Title: The power of forgetting

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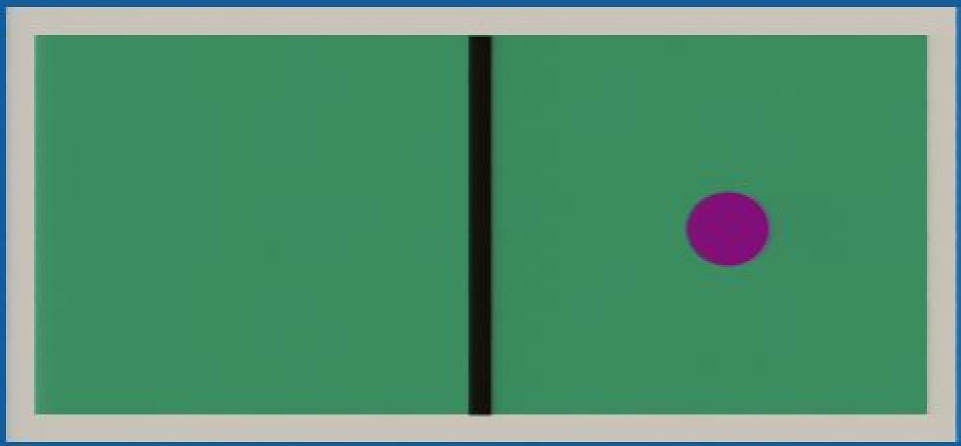
Abstract: Thermodynamics places surprisingly few fundamental constraints on information processing. In fact, most people would argue that it imposes only one, known as Landauer's Principle: a process erasing one bit of information must release an amount kT ln 2 of heat. It is this simple observation that finally led to the exorcism of Maxwell's Demon from statistical mechanics, more than a century after he first appeared.
Ignoring the lesson implicit in this early advance, however, quantum information theorists have been surprisingly slow to embrace erasure as a fundamental primitive. Over the past couple of years, however, it has become clear that a detailed understanding of how difficult it is to erase correlations leads to a nearly complete synthesis and simplification of the known results of asymptotic quantum information theory. As it turns out, surprisingly many of the tasks of interest, from distilling high-quality entanglement to sending quantum data through a noisy medium to many receivers, can be understood as variants of erasure. I'll sketch the main ideas behind these discoveries and end with some speculations on what lessons the new picture might have for understanding information loss in real physical systems.

The power of forgetting

Patrick Hayden (McGill University)

Perimeter Institute, 26 March 2007

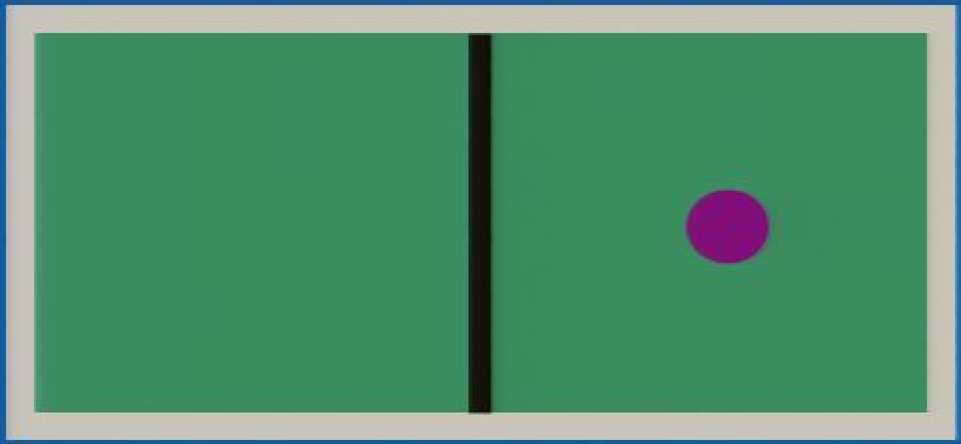
Landauer's Principle



State 1

Landauer's Principle

Erasure: A process that, regardless of the input state, results in output state 0



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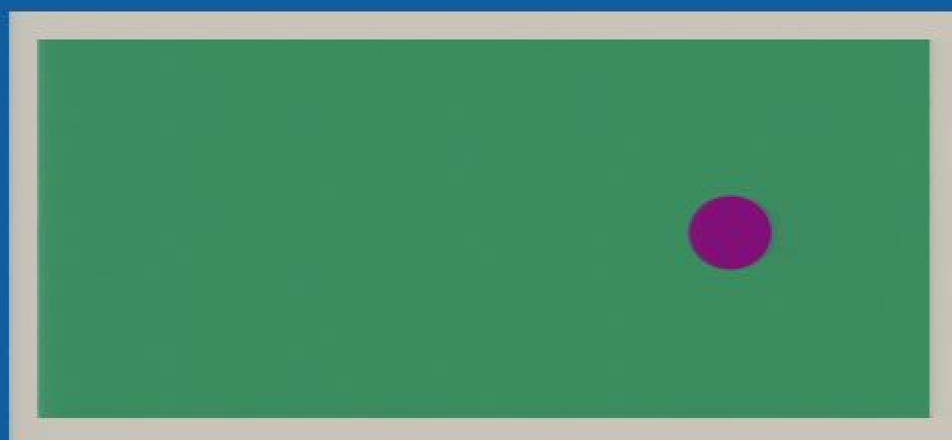

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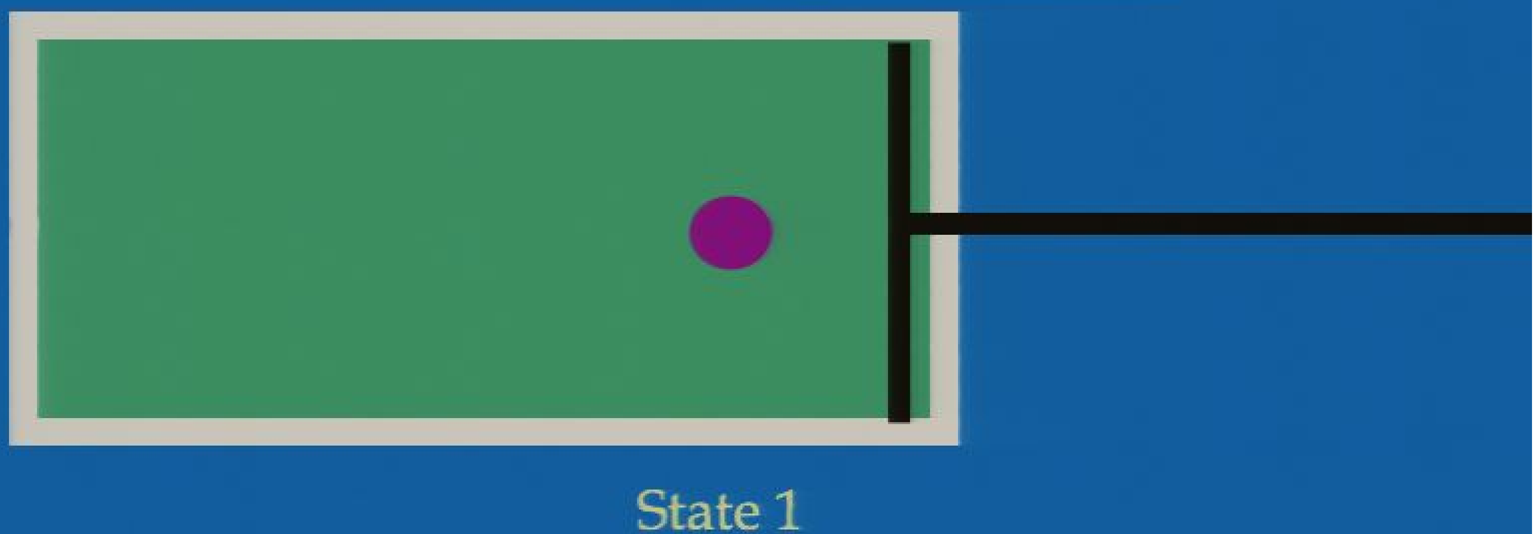

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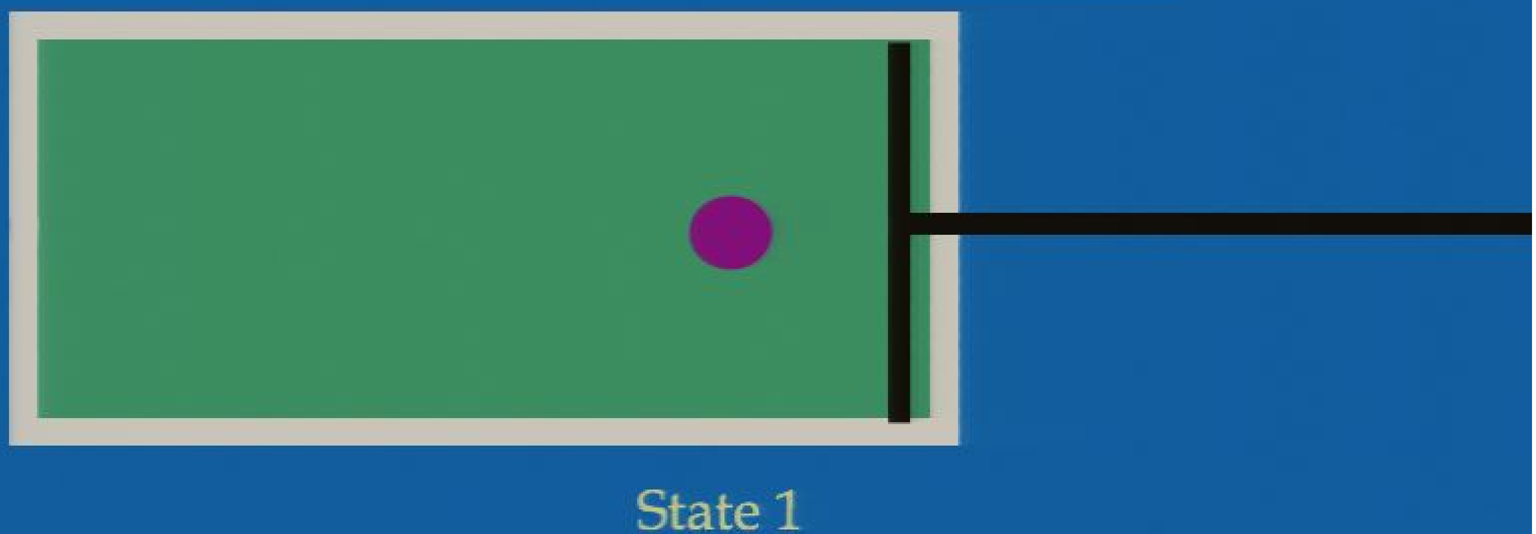

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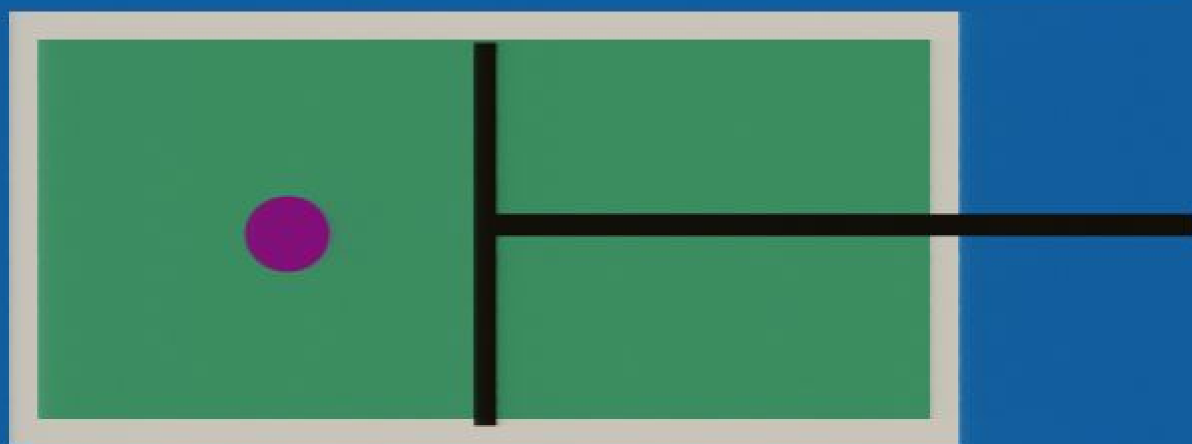

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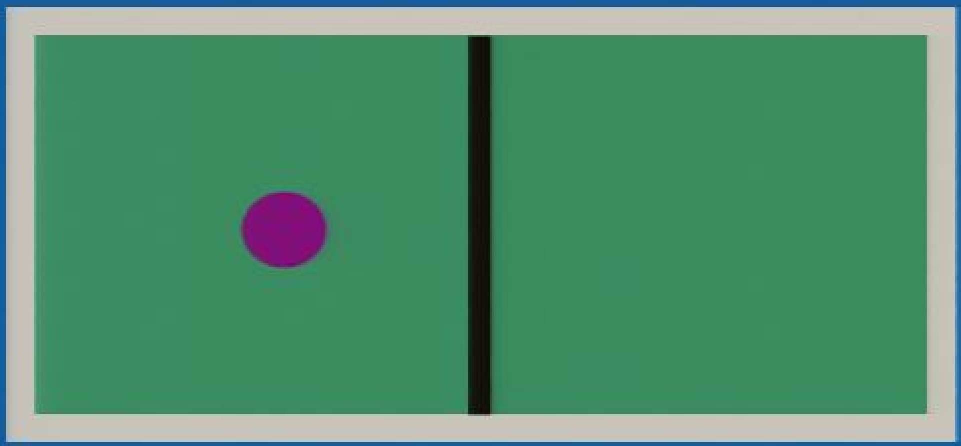

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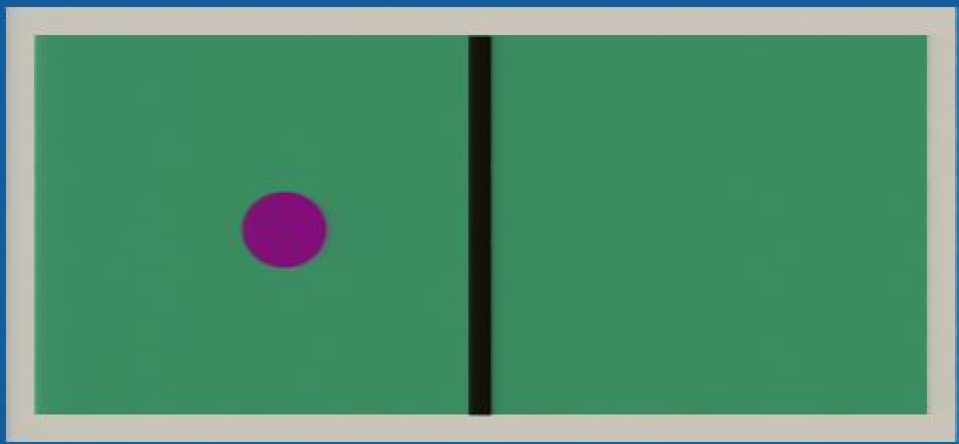

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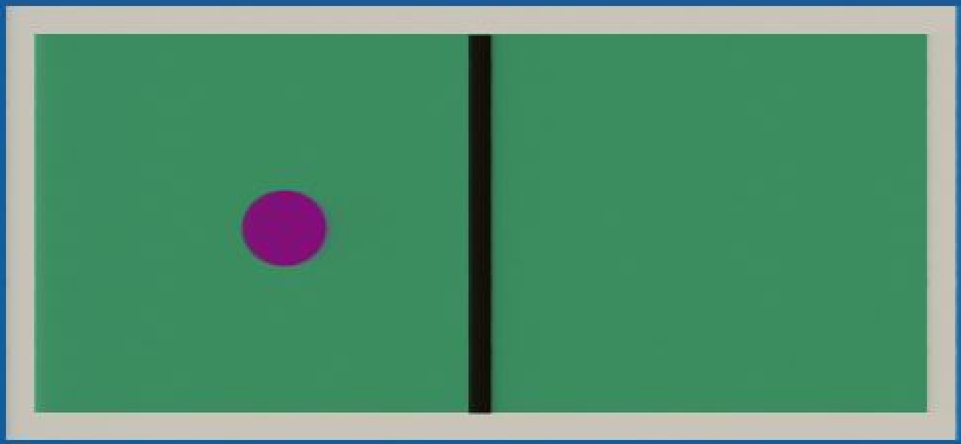

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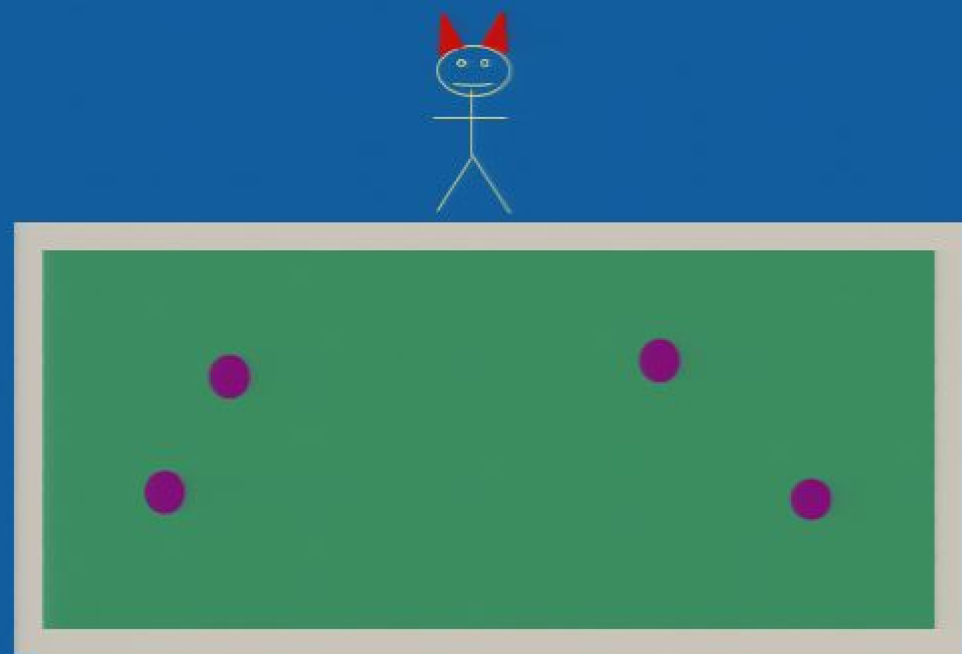
Erasing information requires a process that can reduce in uncertainty

Thermodynamic entropy of the gas is reduced by $k \ln 2$ so amount $kT \ln 2$ of heat released to the environment.

Maxwell's Demon



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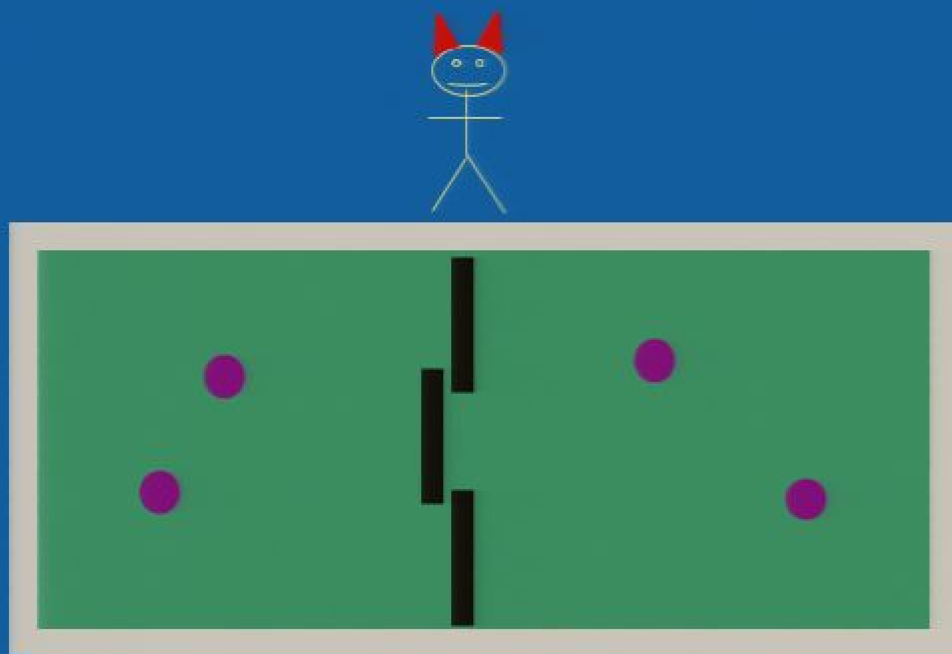

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Demon uses door to allow particles to move left to right, but not right to left.

