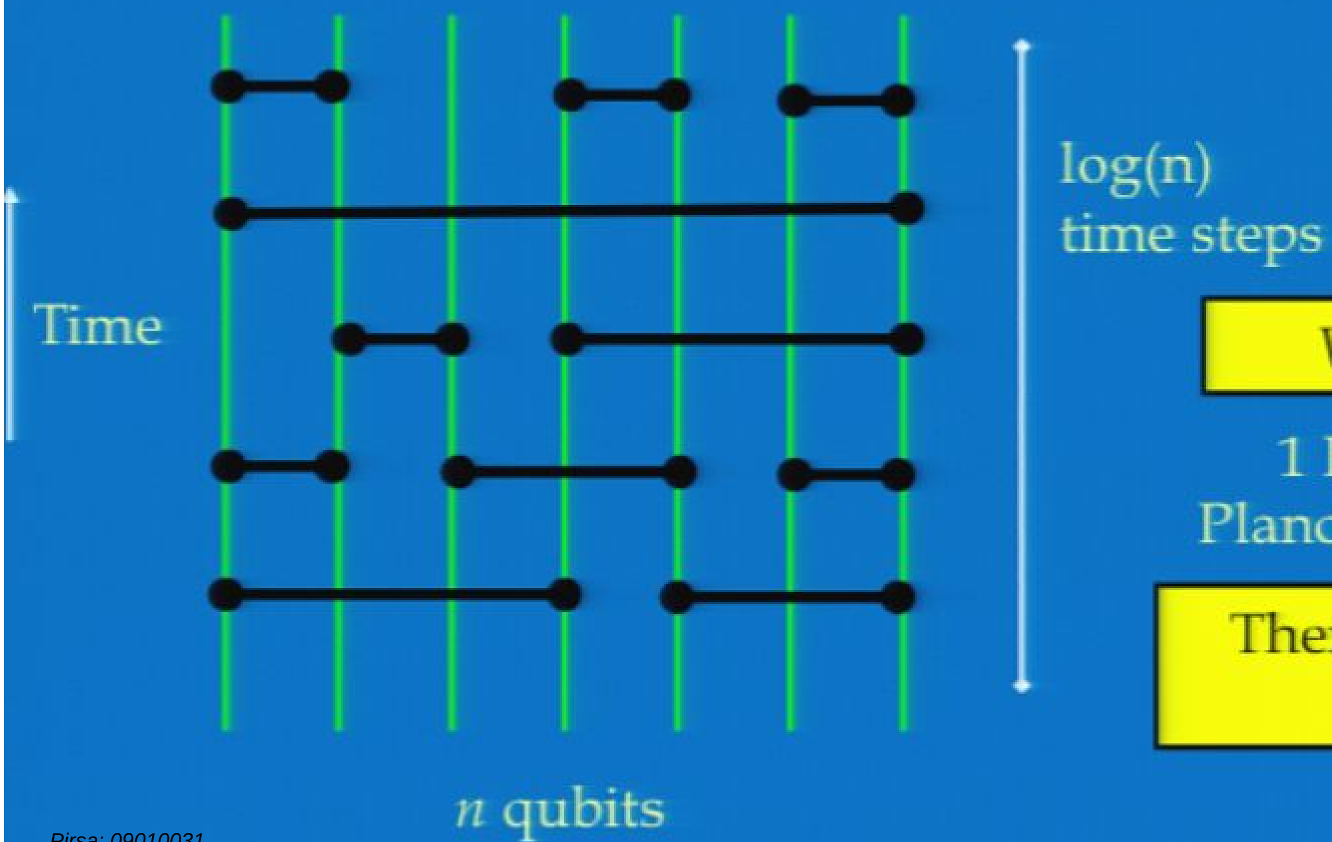

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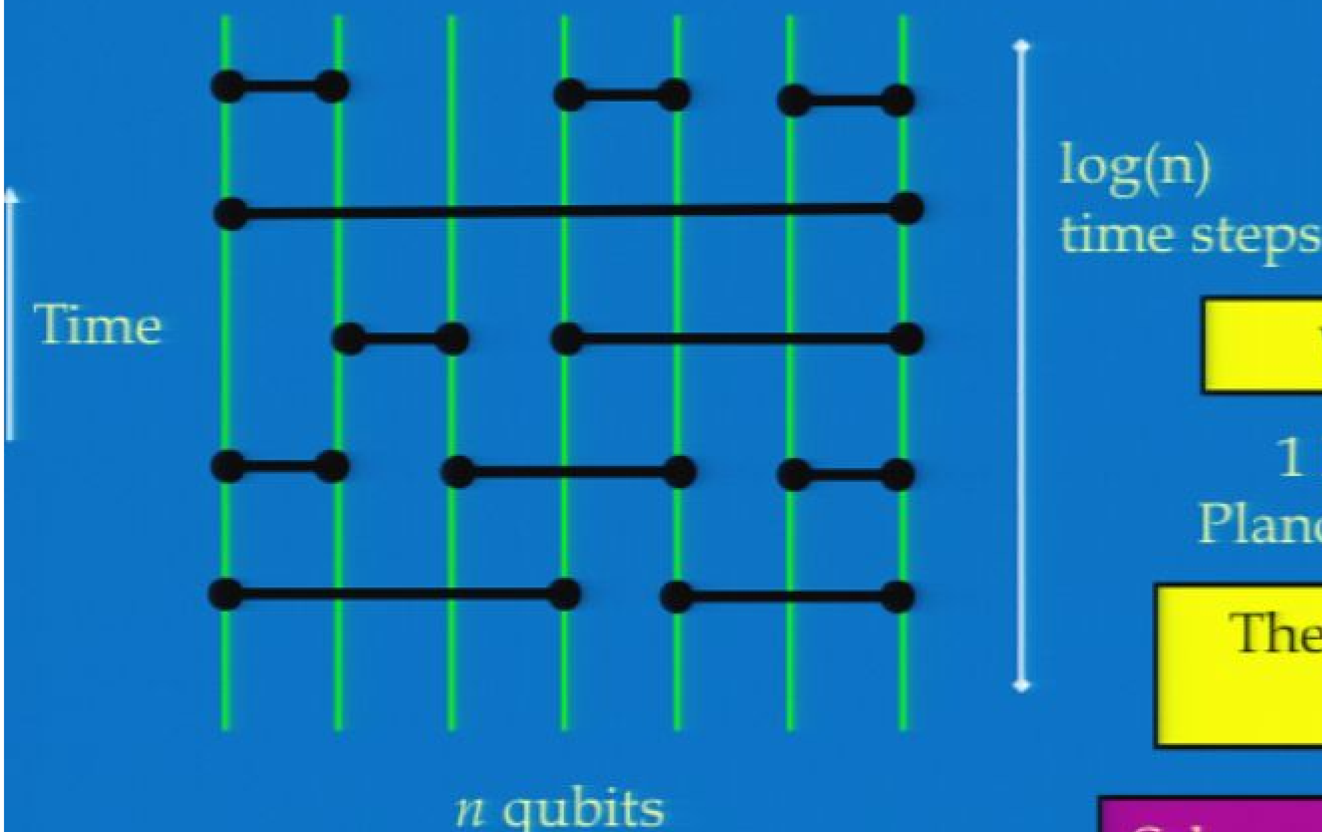