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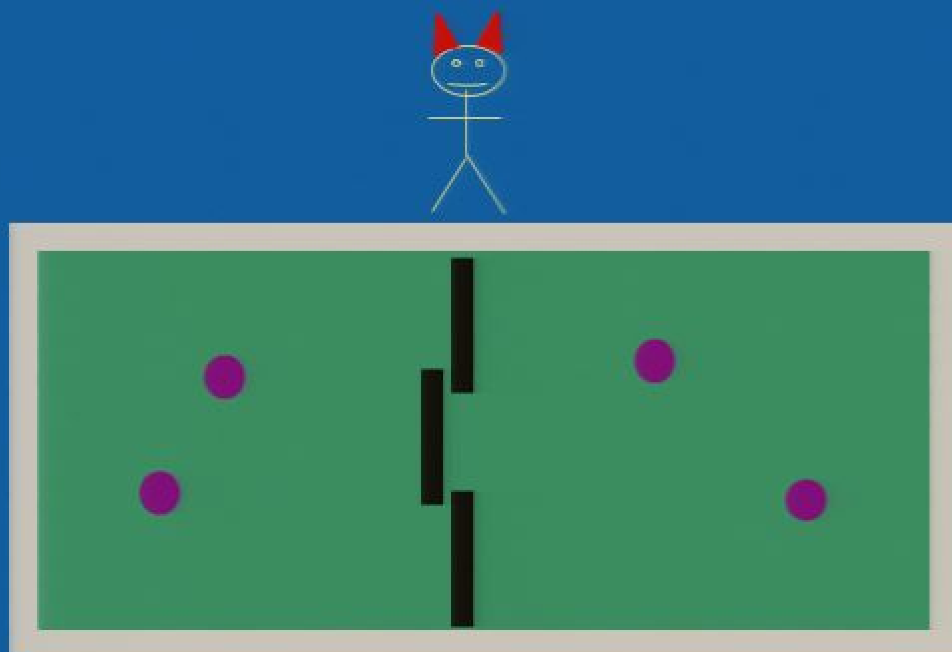

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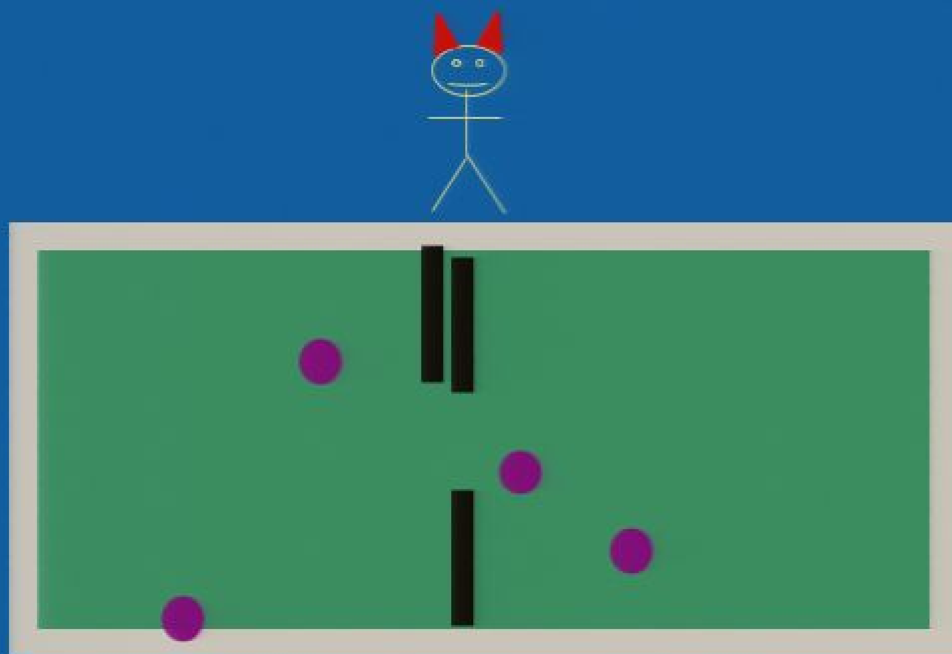

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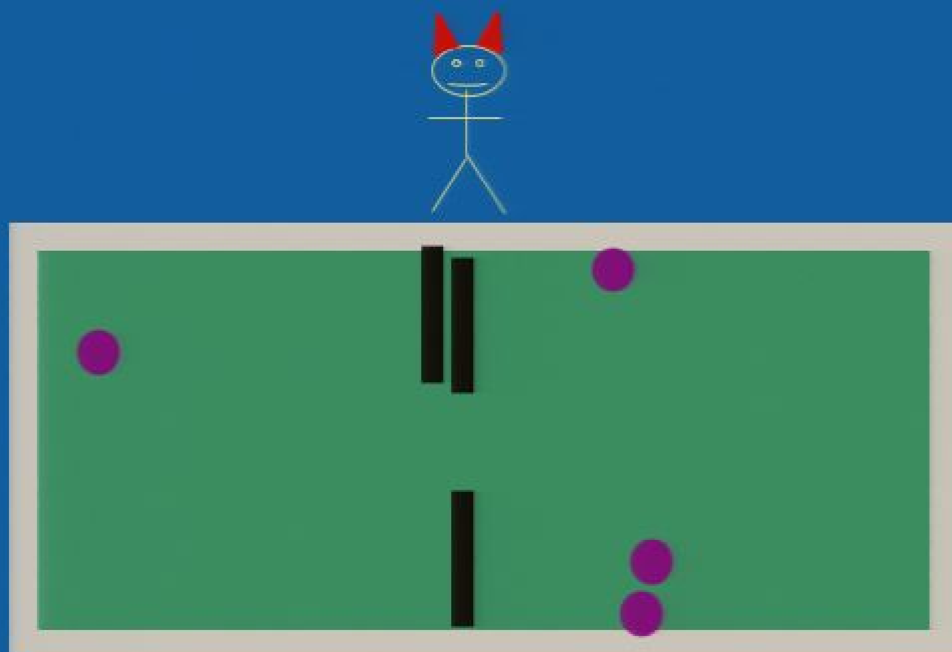

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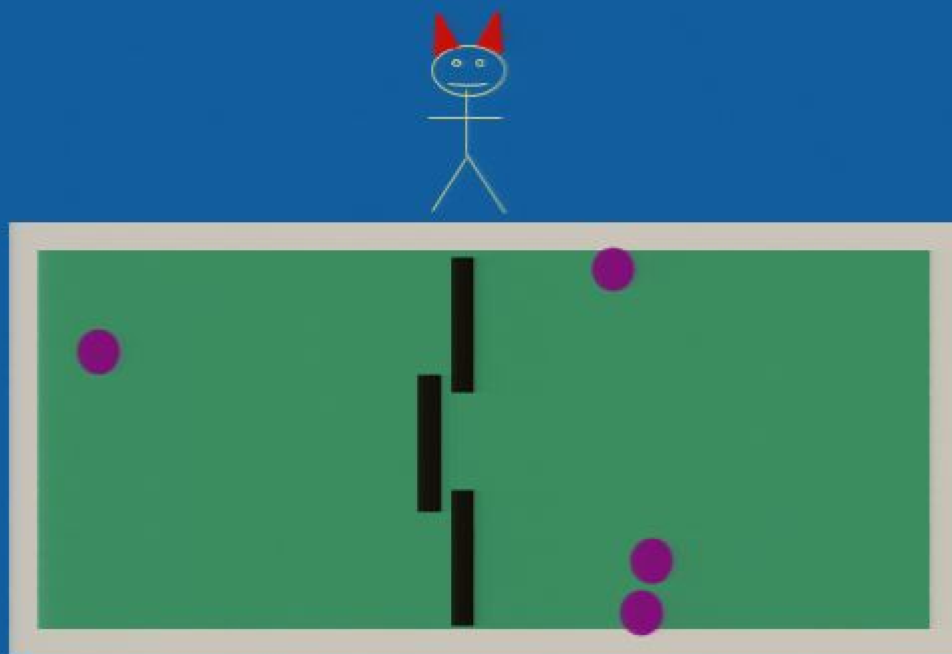

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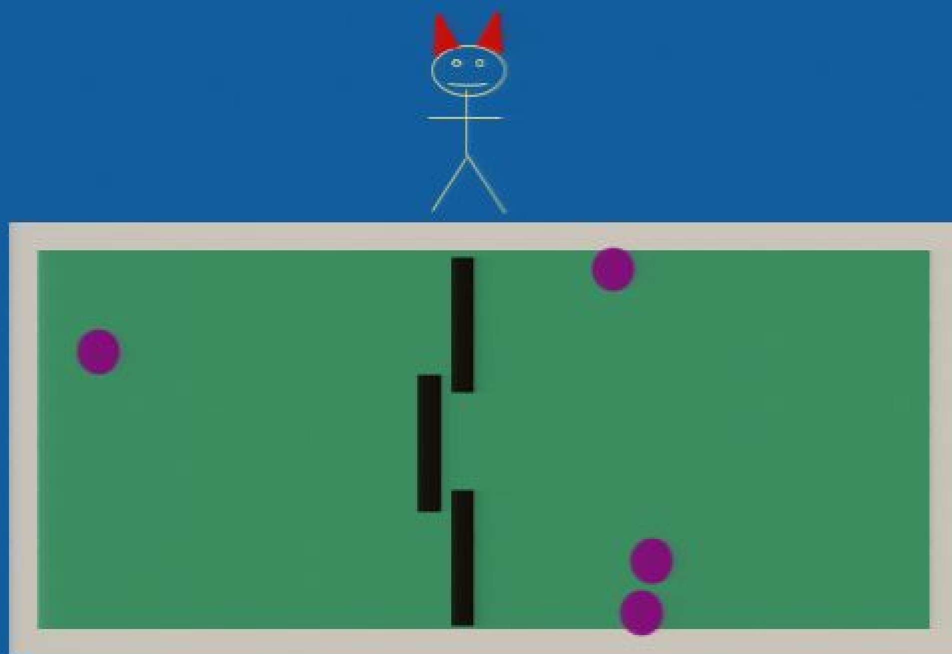

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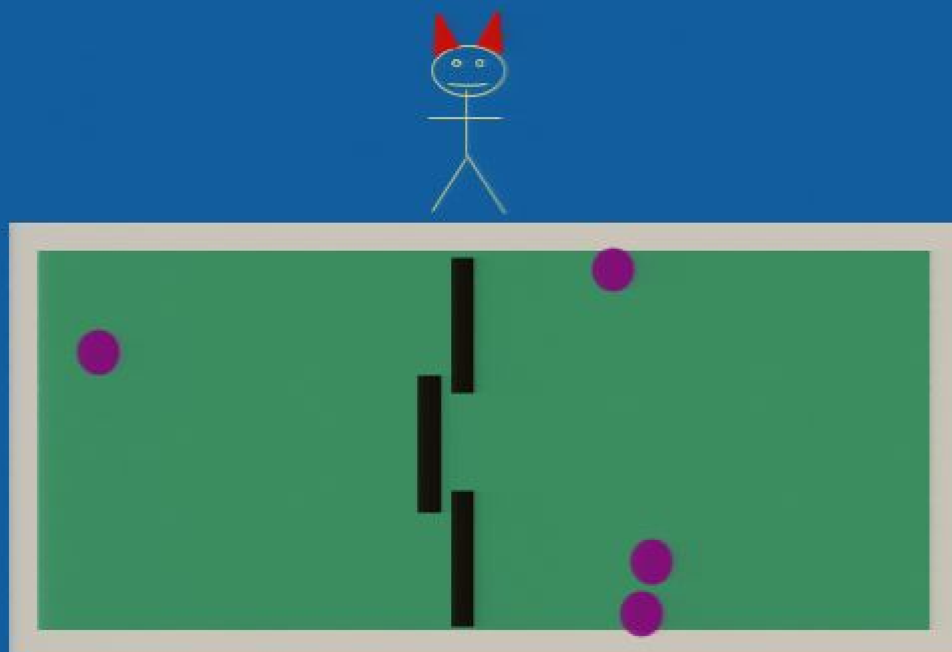

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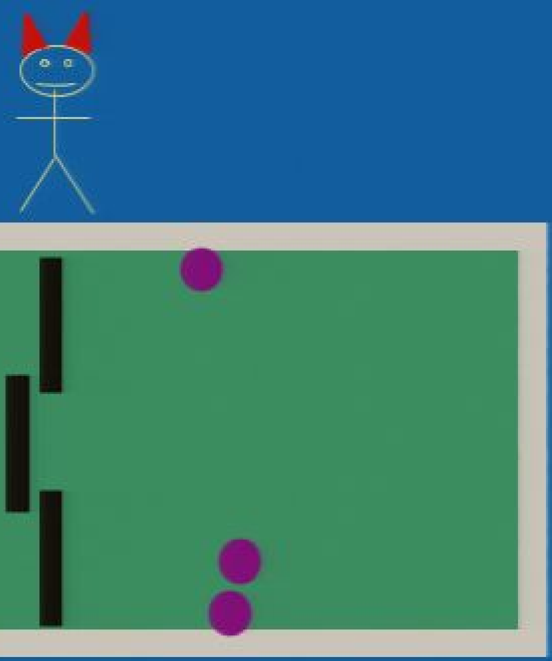

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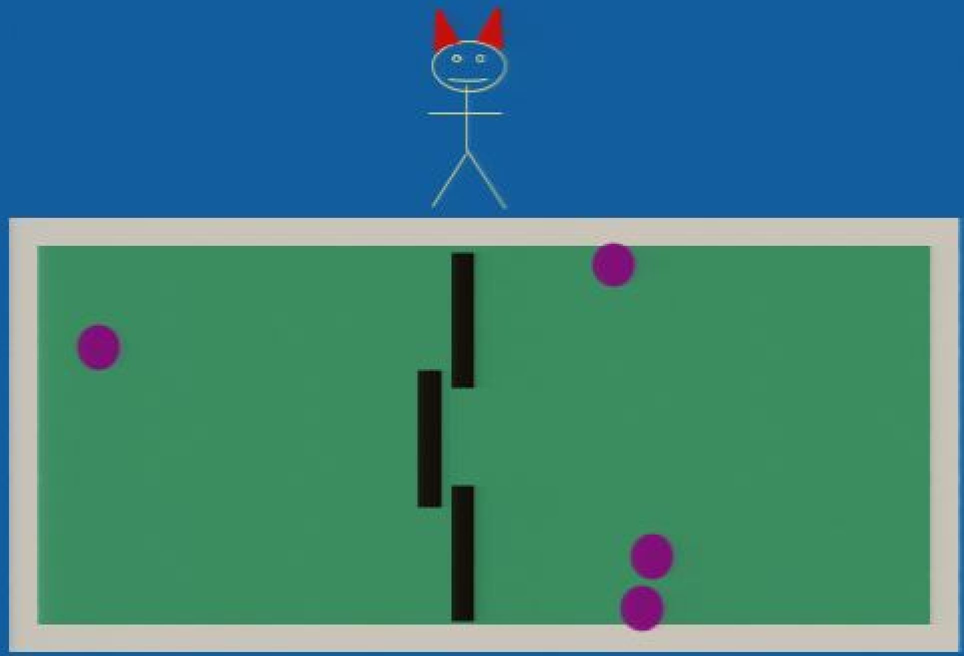

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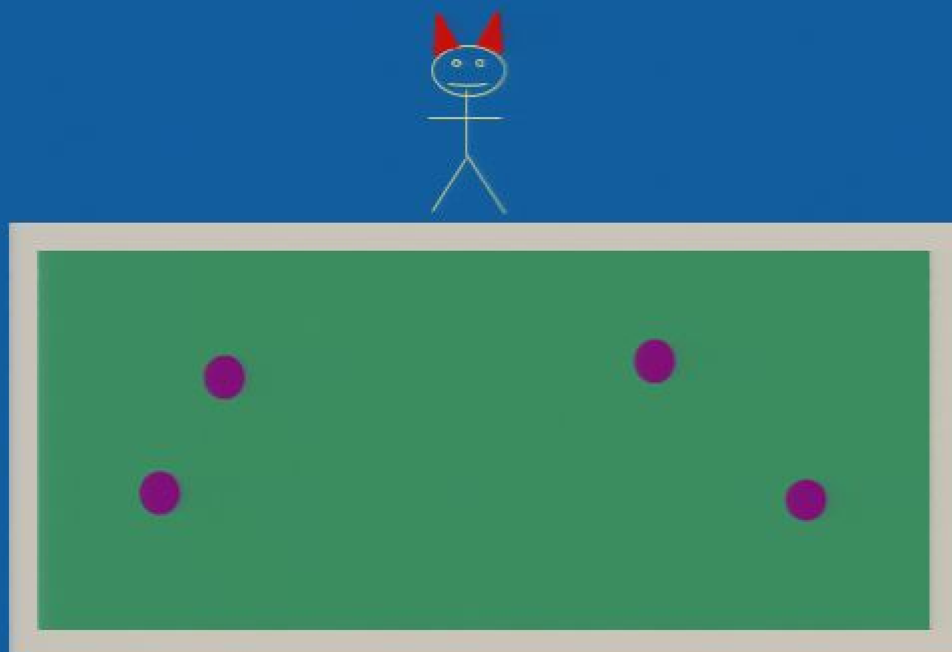

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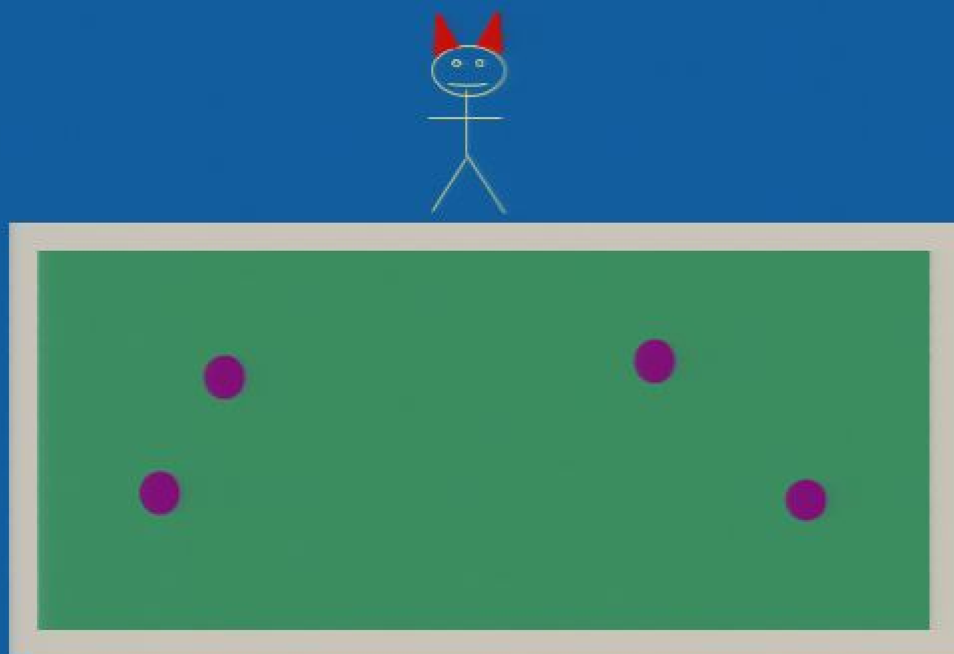

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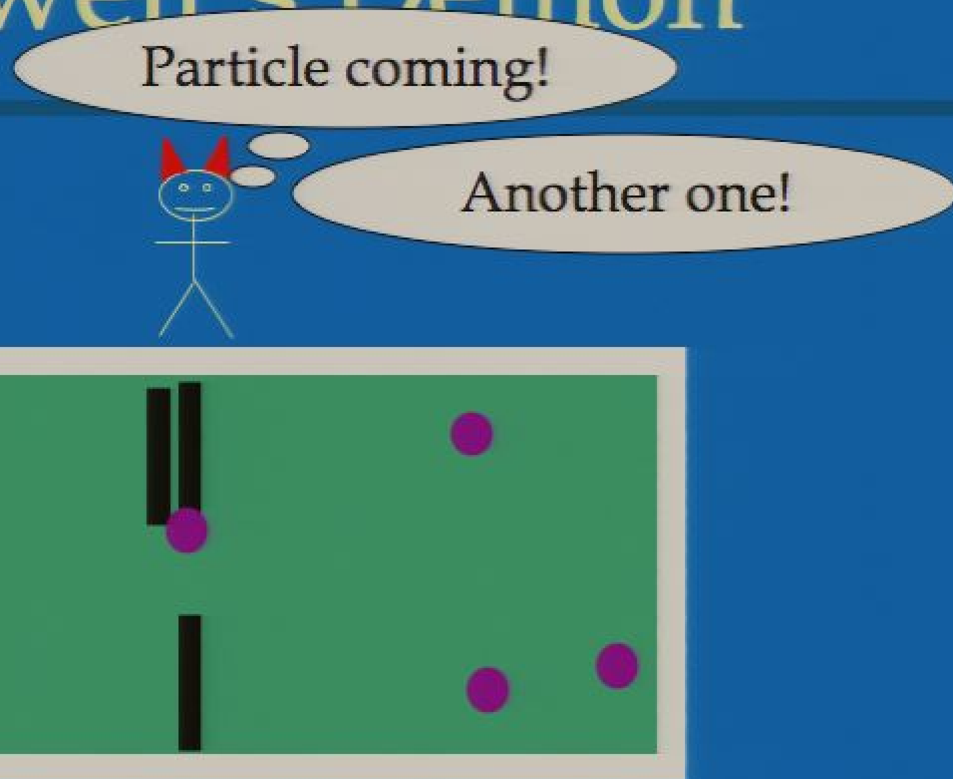

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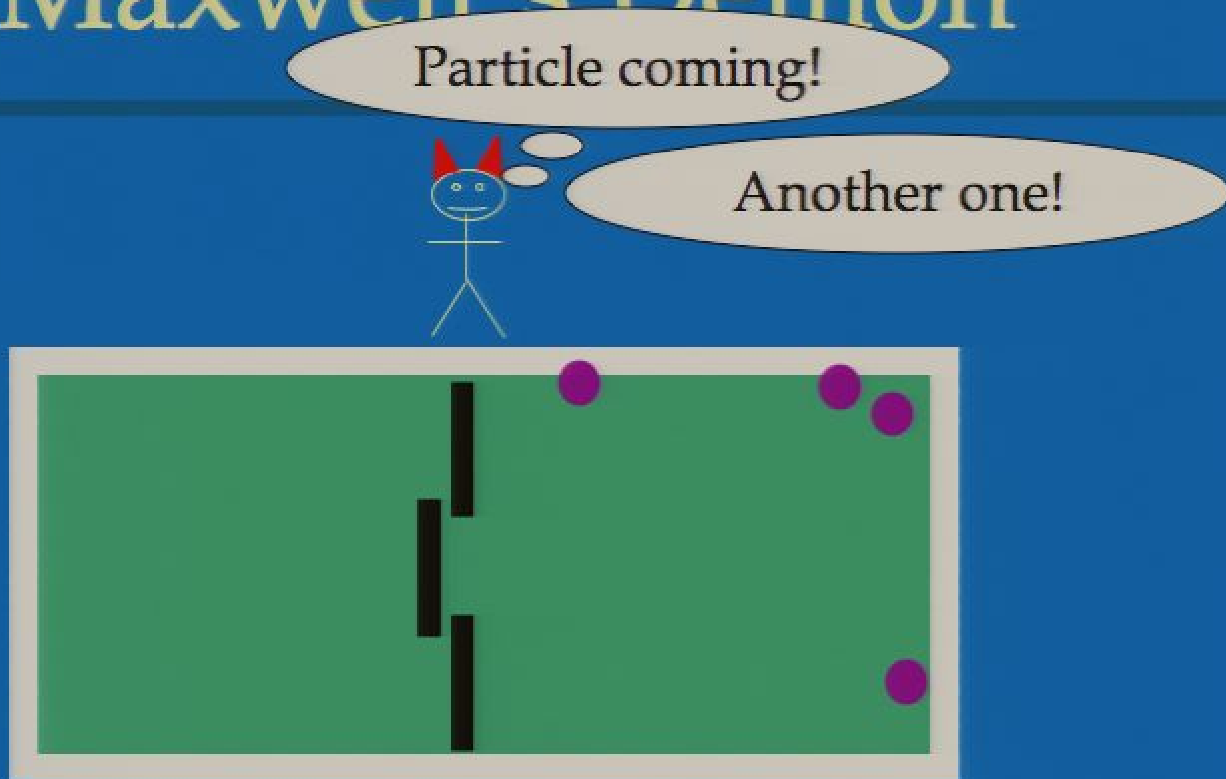

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Demon must process information about incoming particles.

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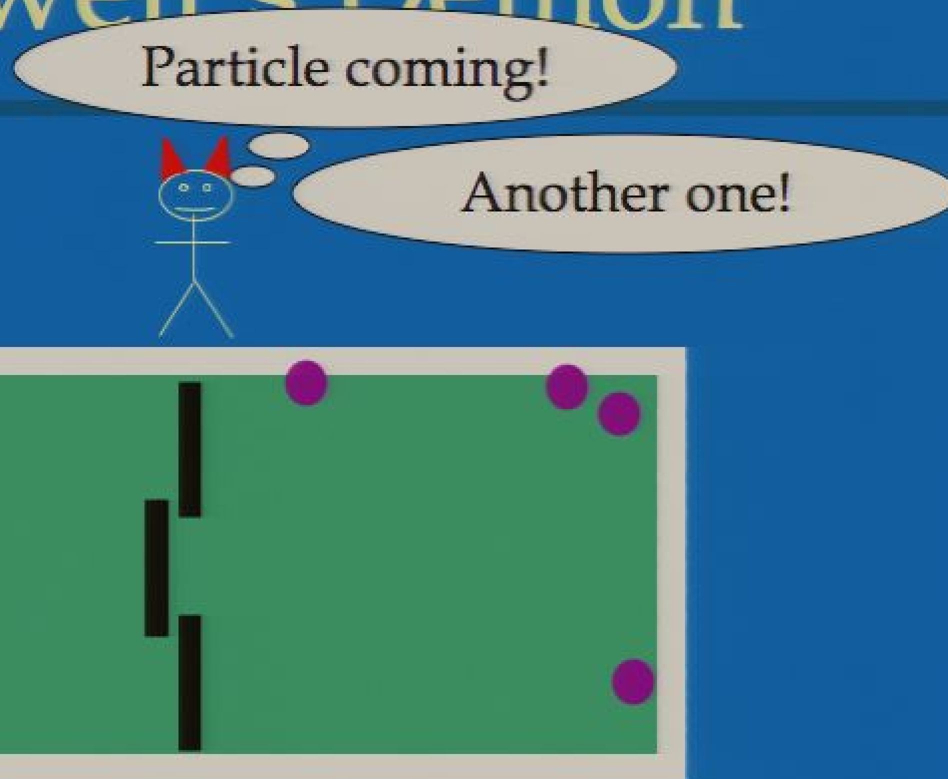

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Finite memory: he must eventually start *forgetting*.

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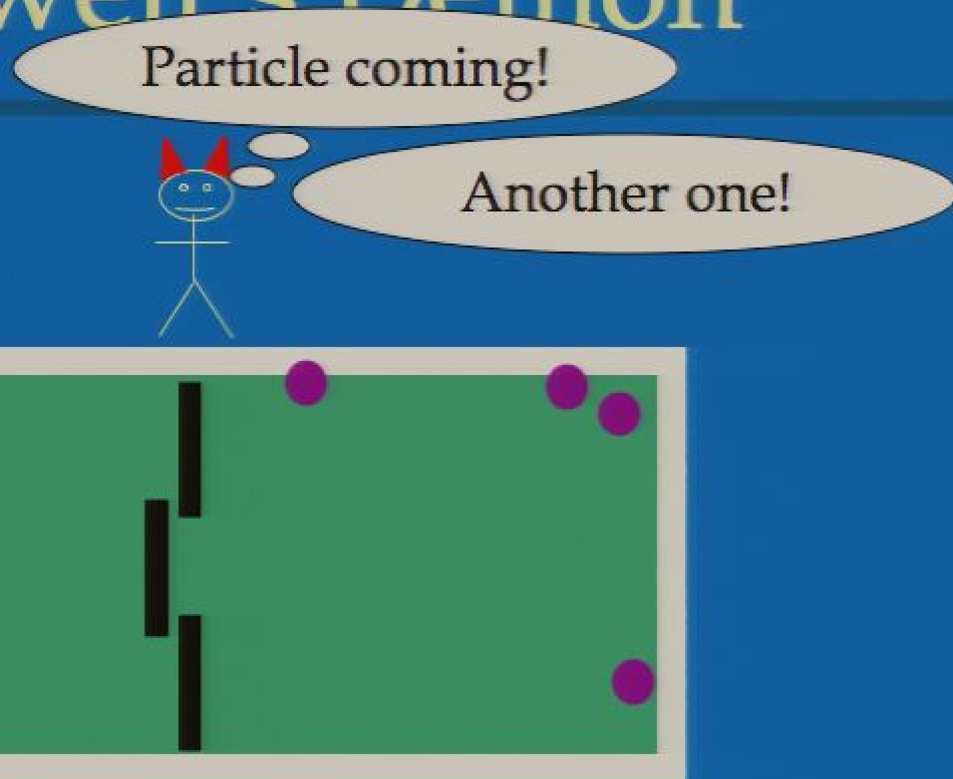

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Landauer's principle restores global increase of entropy.

Church of the Larger Hilbert Space

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ρ_A

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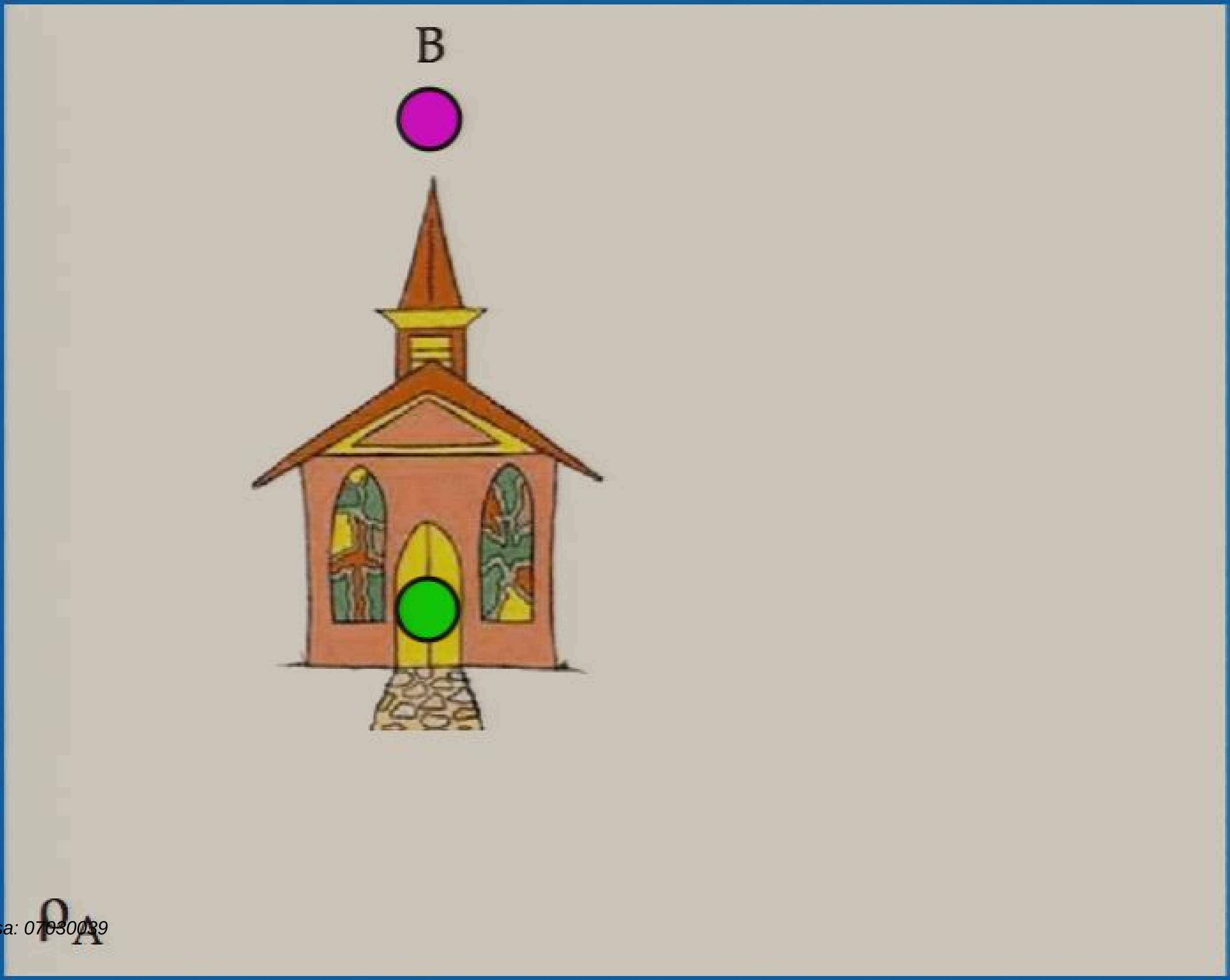

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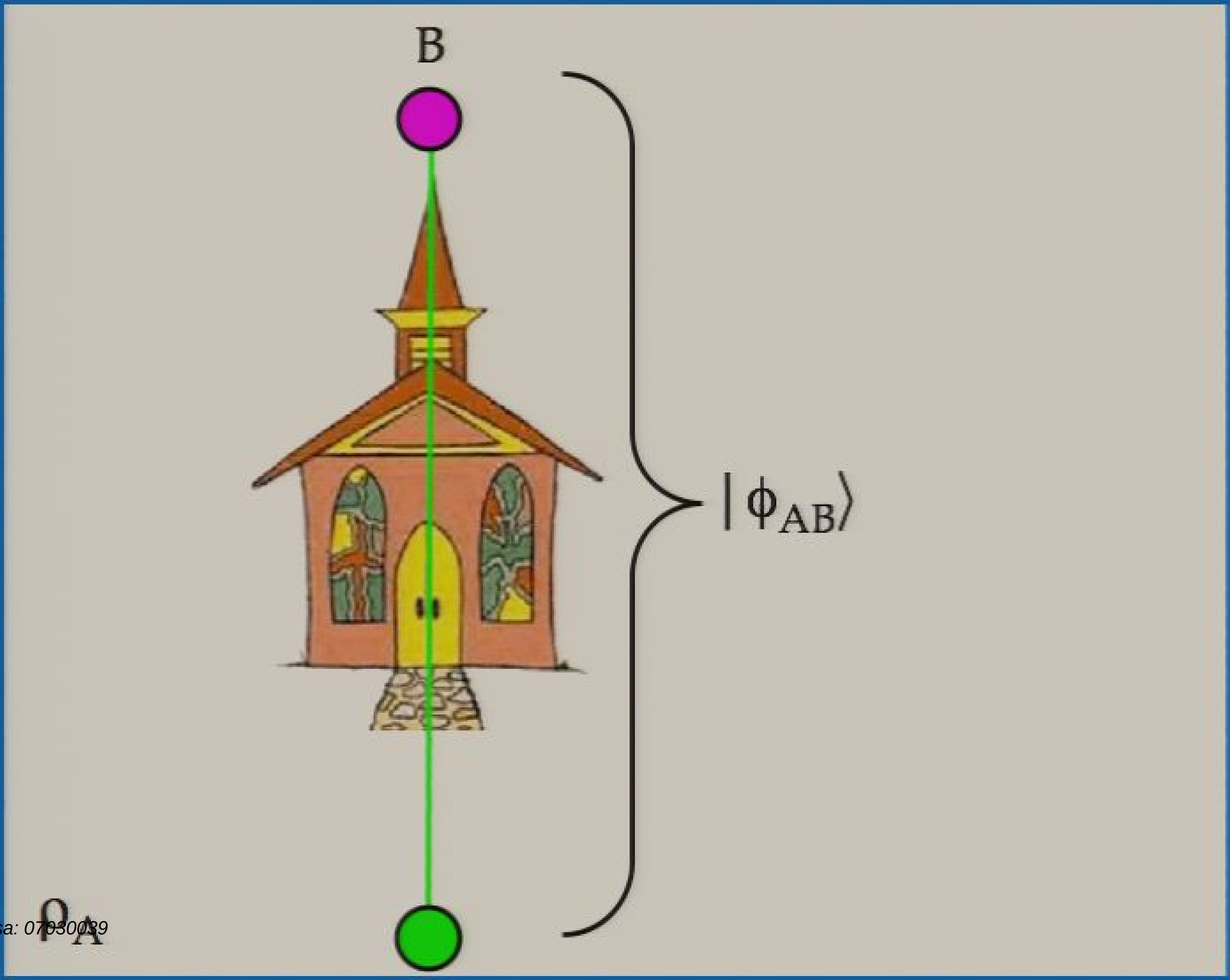

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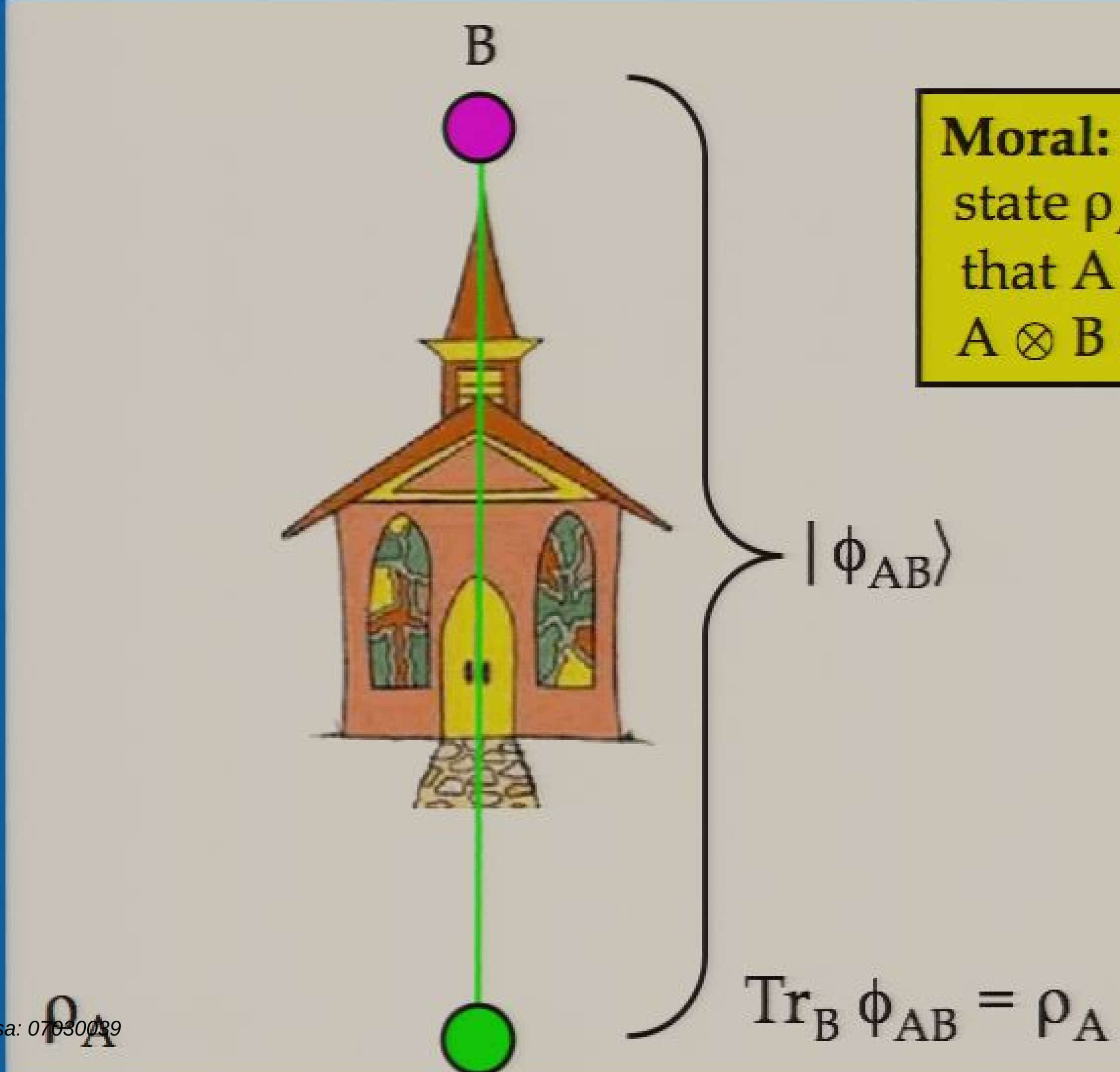

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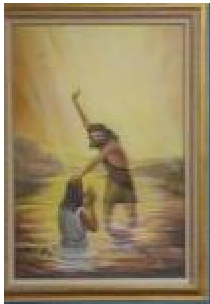