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$M_\odot$

Milliseconds vs milliseconds

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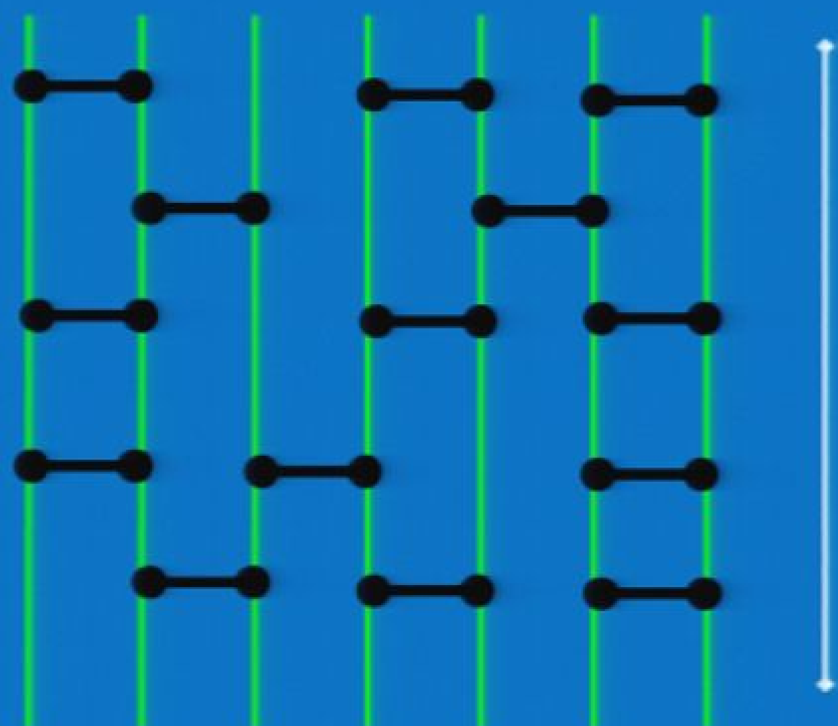

n qubits

$r_s \log(n)$ time steps

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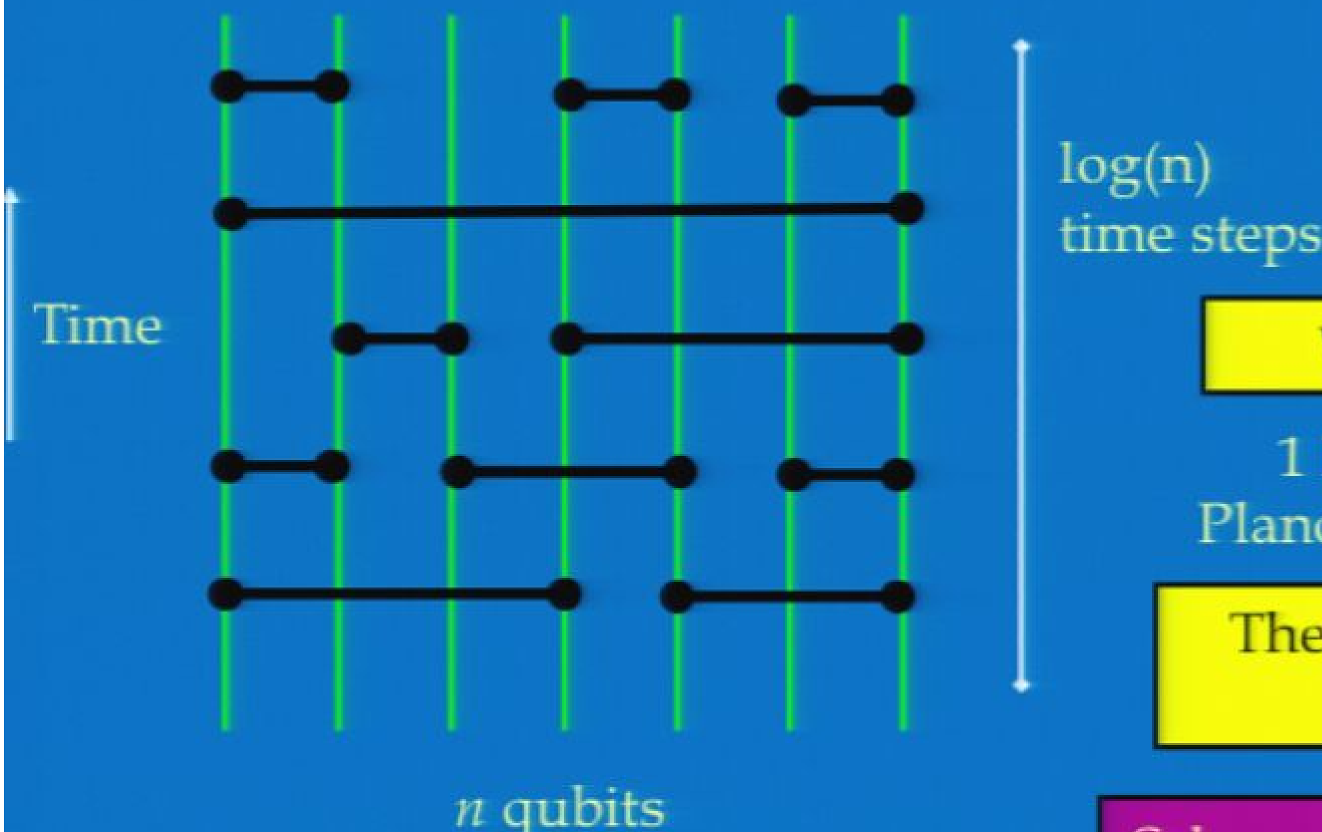

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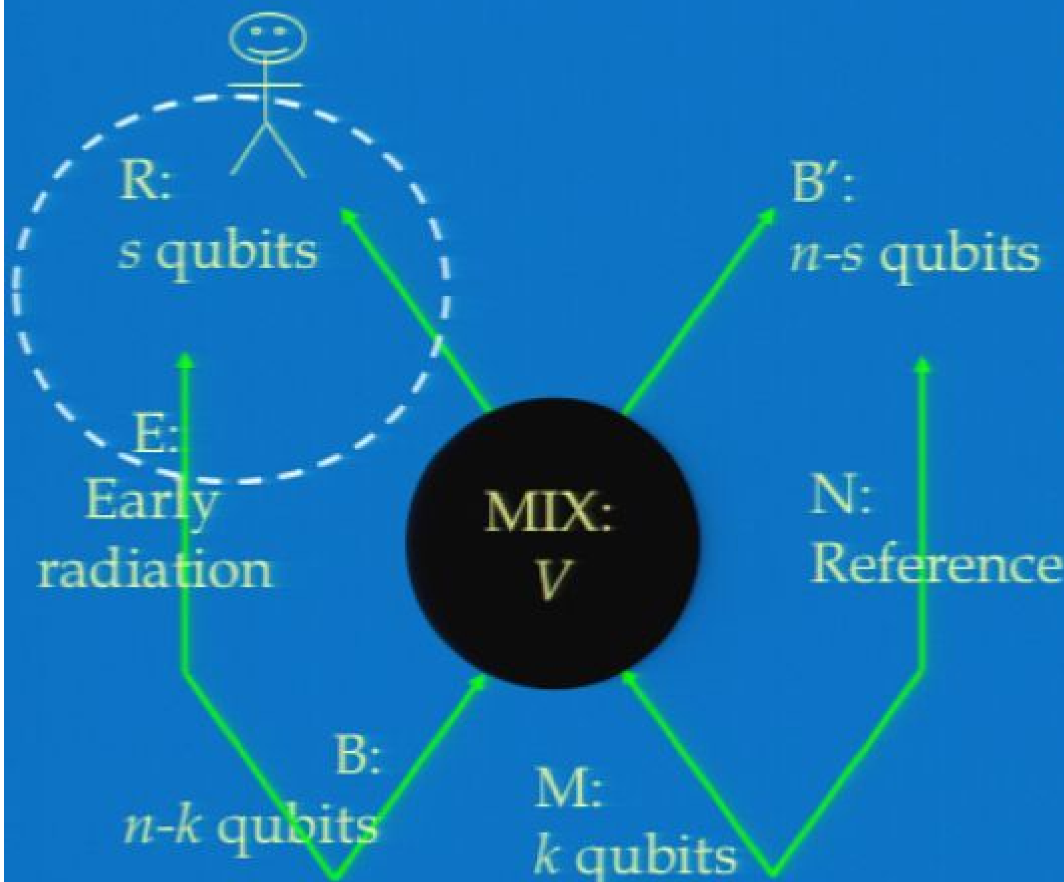

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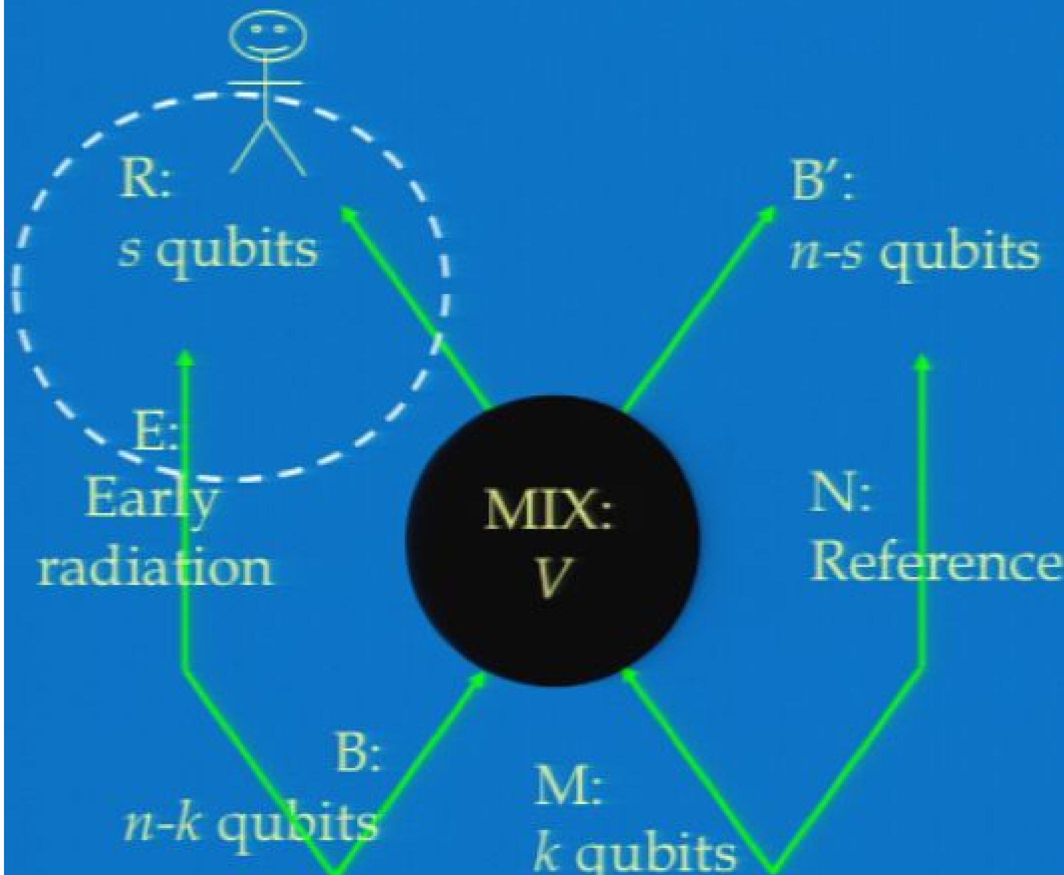