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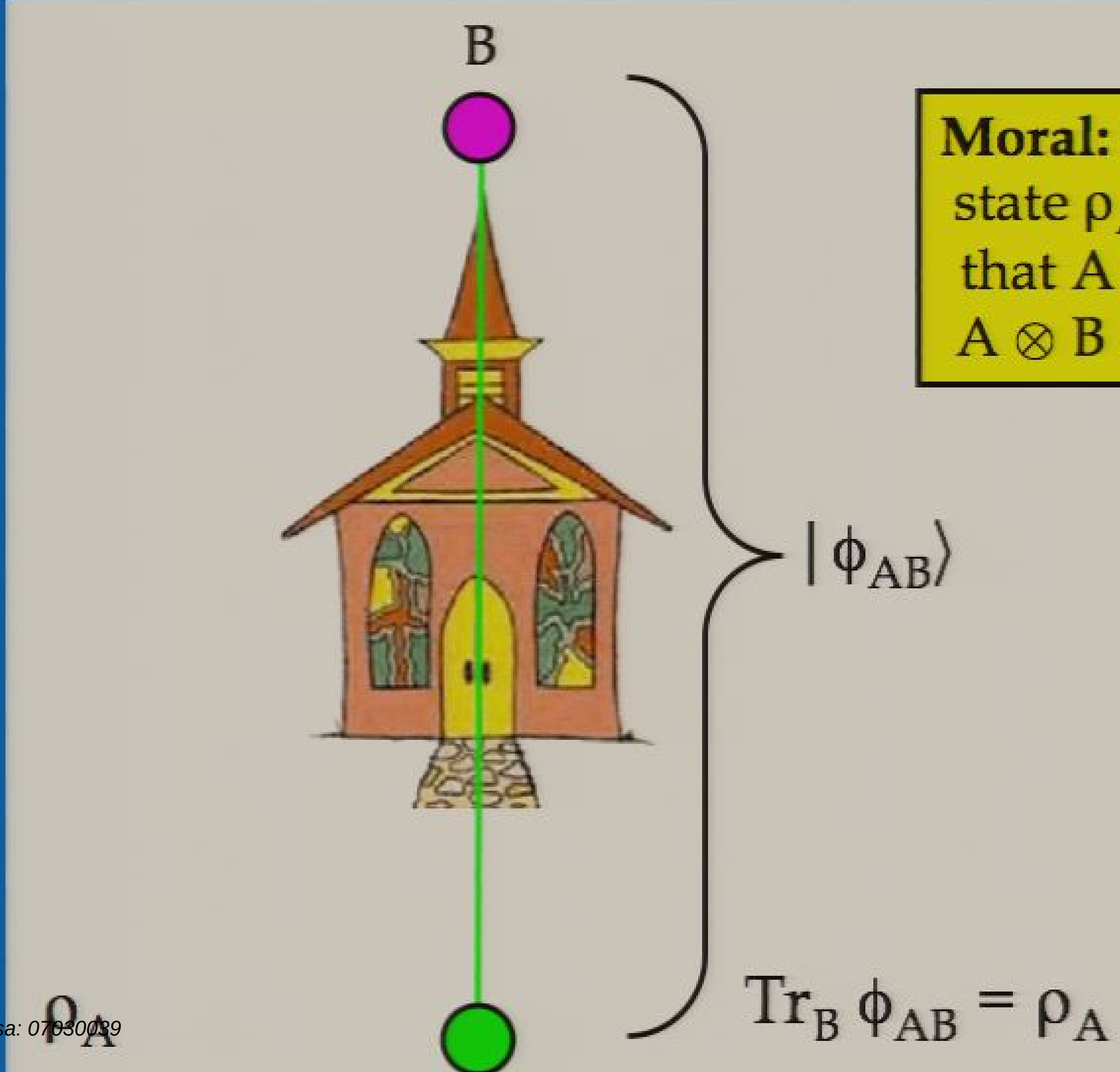

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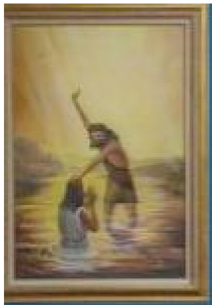

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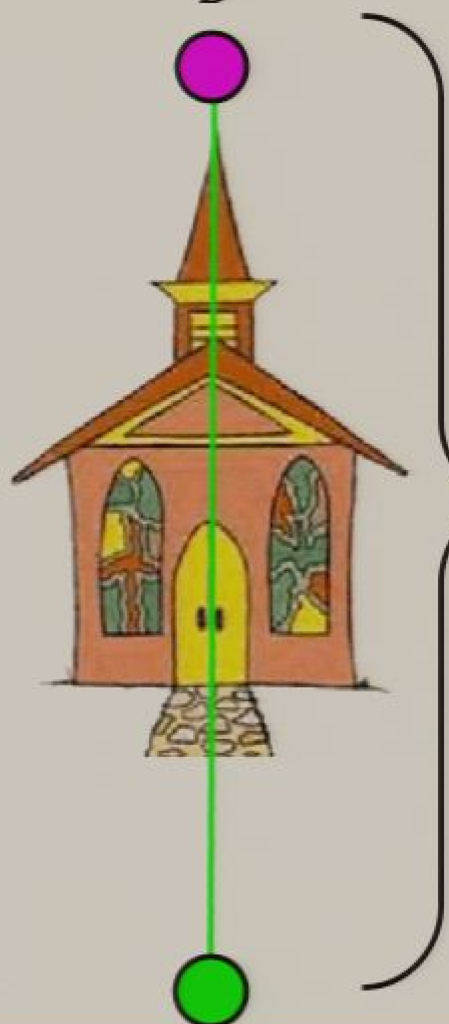

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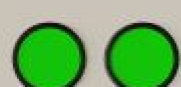

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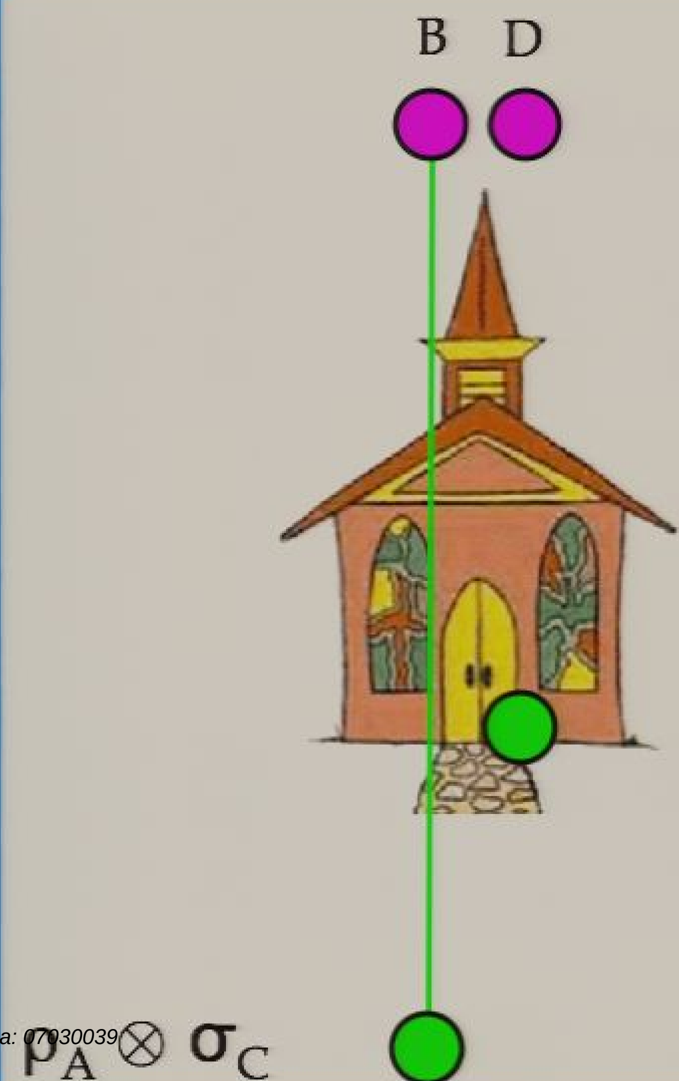

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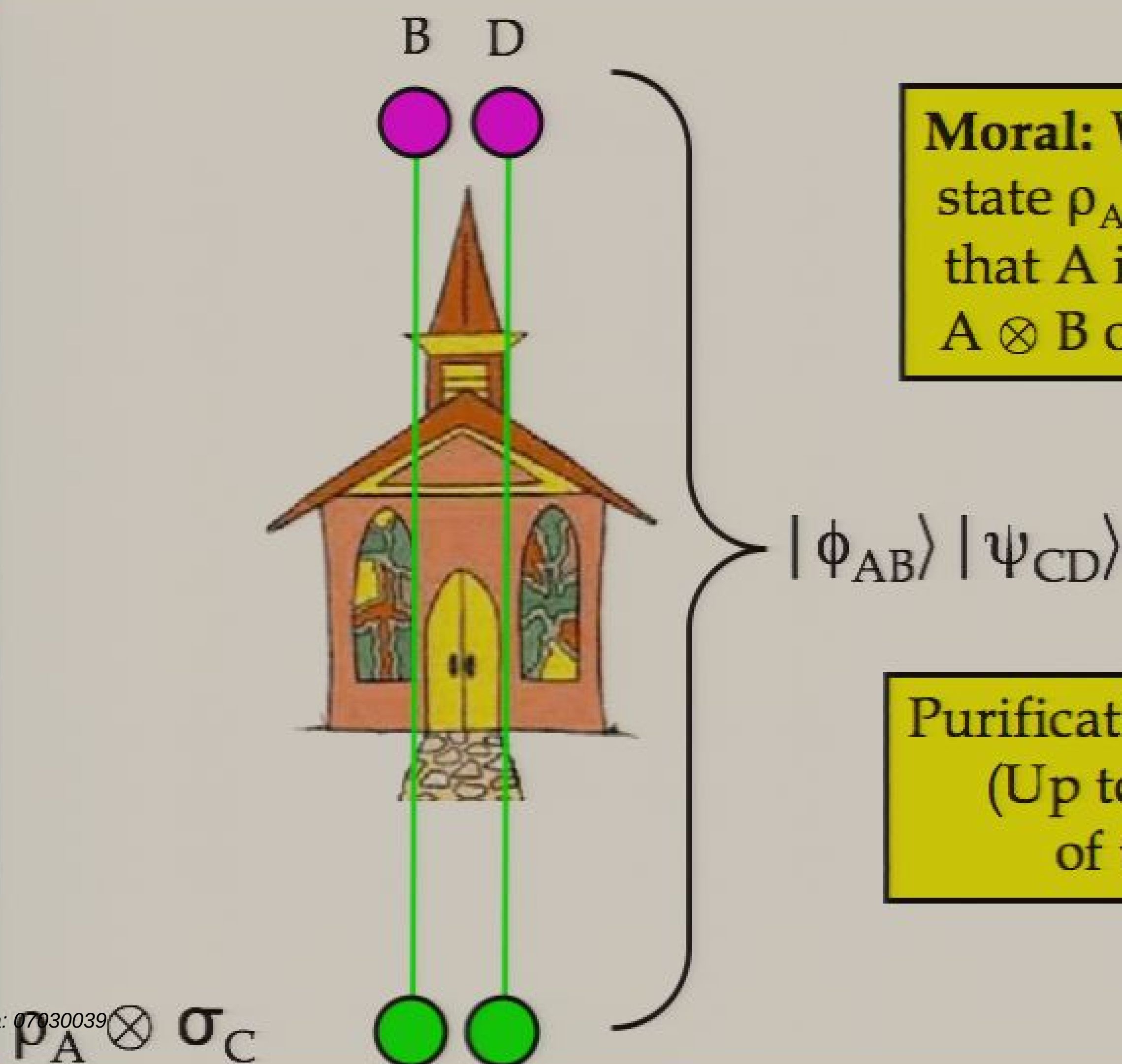

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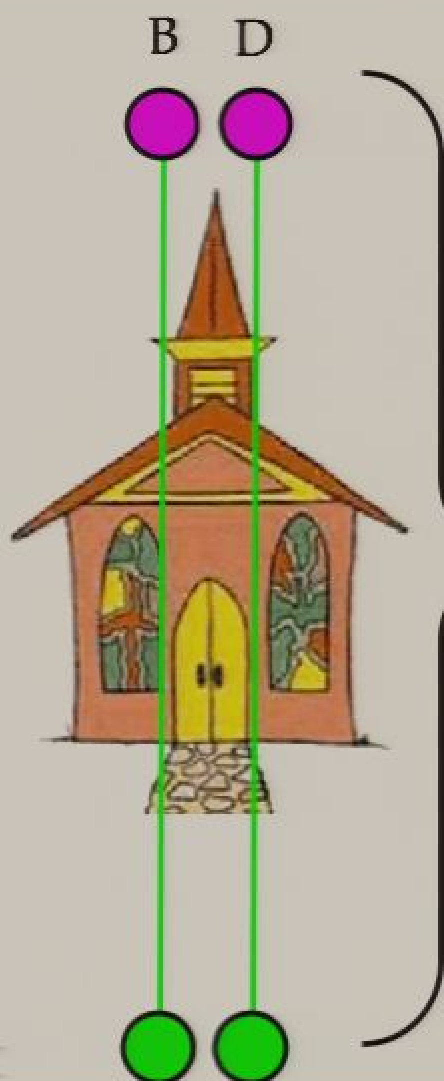

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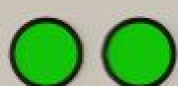

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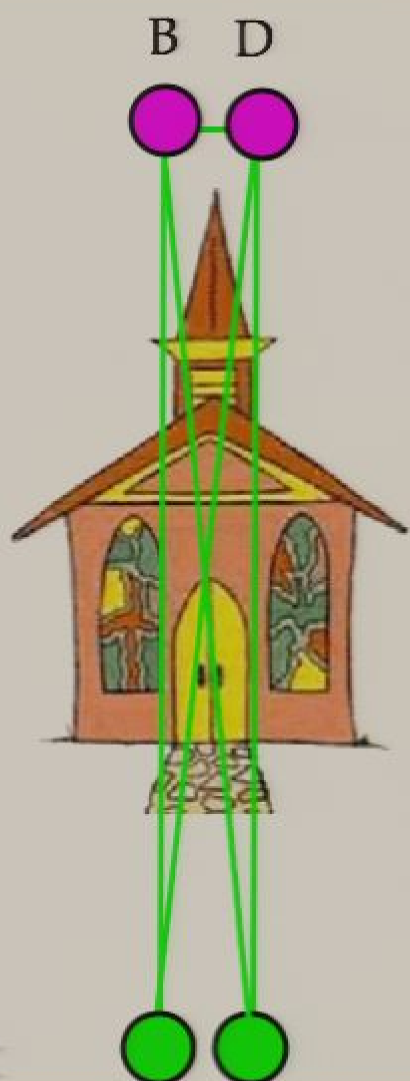

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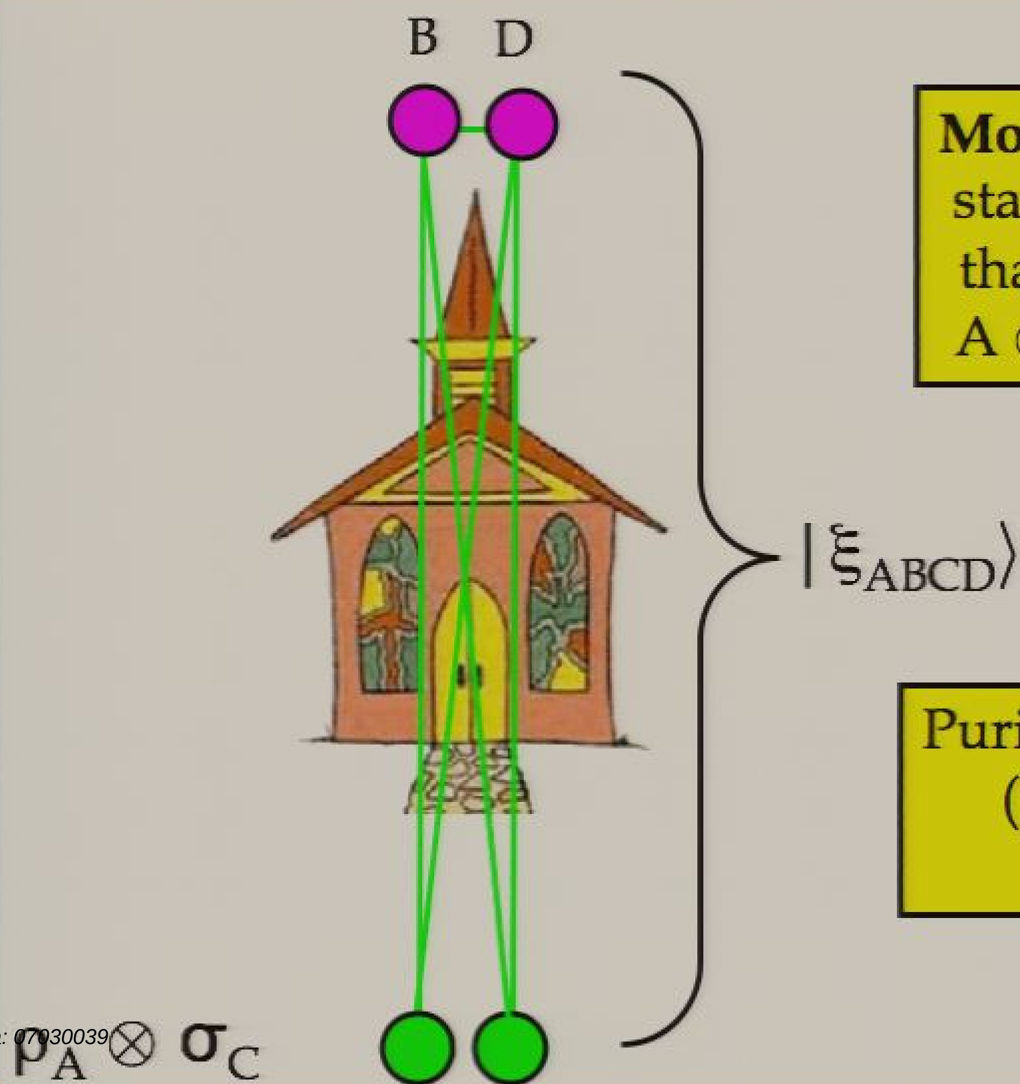

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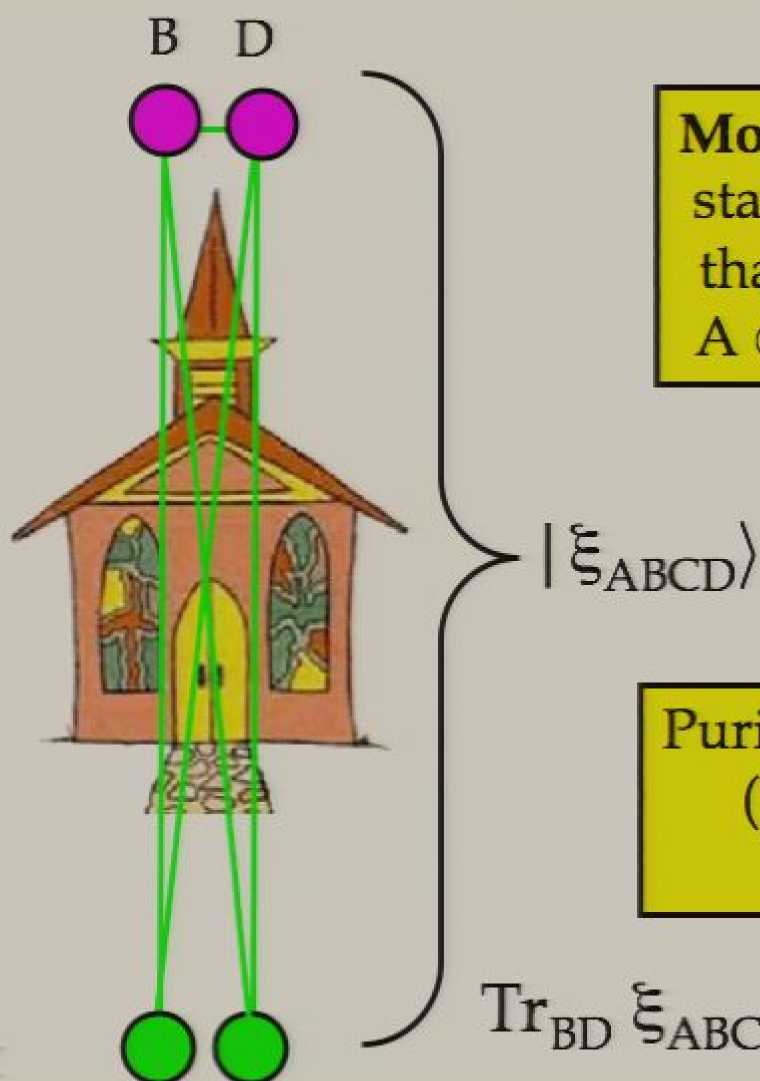

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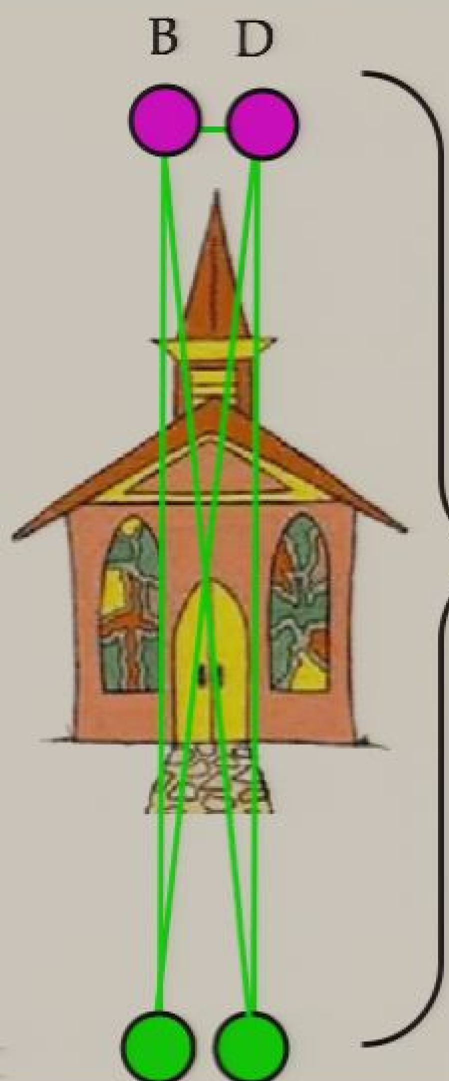