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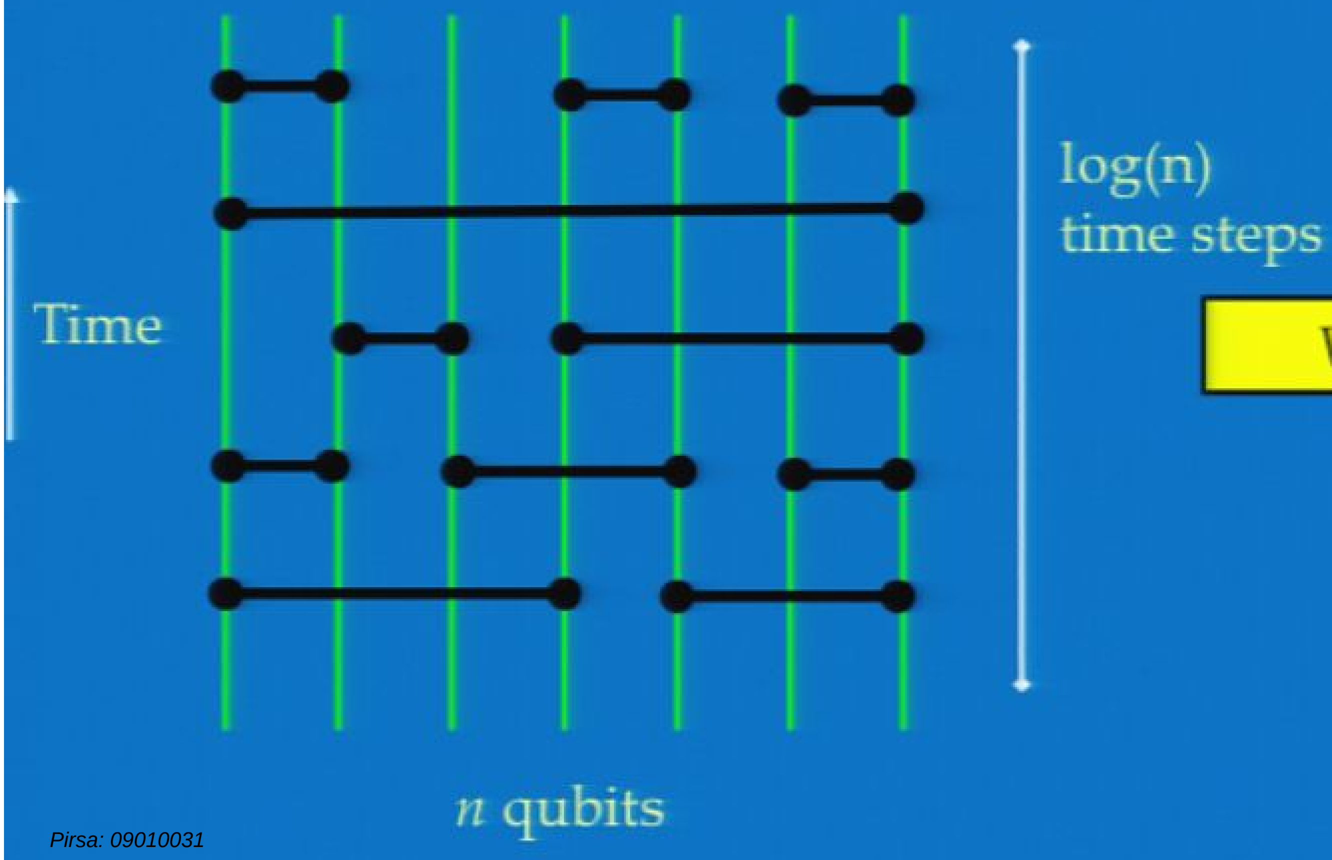

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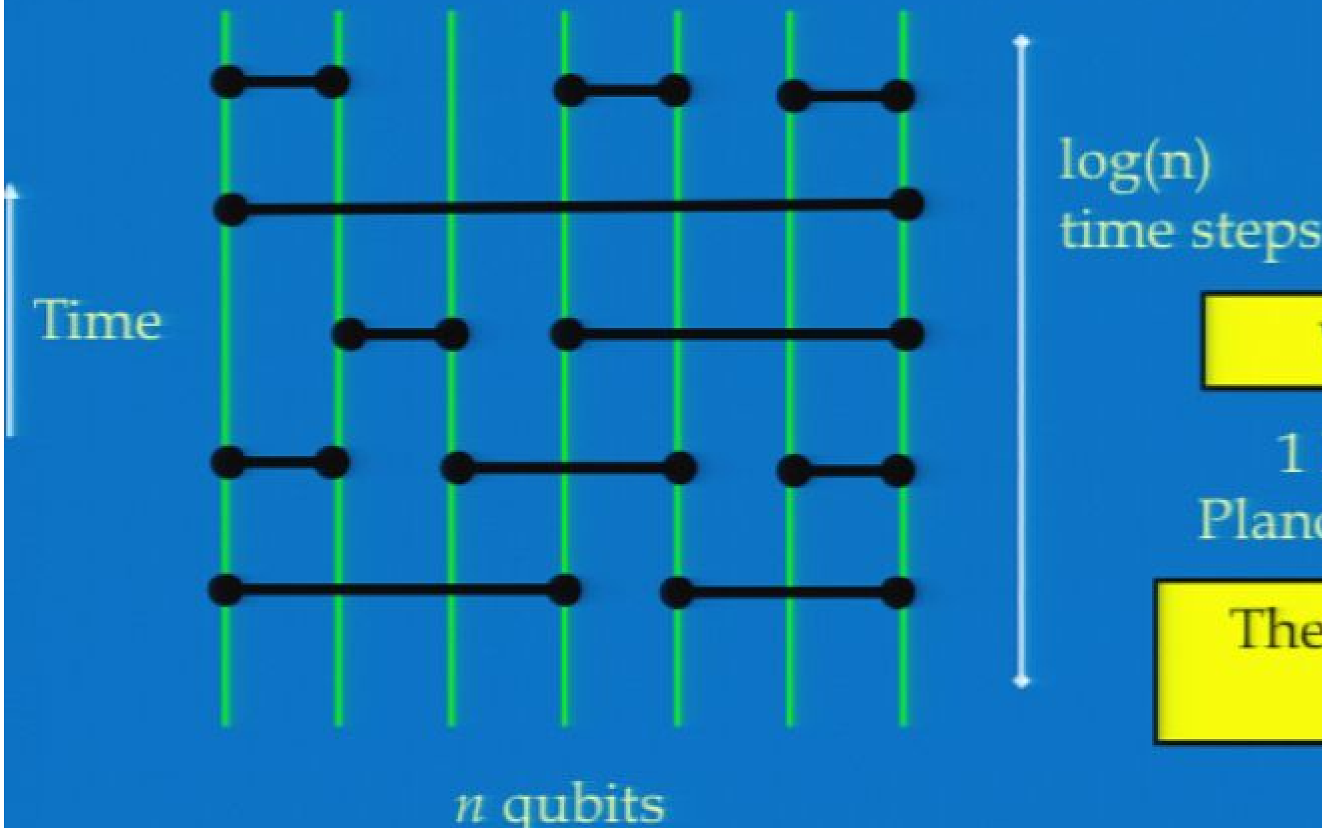