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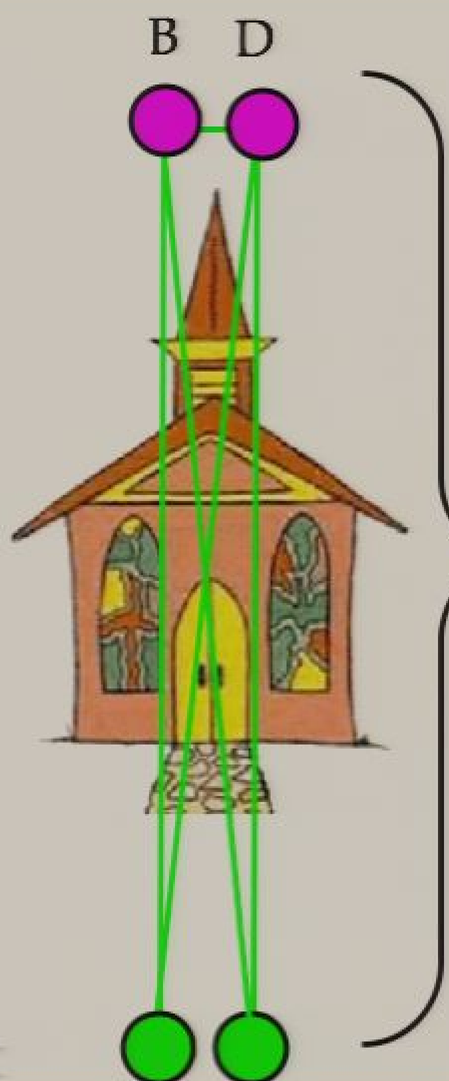

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$$|\xi_{ABCD}\rangle = (id_{AC} \otimes U_{BD})\,|\phi_{AB}\rangle\,|\psi_{CD}\rangle$$

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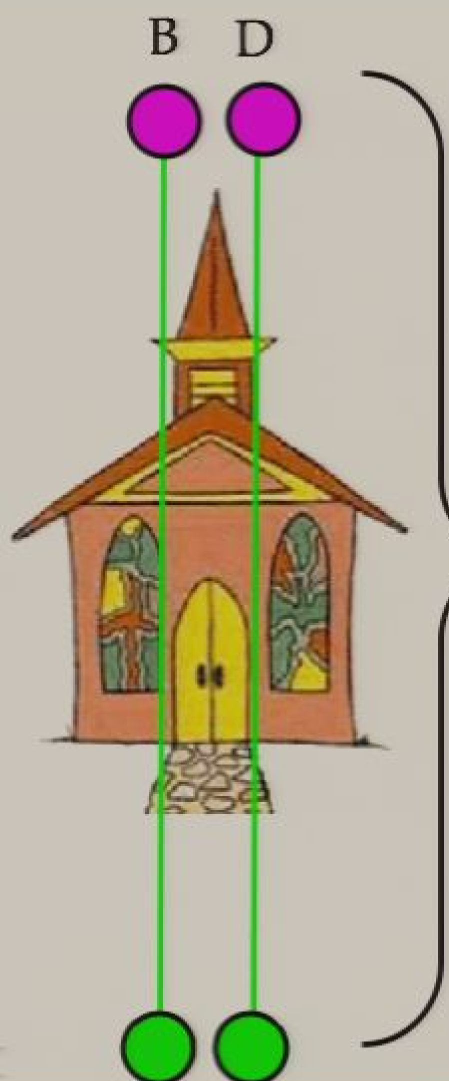

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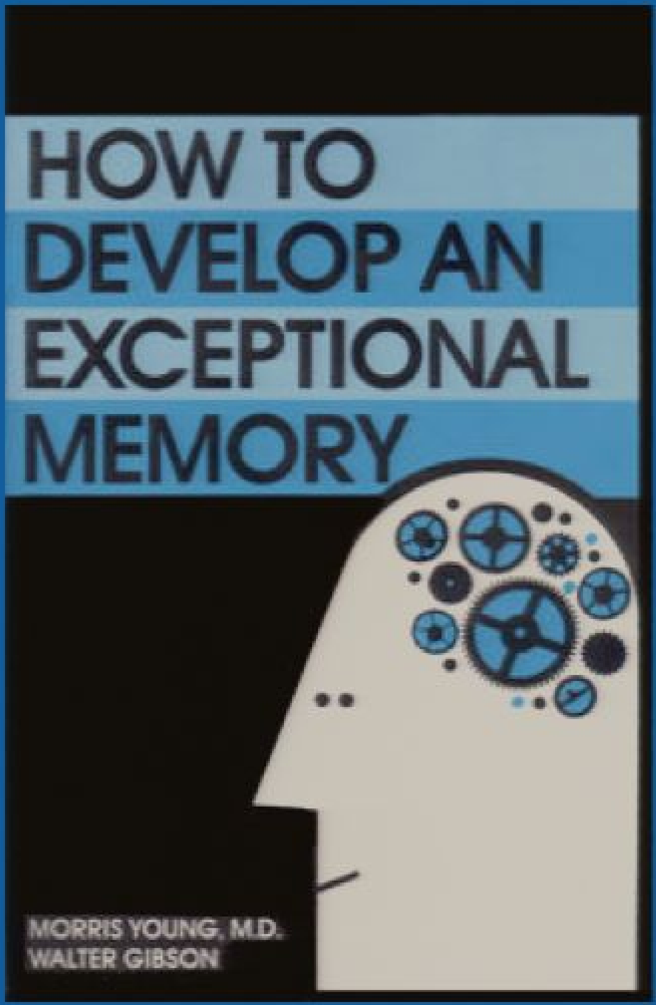

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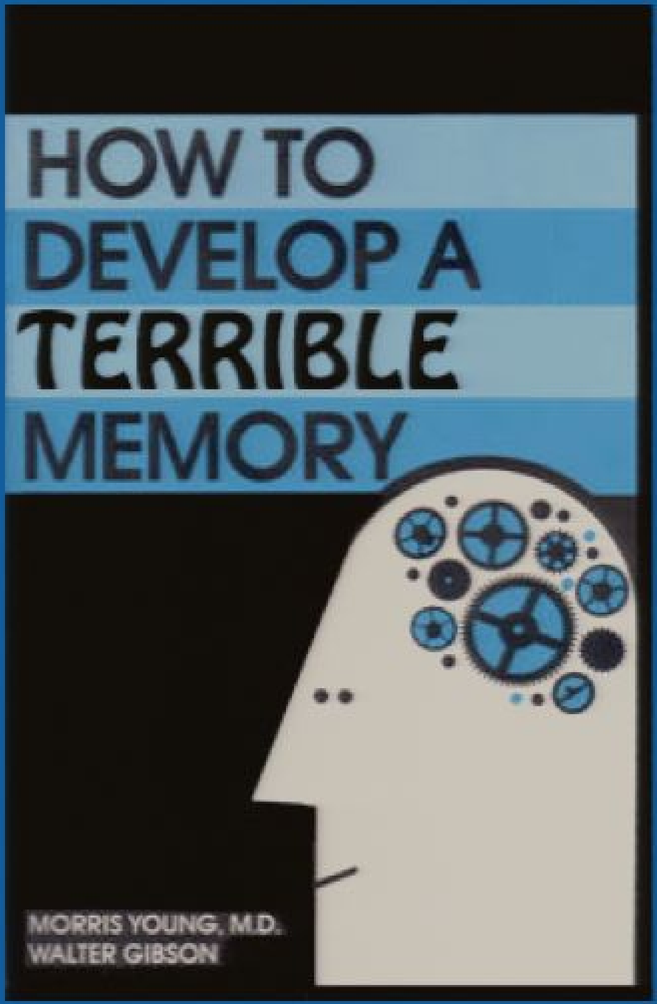

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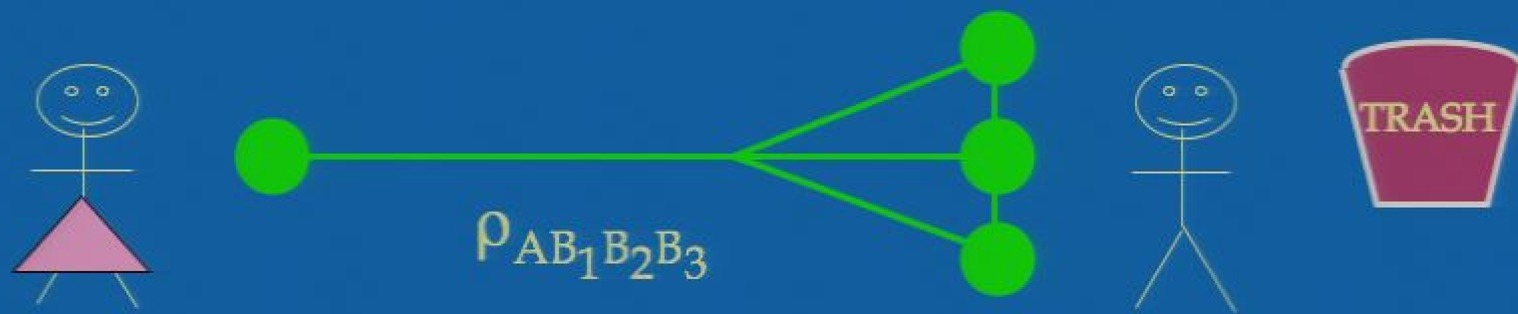

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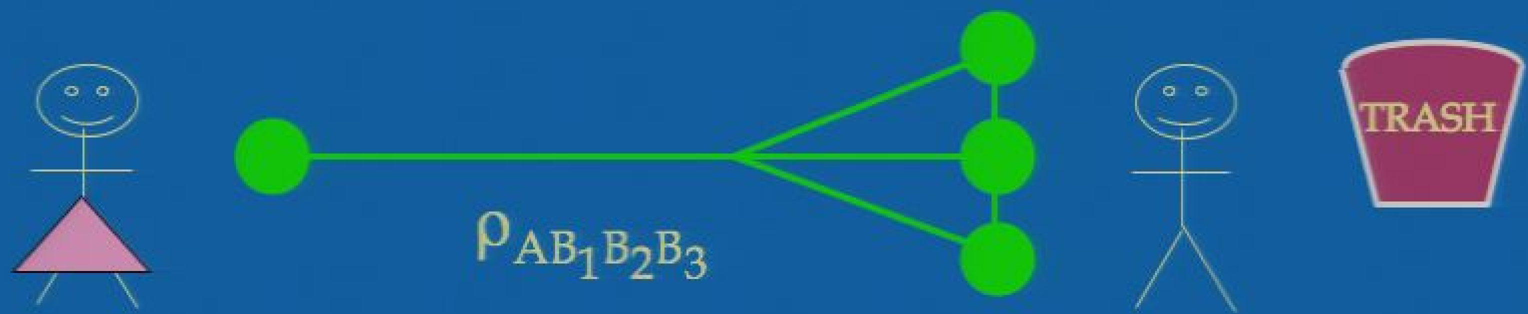
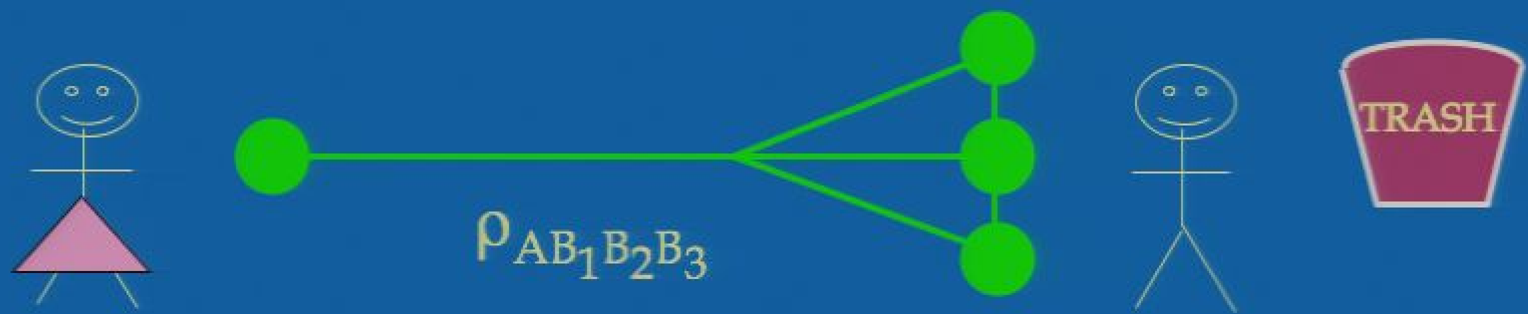


How can Bob unilaterally destroy his correlation with Alice?

The art of forgetting



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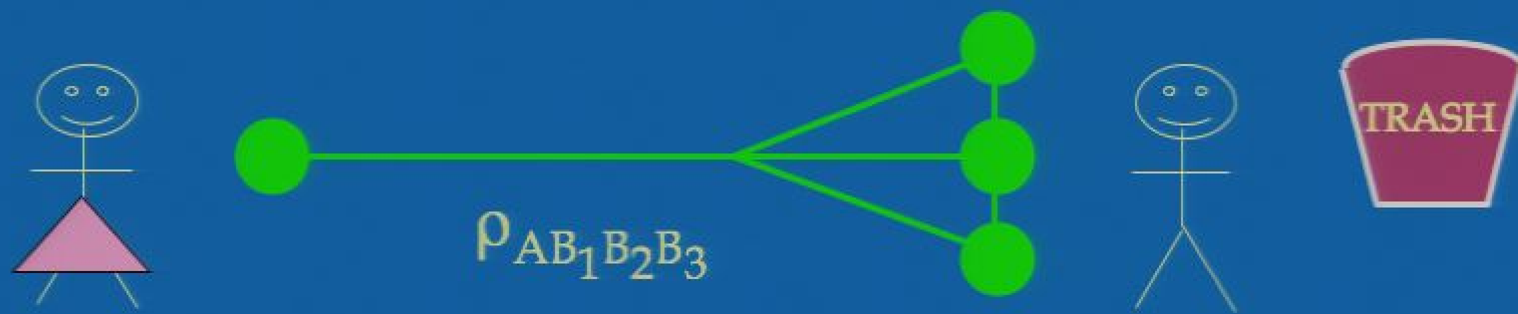
What is the minimal number of particles he must discard before the remaining state is uncorrelated?

The art of forgetting



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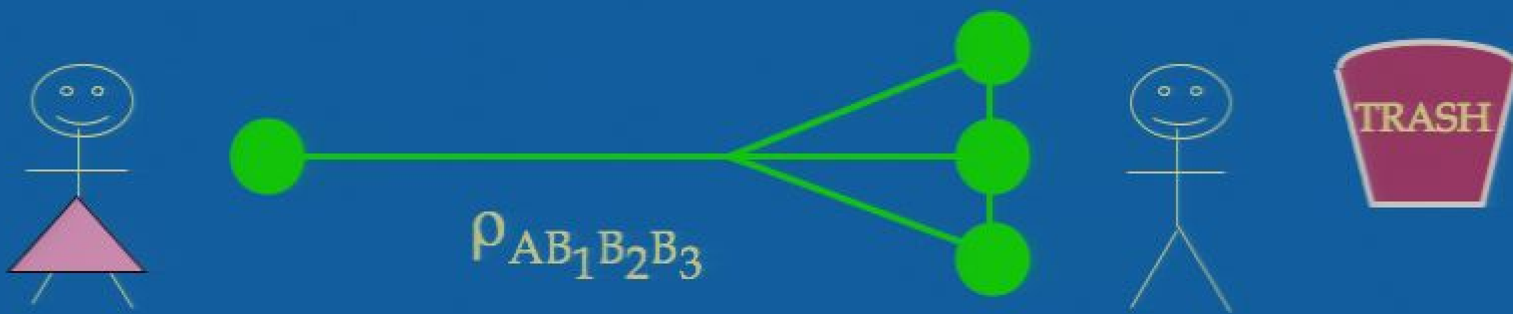

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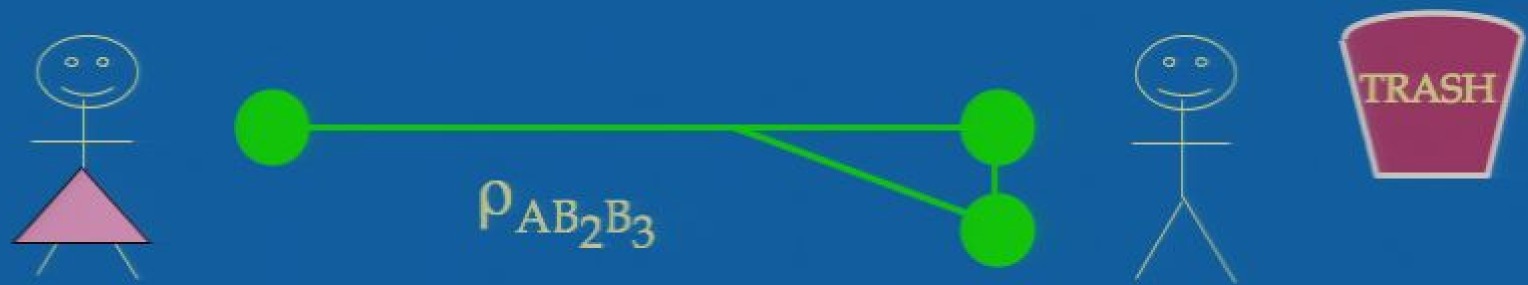

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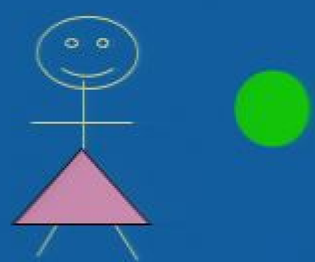
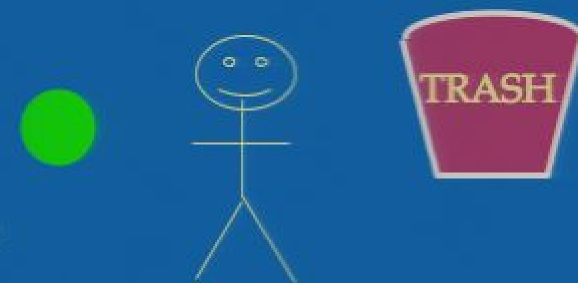


$$\rho_{AB_2} = \rho_A \otimes \rho_{B_2}$$



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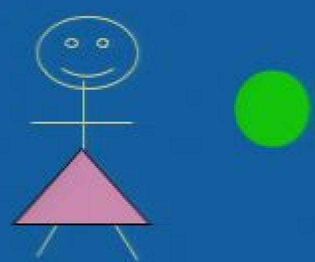

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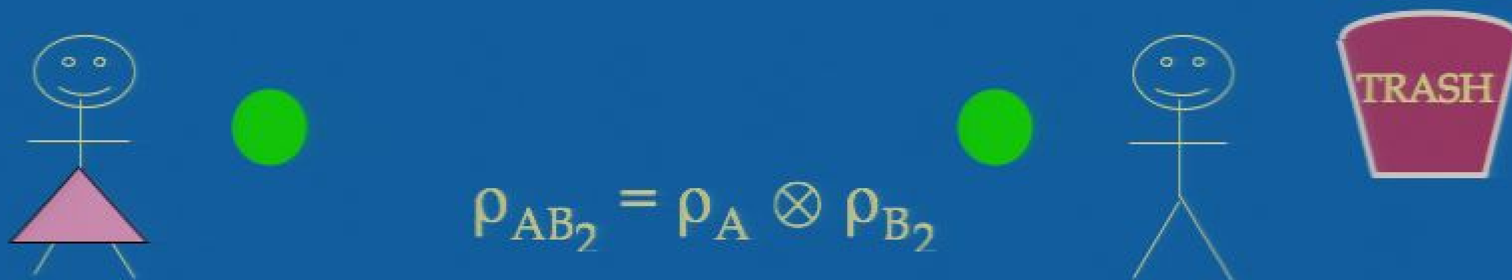


$$\rho_{AB_2} = \rho_A \otimes \rho_{B_2}$$

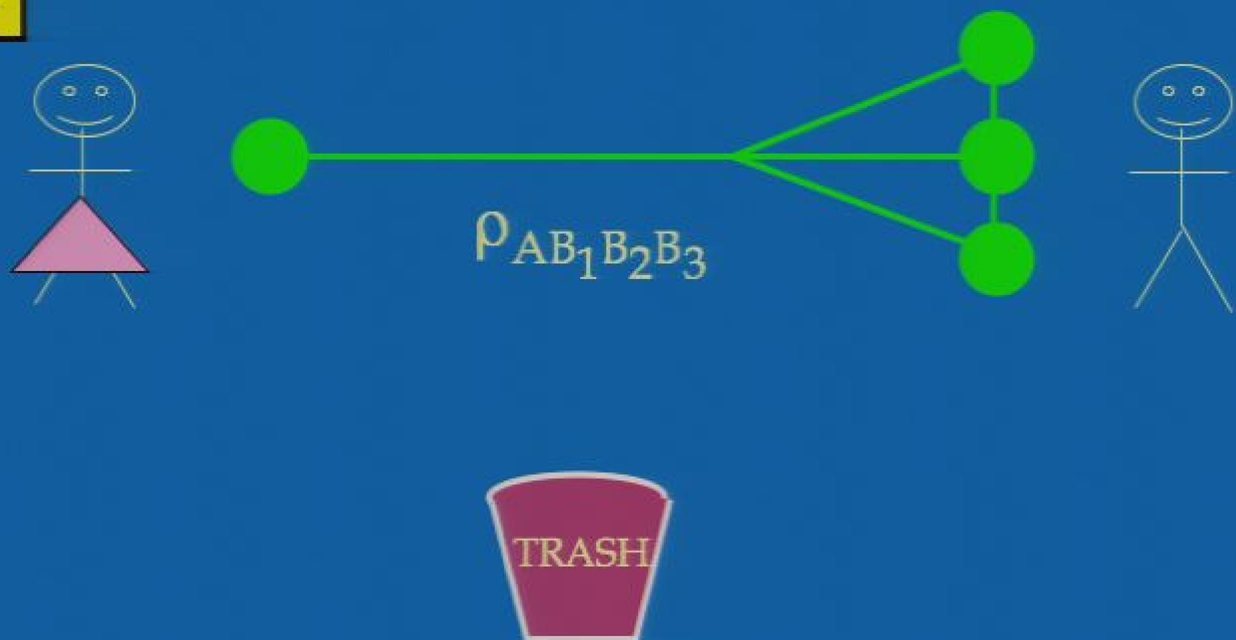
How can Bob unilaterally destroy his correlation with Alice?

What is the minimal number of particles he must discard before the remaining state is uncorrelated?

In this case, by discarding 2 particles, Bob succeeded in eliminating all correlations with Alice's particle

The benefits of forgetting: Applied theology

Watch again:



The benefits of forgetting: Applied theology

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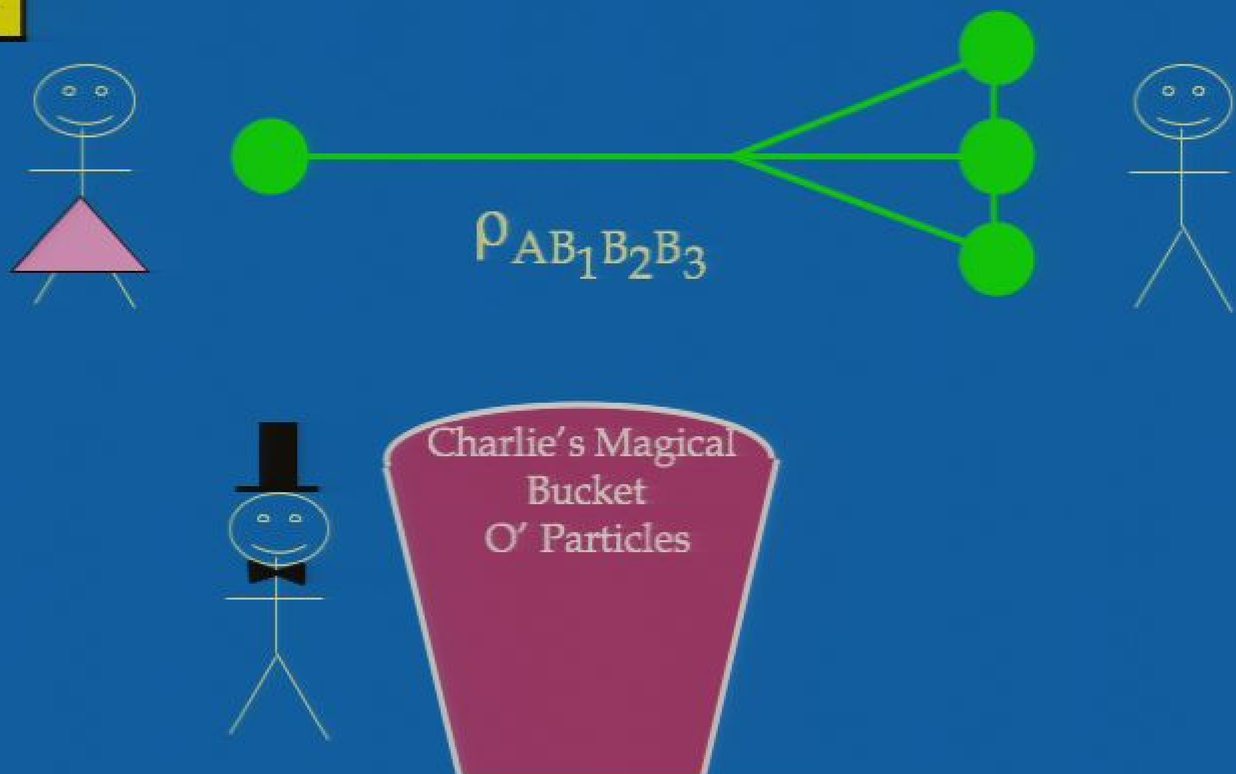

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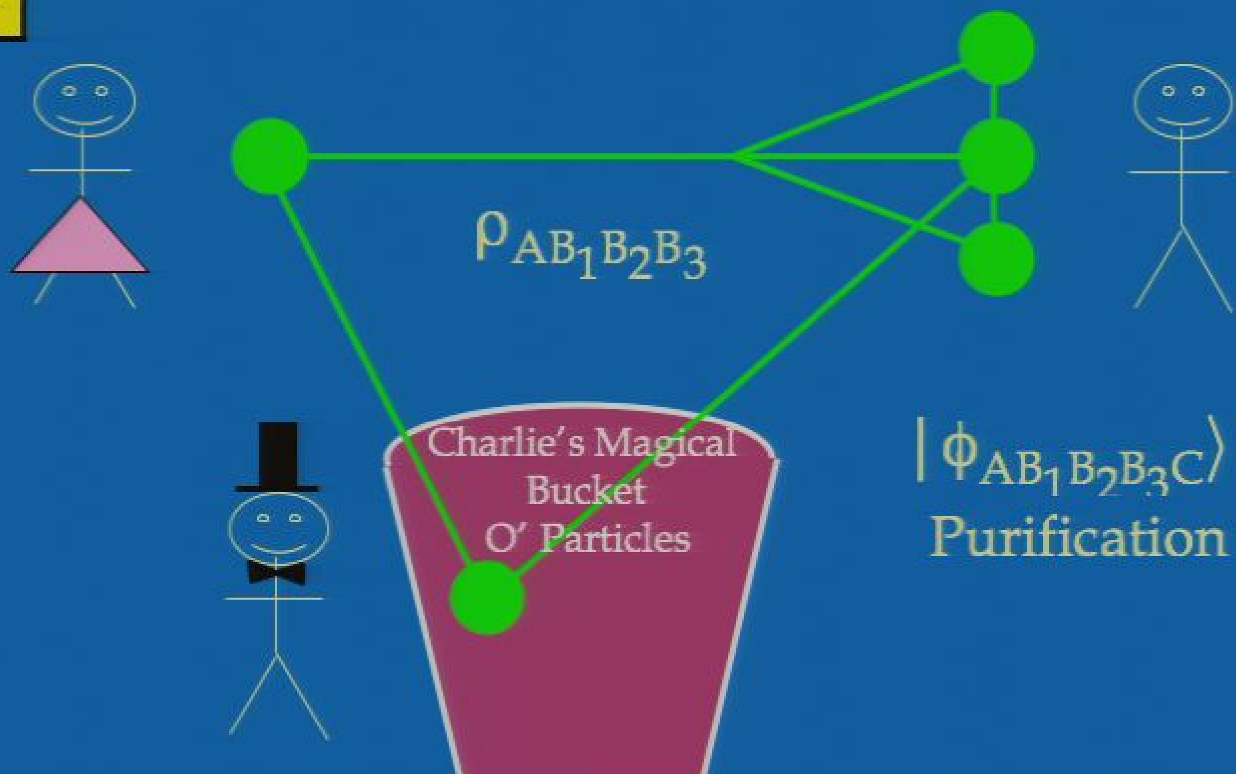

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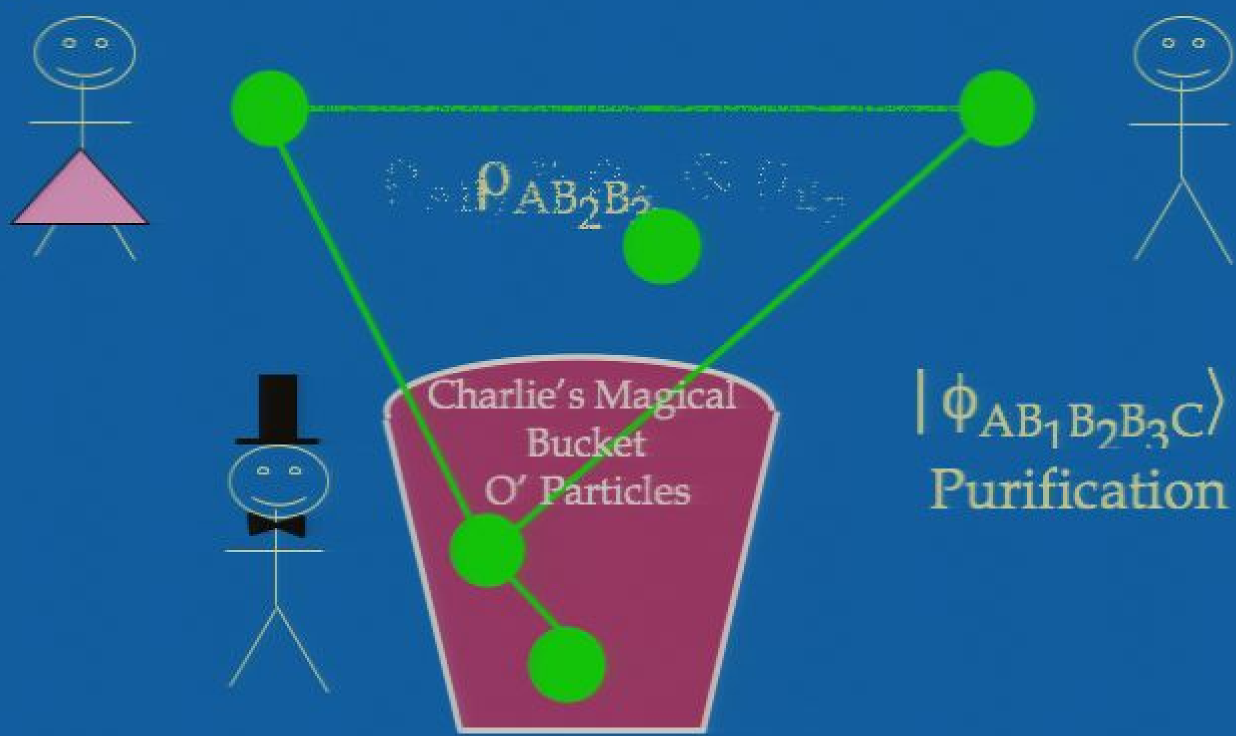

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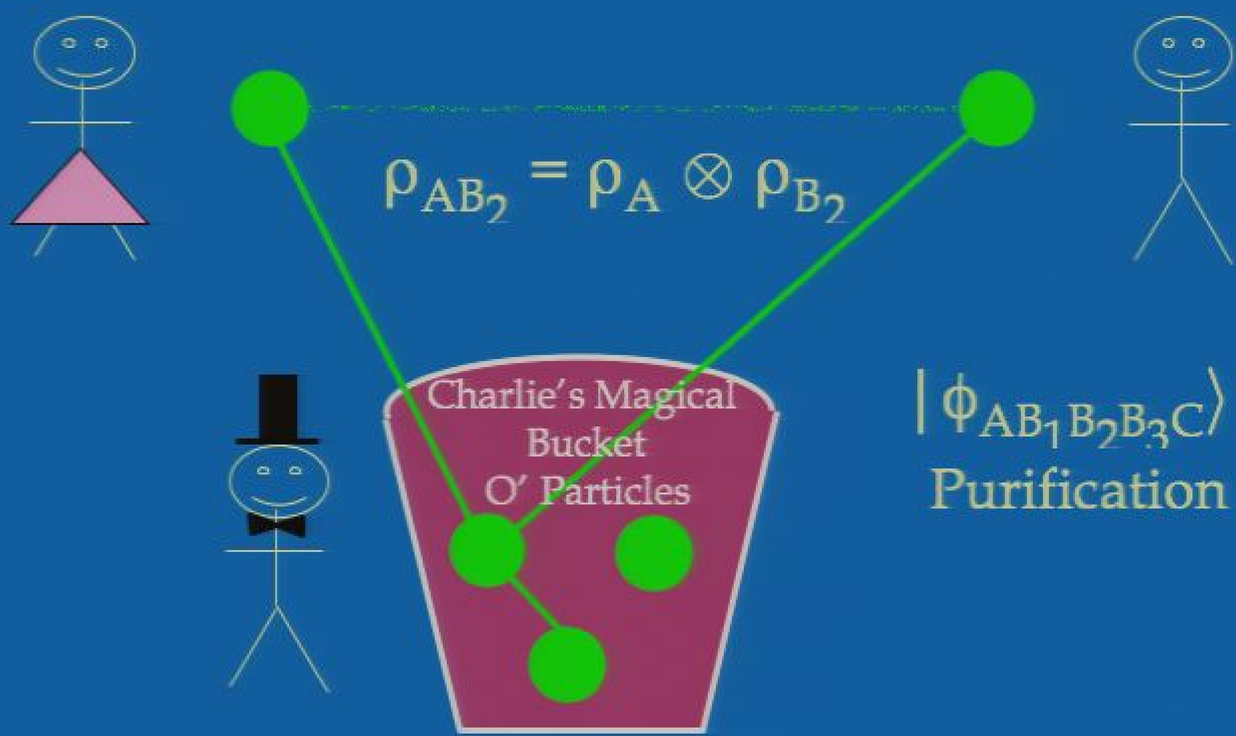

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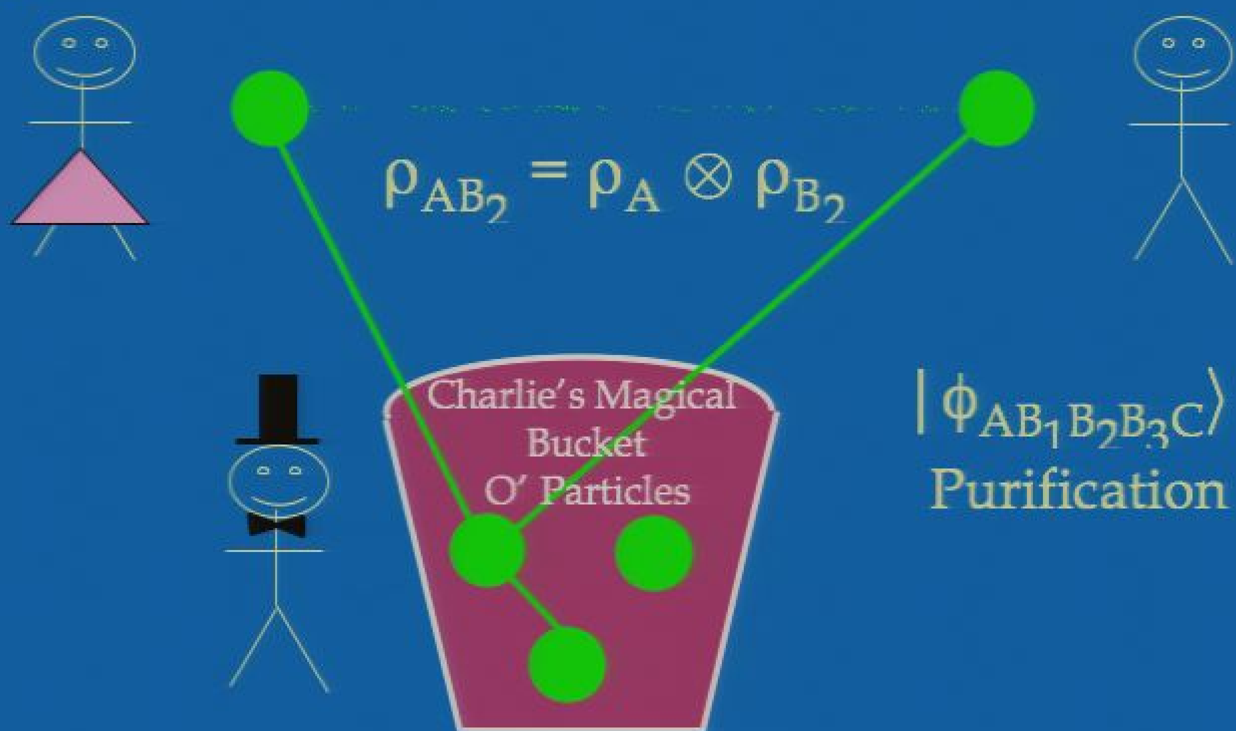
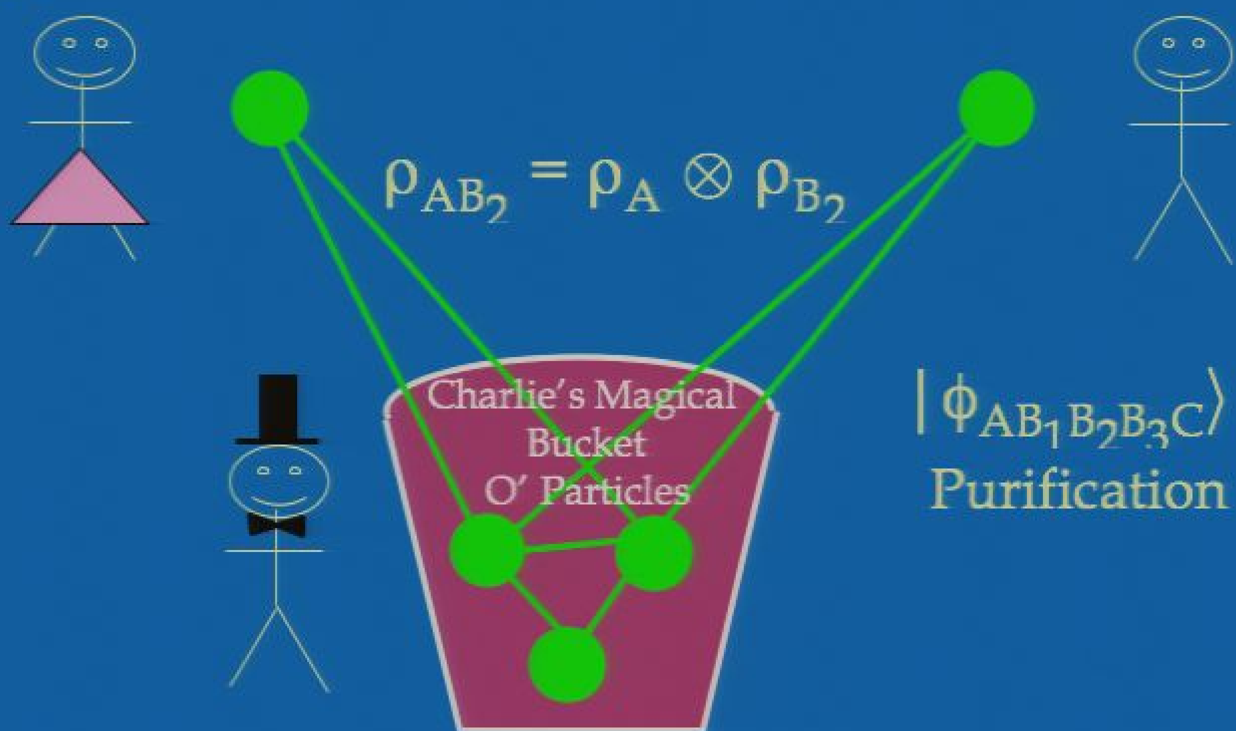


$|\phi_{AB_1B_2B_3C}\rangle$

Purification

The benefits of forgetting: Applied theology

Watch again:



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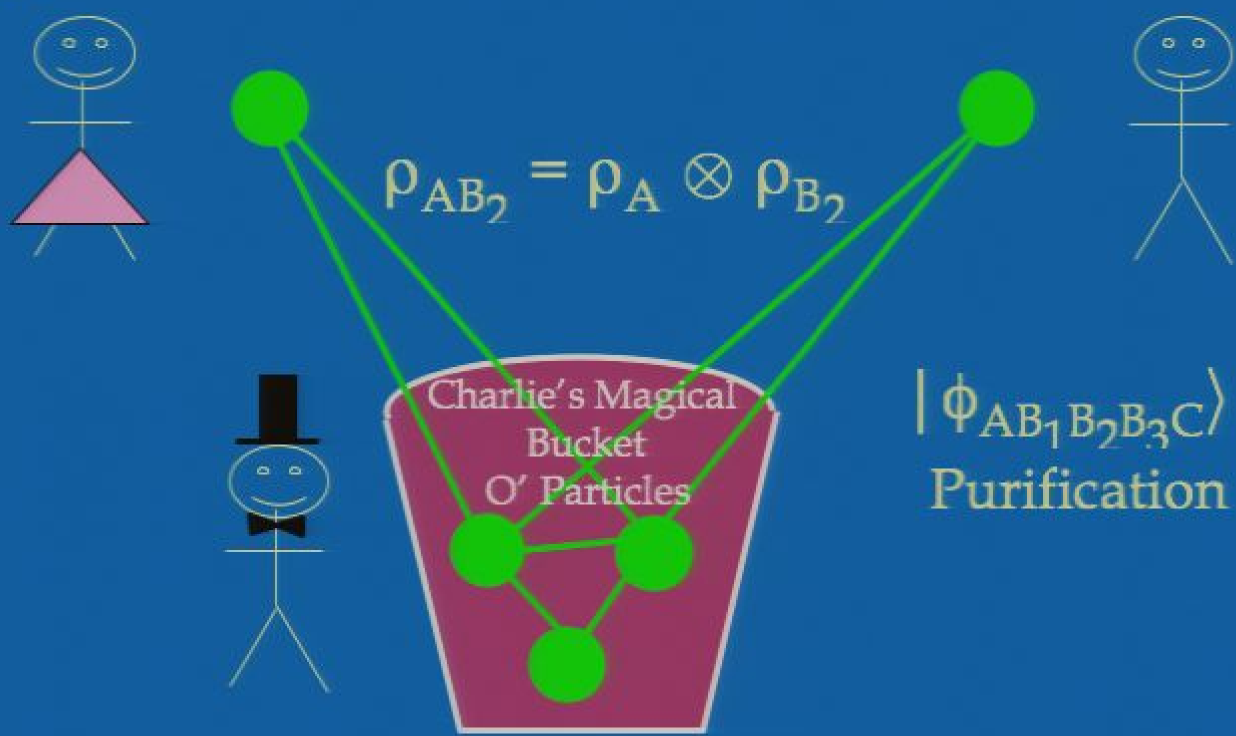

All purifications equivalent up to a local transformation in Charlie's lab.