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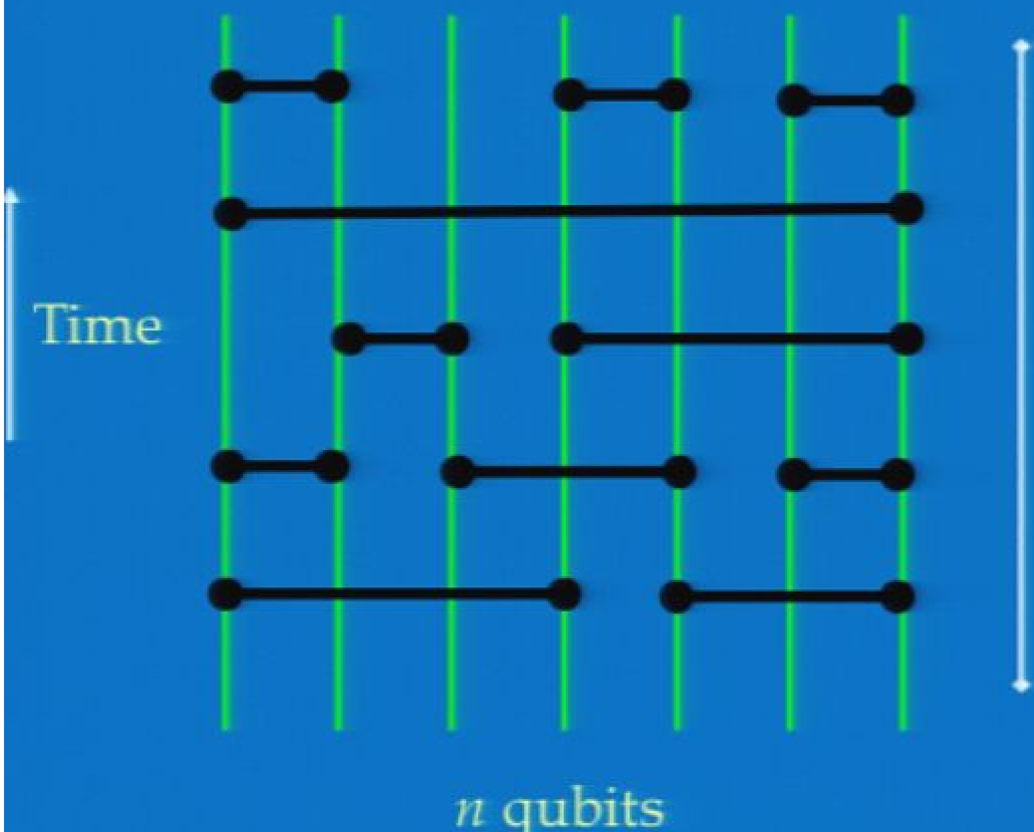

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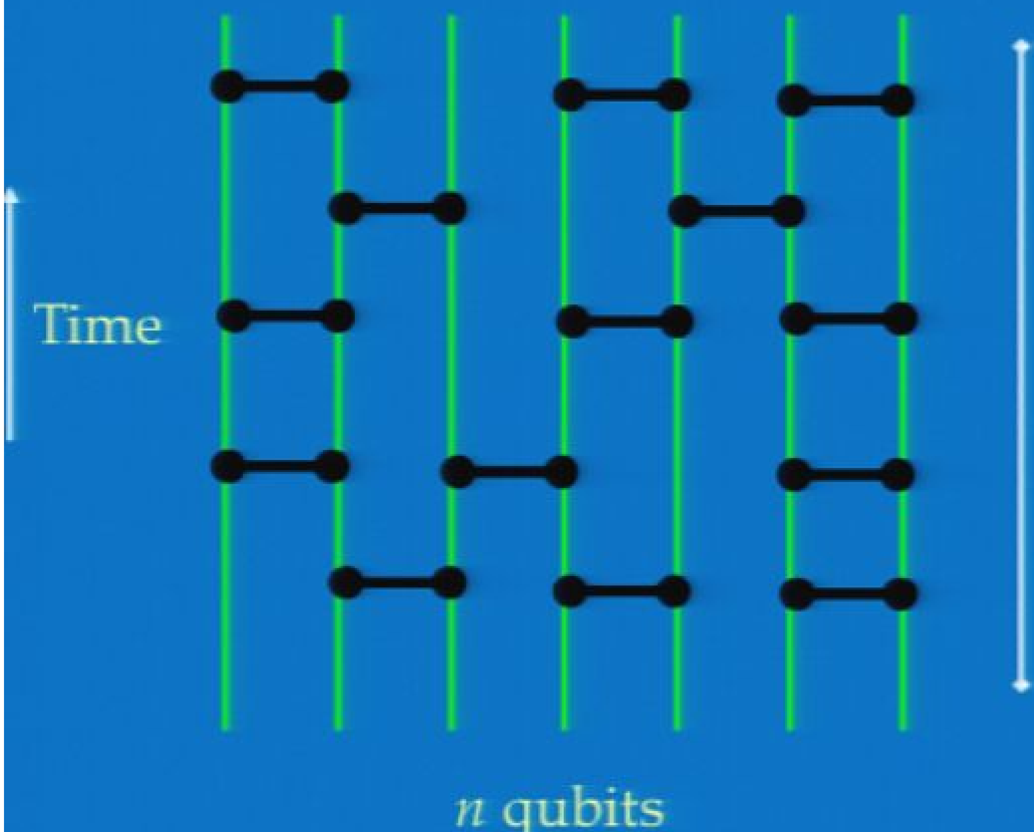

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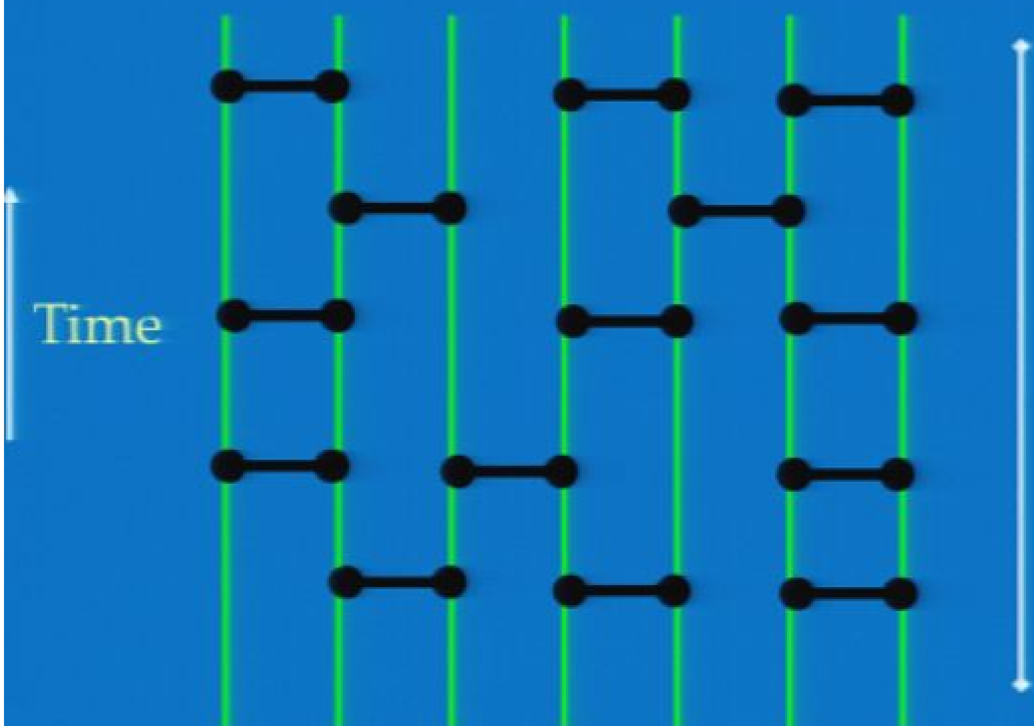

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Slowdown by light crossing time to compensate for local gates

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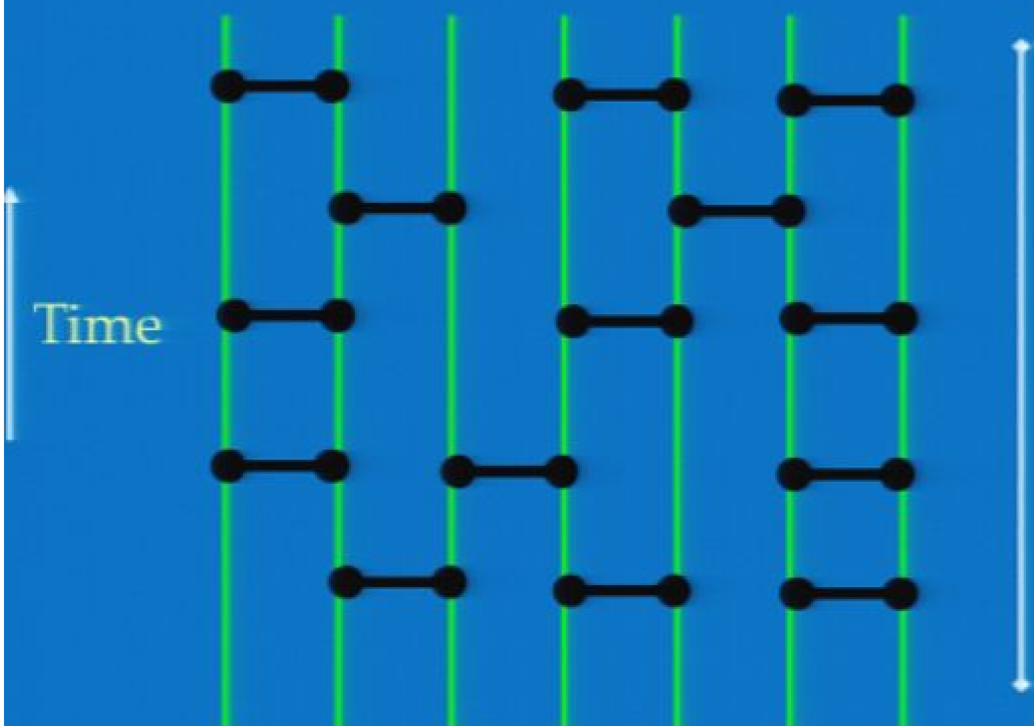