The benefits of forgetting: Applied theology

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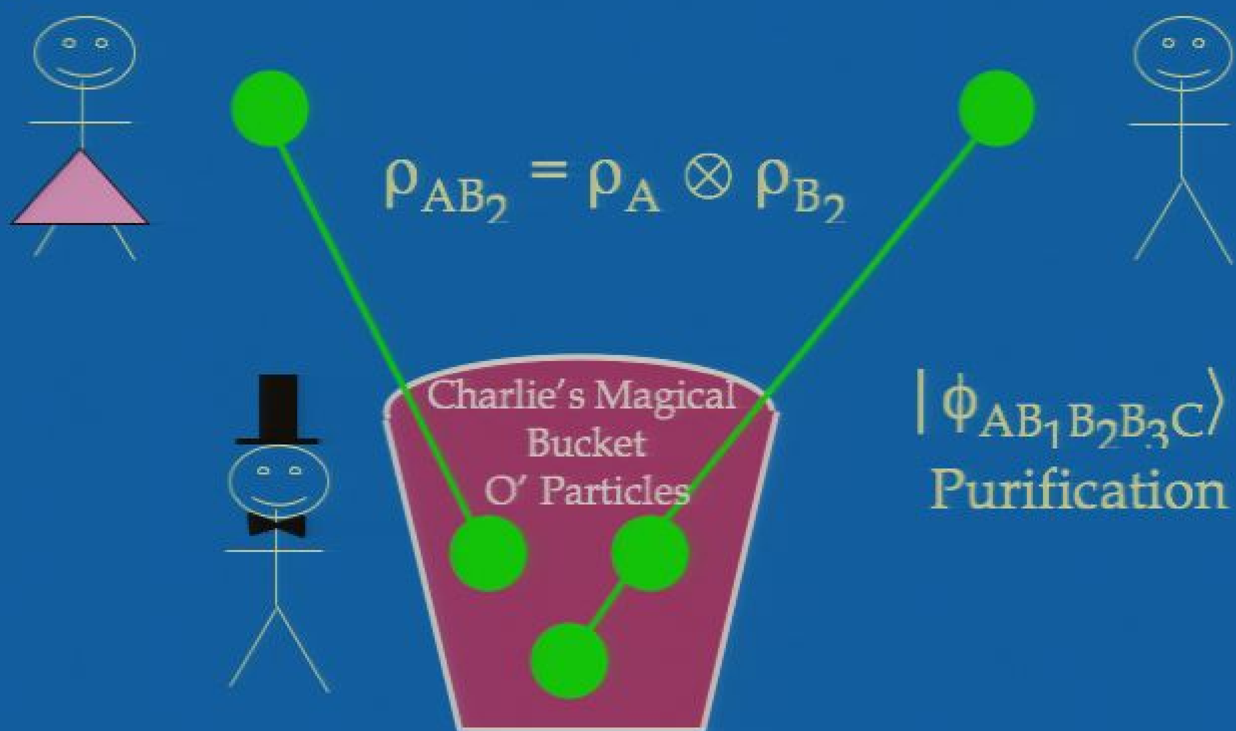

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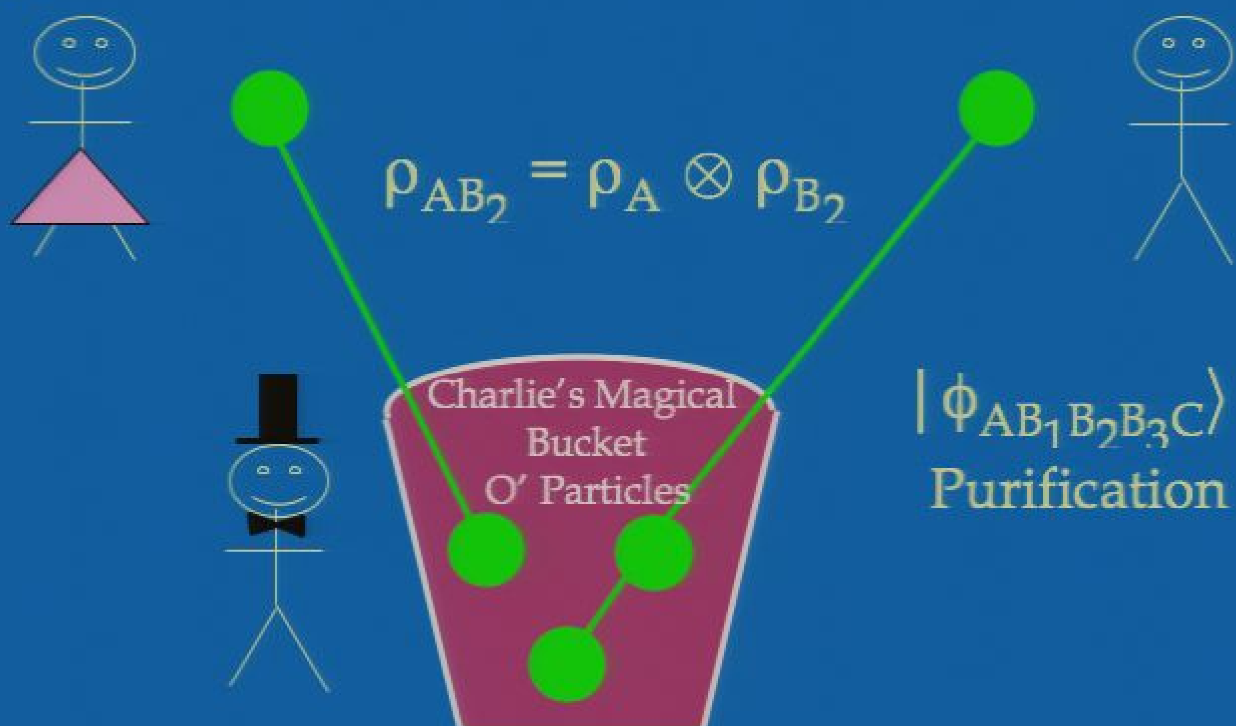
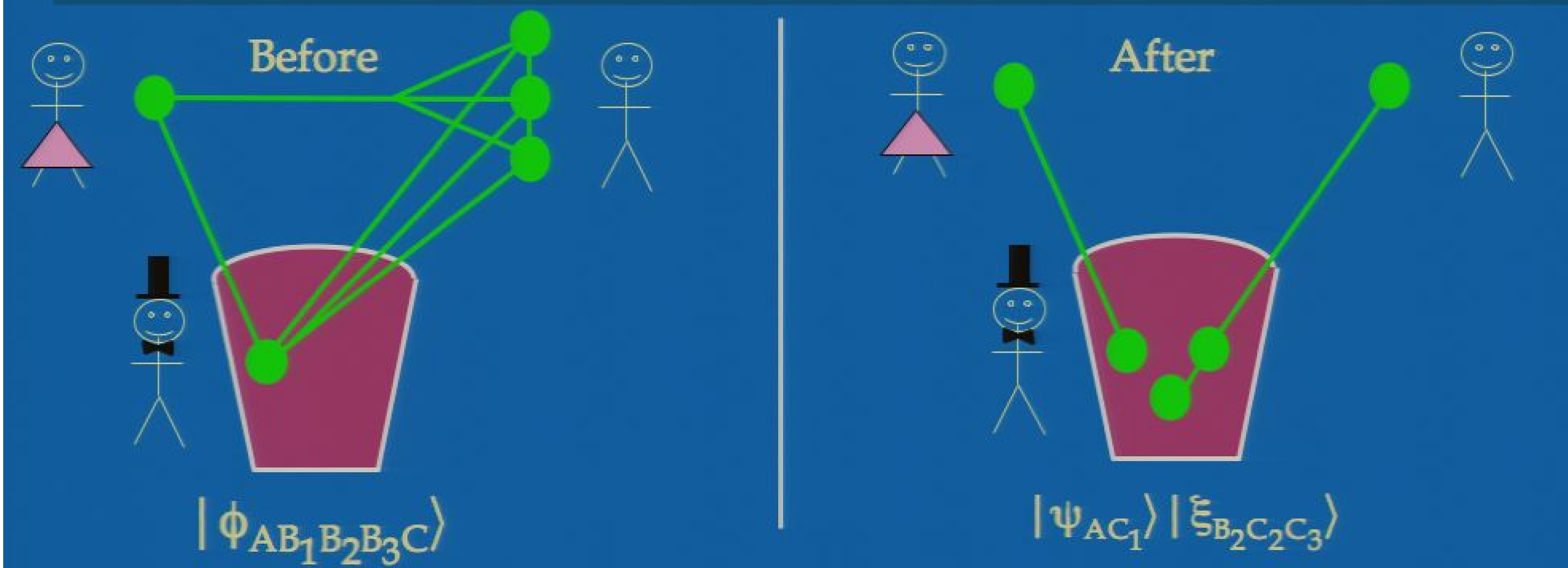


All purifications equivalent up to a local transformation in Charlie's lab.

Charlie holds **uncorrelated** purifications of **both** Alice's particle and Bob's remaining particles.

The benefits of forgetting: Applied theology



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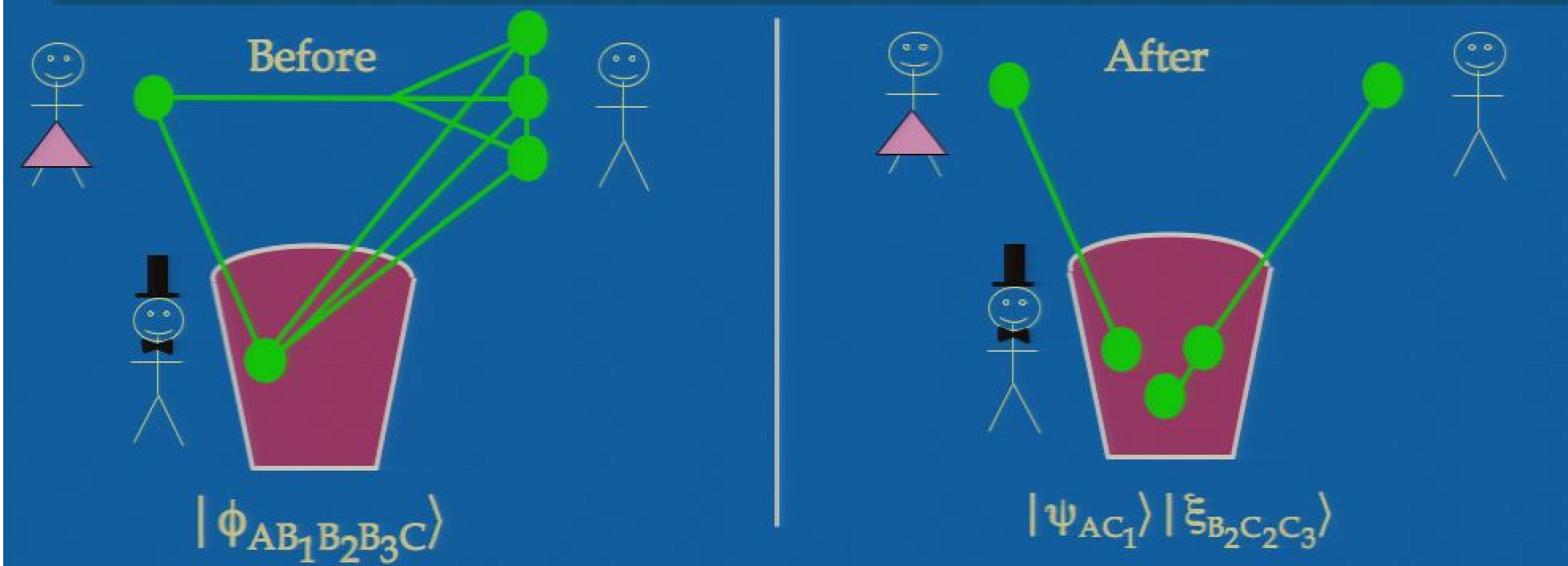
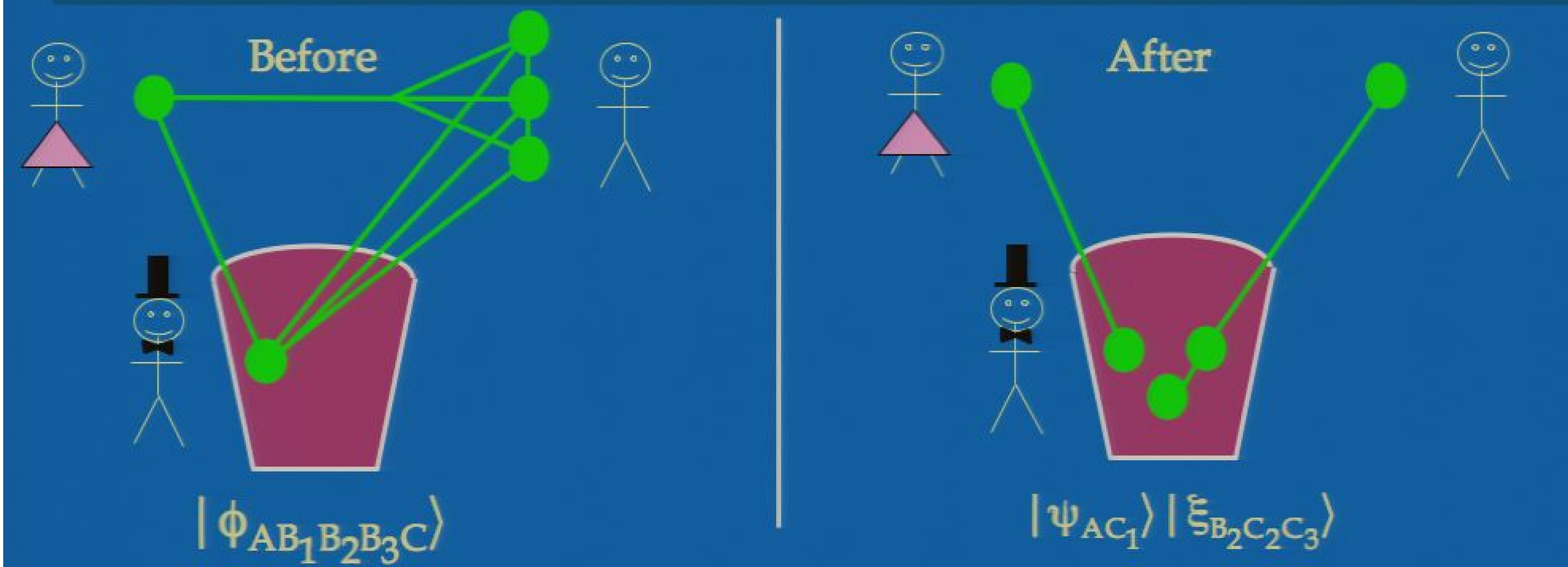


Alice never did anything ⇒ Her marginal state $\phi_A = \psi_A$ is unchanged

The benefits of forgetting: Applied theology



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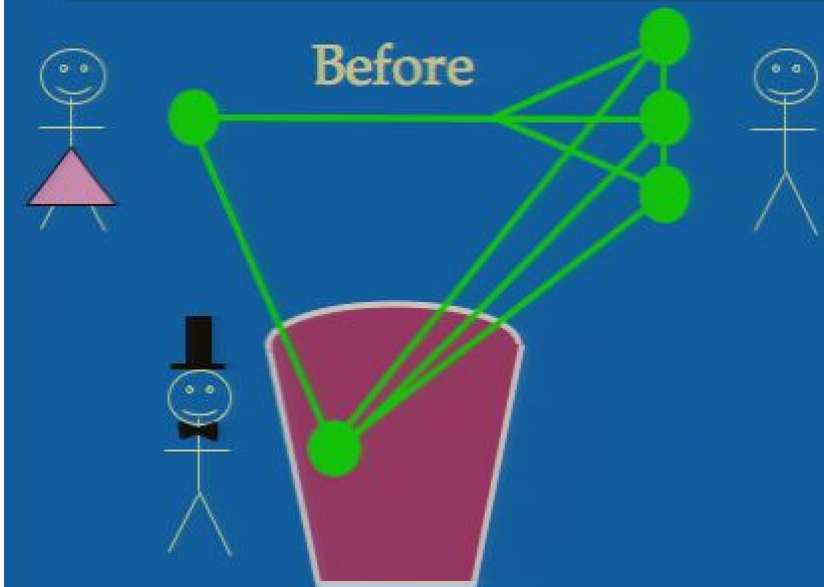
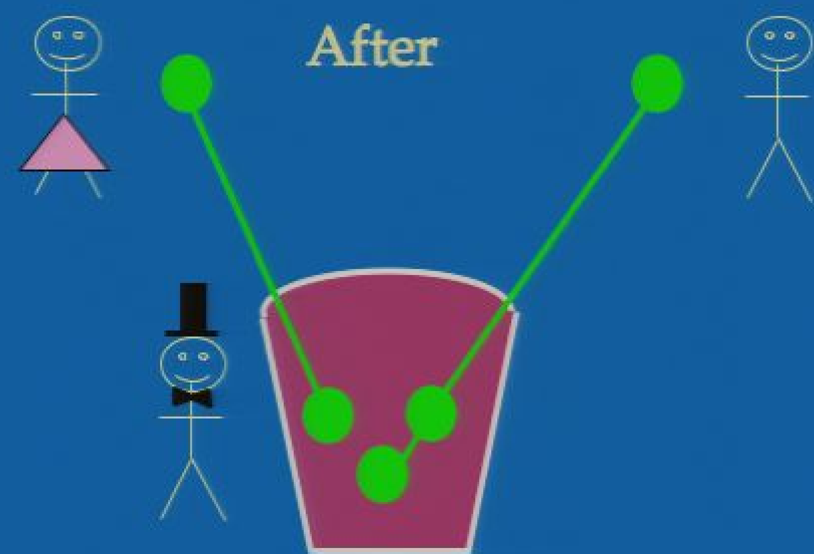
Originally, her purification is held by both Bob and Charlie.
Afterwards, entirely by Charlie.