r_s log(n)
time steps

n qubits

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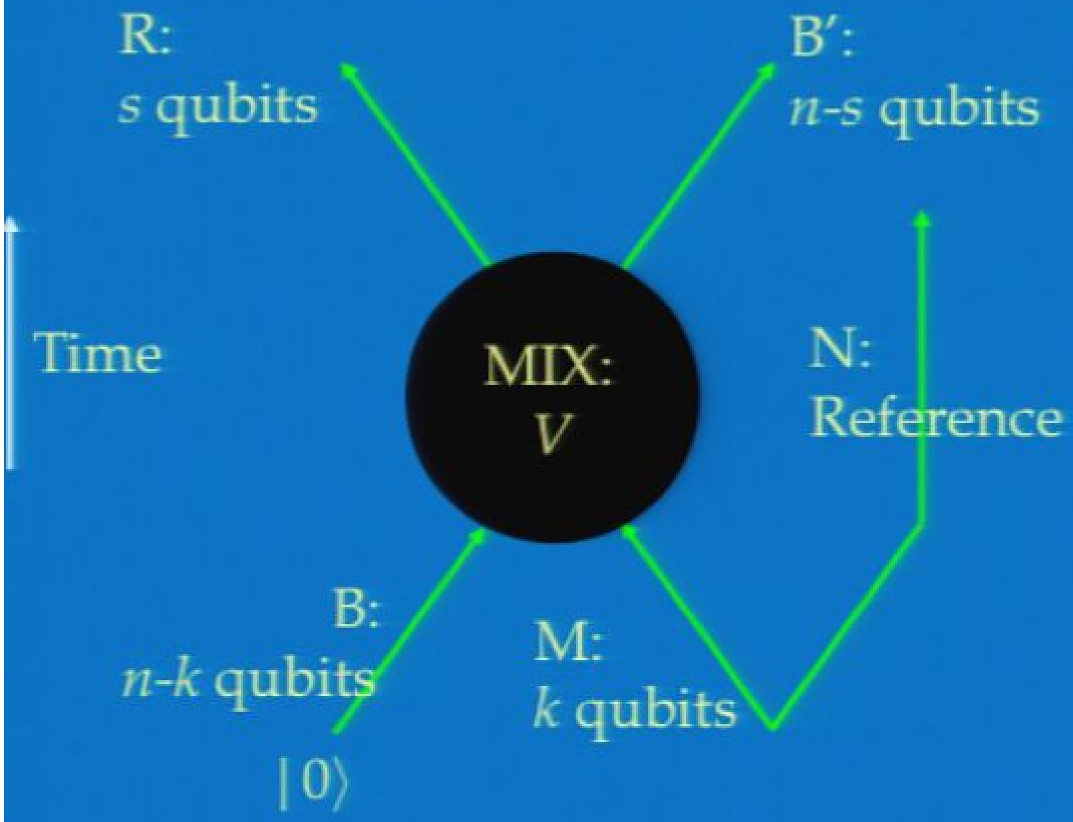
Black Holes as Erasure Channels



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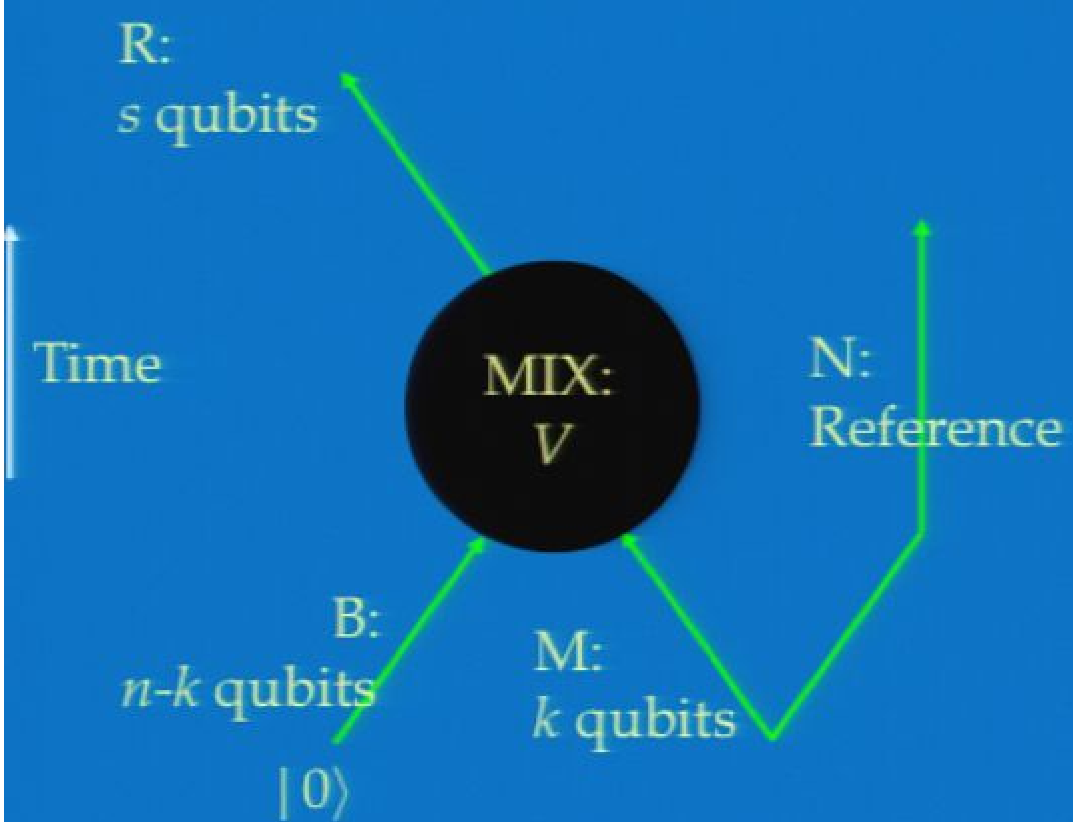

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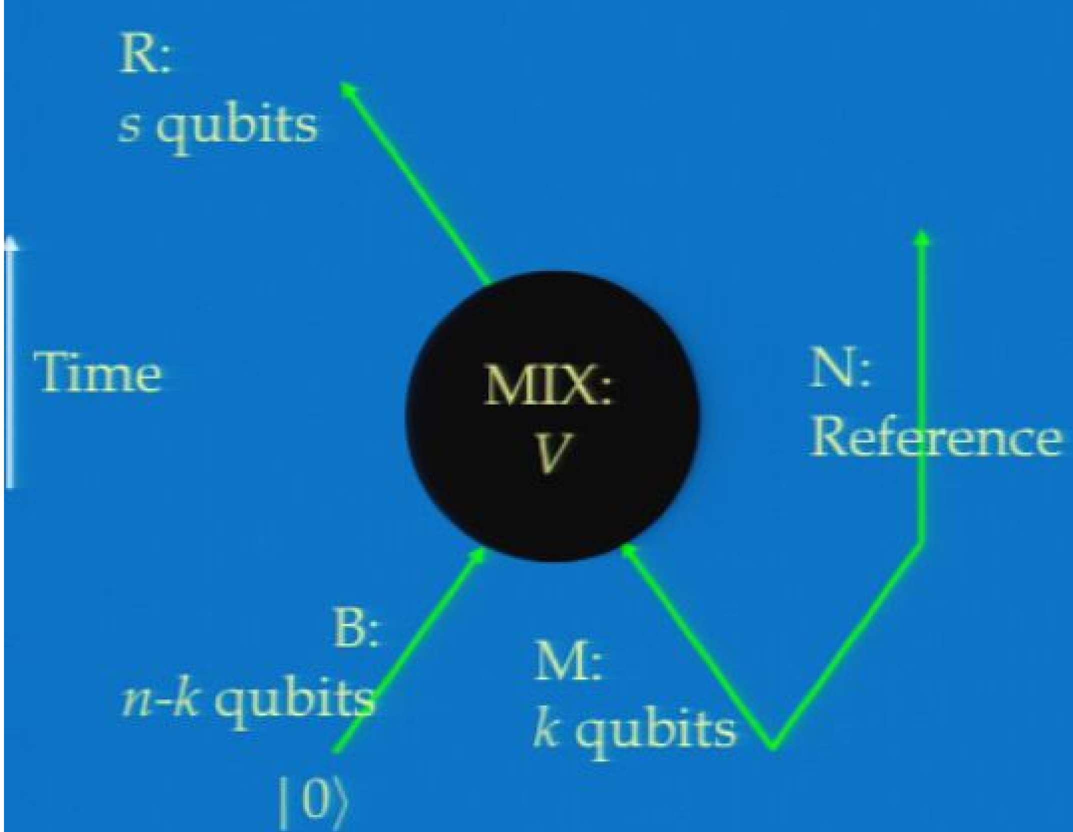

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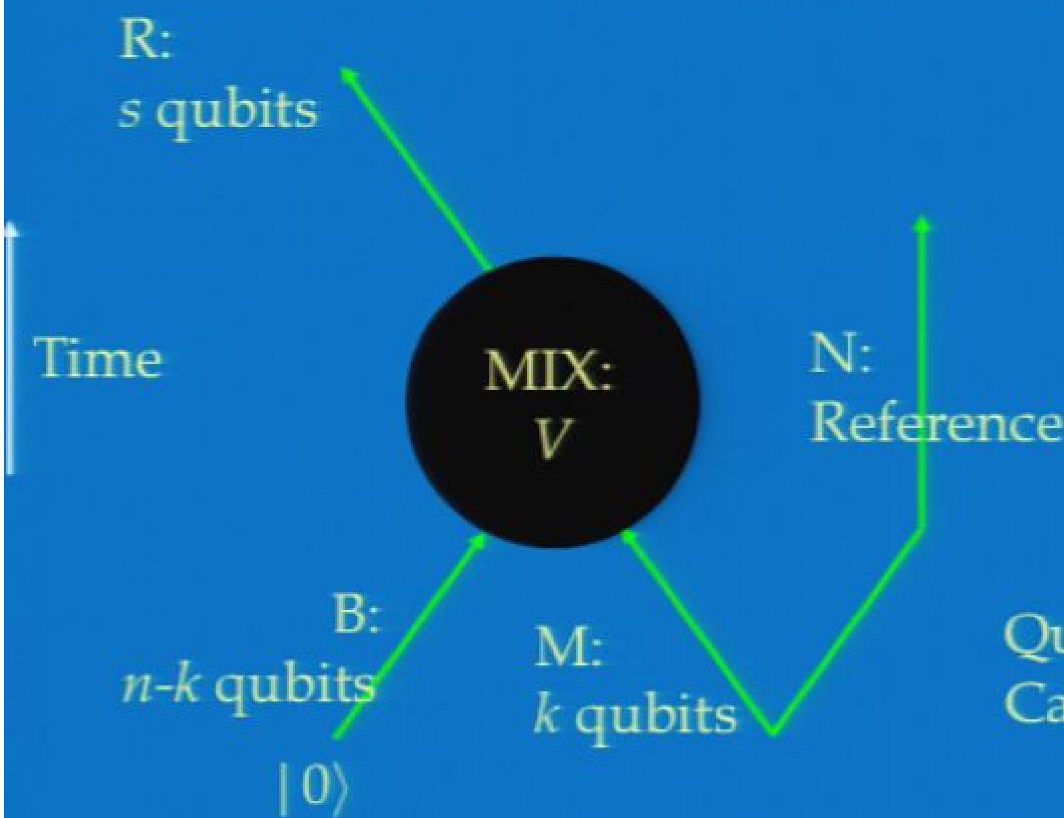

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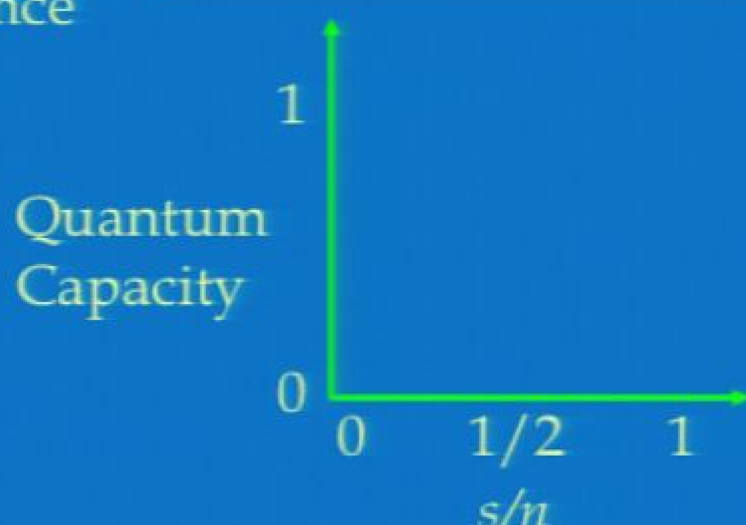

Summary

- For black holes maximally entangled with their Hawking radiation, t_{info} is determined by the time scale for thermalization
- Our best estimates are that this is *just barely* compatible with the black hole complementarity hypothesis

What next?

- Consistency of BH complementarity in other geometries
- Decoding complexity
- Thermalization
  - Study convergence of random circuits [Harrow-Lo 2007]
  - Study convergence for toy nonlocal, nonintegrable Hamiltonian QM systems [H-Lashkari-Osbourne]
  - Study thermalization in stringy models of black holes (matrix theory) [Sekino-Susskind]