The benefits of forgetting: Applied theology



$|\phi_{AB_1B_2B_3C}\rangle$



$|\psi_{AC_1}\rangle|\xi_{B_2C_2C_3}\rangle$

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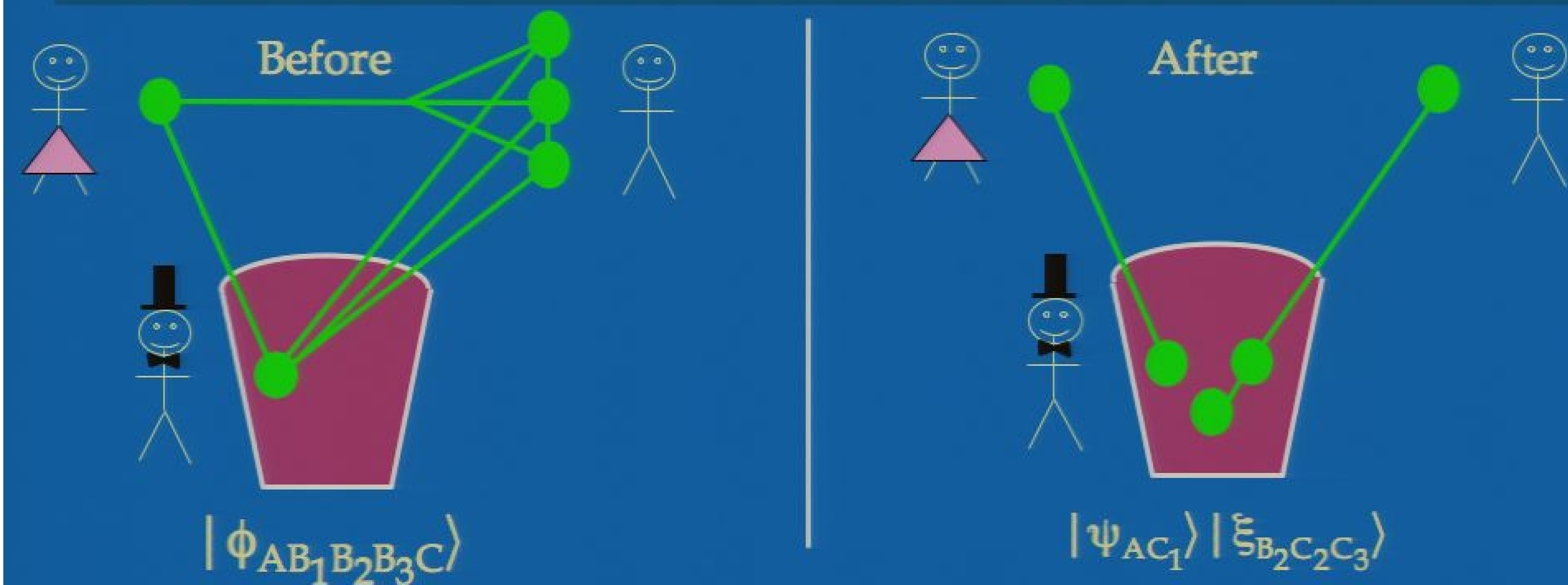
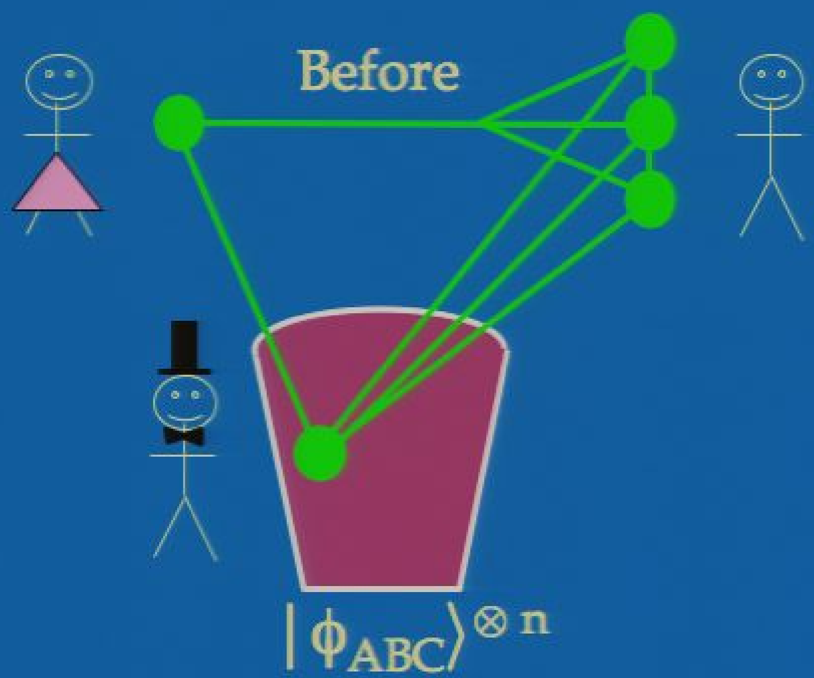


Alice never did anything $\Rightarrow$ Her marginal state $\phi_A = \psi_A$ is unchanged

Originally, her purification is held by both Bob and Charlie.
Afterwards, entirely by Charlie.

Bob **transferred** his Alice entanglement to Charlie
and **distilled** entanglement with Charlie, just by discarding particles!

Time for some formulas: How much does Bob need to send?



Uncertainty: von Neumann entropy

$$H(A)_\rho = H(\rho_A) = -\,\mathrm{tr}[\,\rho_A \log \rho_A\,]$$

Correlation: mutual information

$$I(A;B)_\rho = H(A)_\rho + H(B)_\rho - H(AB)_\rho$$

$$I(A;B)_\rho = \begin{cases} 0 \text{ if and only if } \rho_{AB} = \rho_A \otimes \rho_B \\ m \text{ for } m \text{ pairs of correlated bits} \\ 2m \text{ for } m \text{ ebits (maximal)} \end{cases}$$

$$\frac{1}{\sqrt{2}}\left(|0\rangle^A|0\rangle^B+|1\rangle^A|1\rangle^B\right)$$

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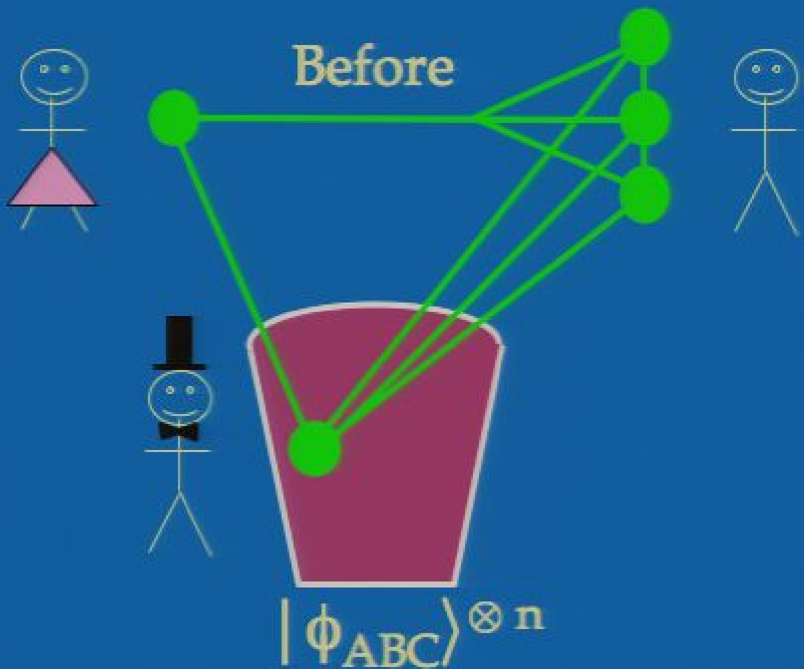

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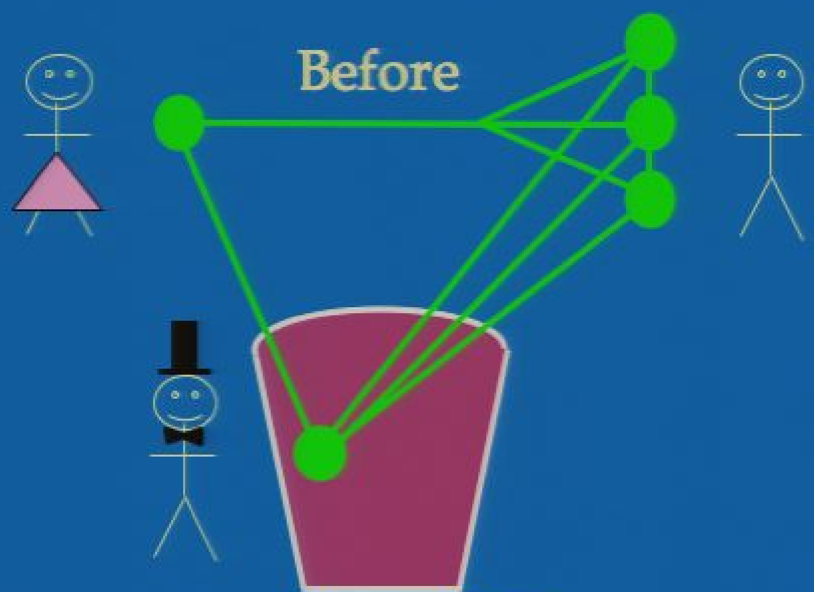

$|\phi_{ABC}\rangle^{\otimes n}$

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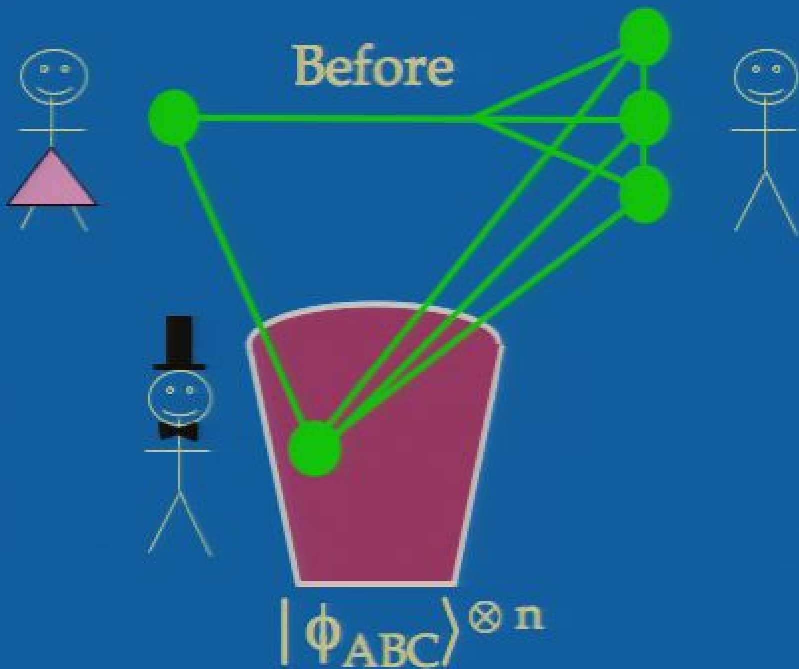

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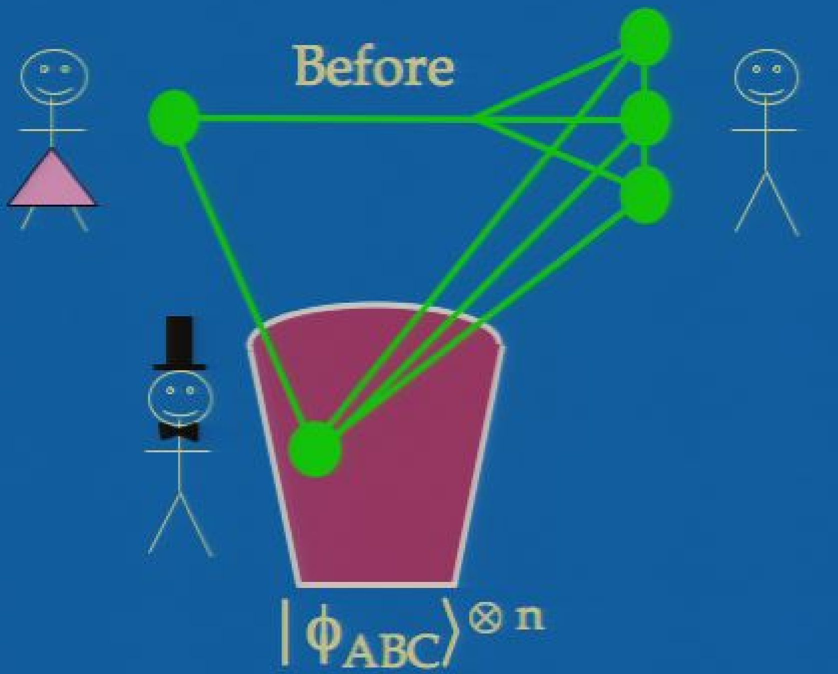

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Each qubit Bob discards has the potential to eliminate at most 2 bits of correlation

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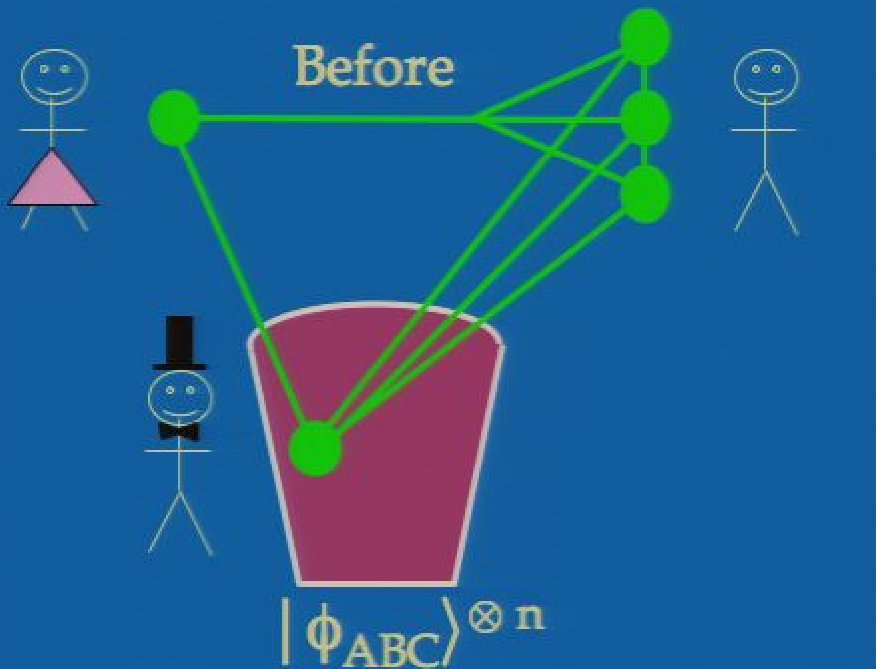

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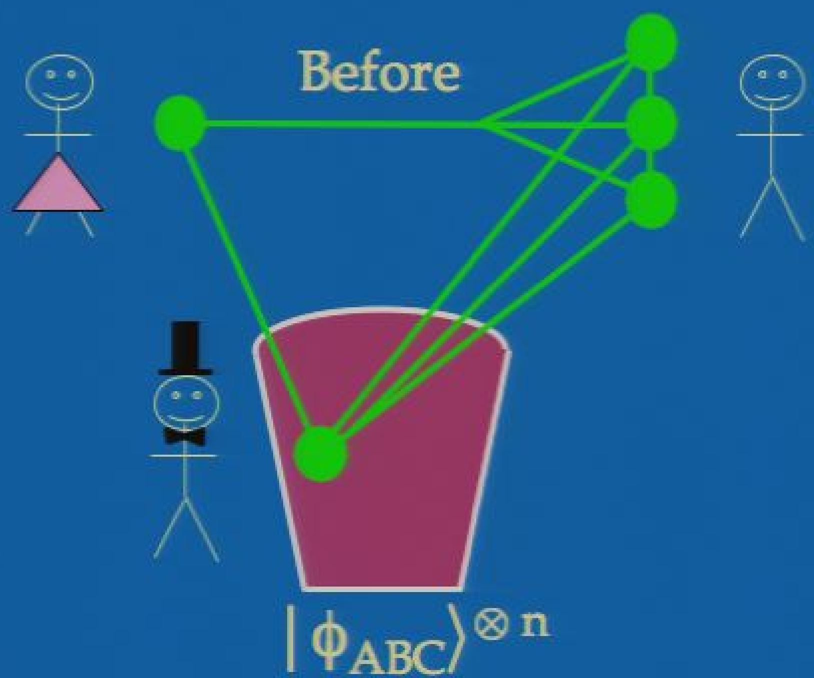
Each qubit Bob discards has the potential to eliminate at most 2 bits of correlation

Bob should (ideally) send around $nI(A;B)_\phi/2$ qubits to Charlie

How does Bob choose *which* qubits?



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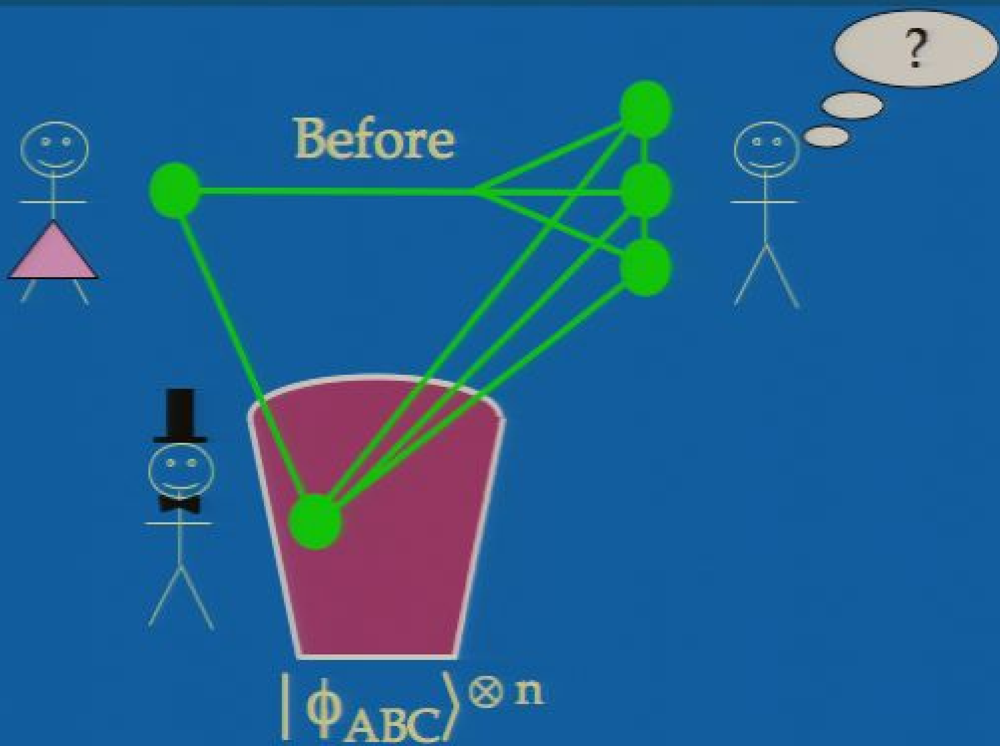

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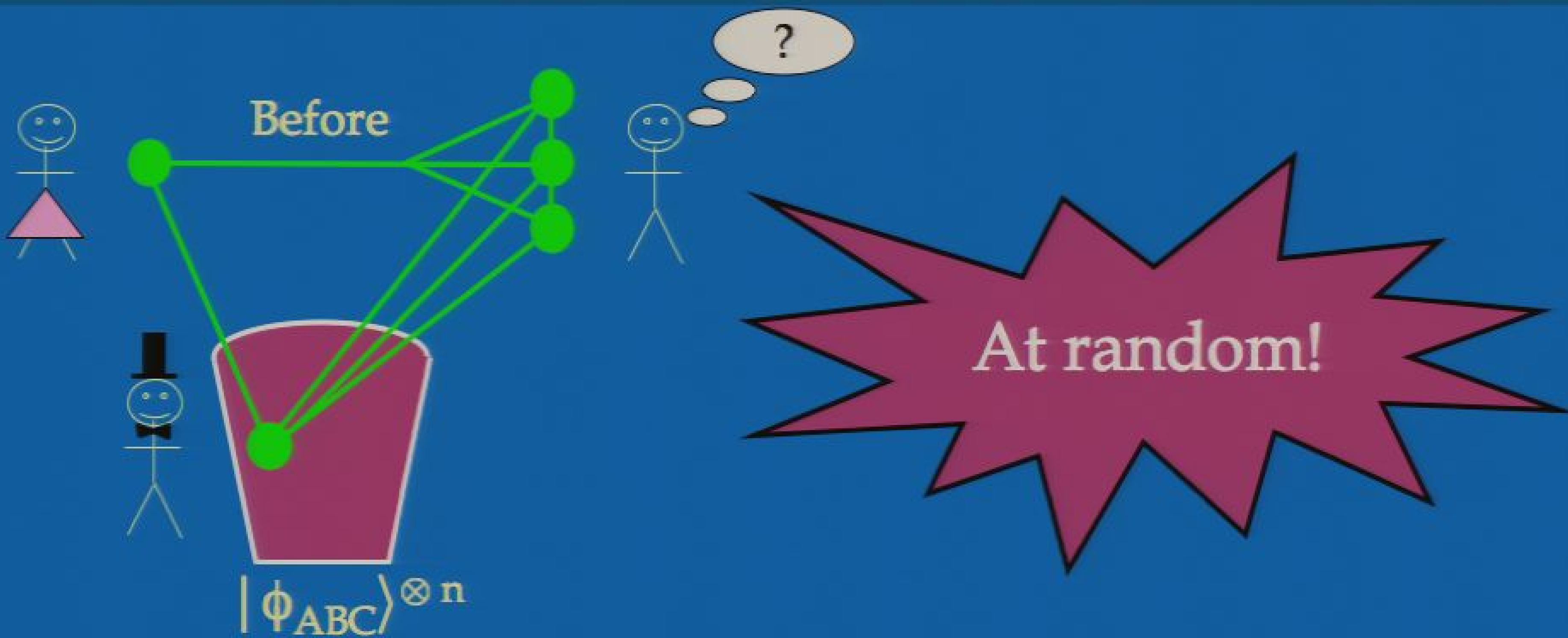

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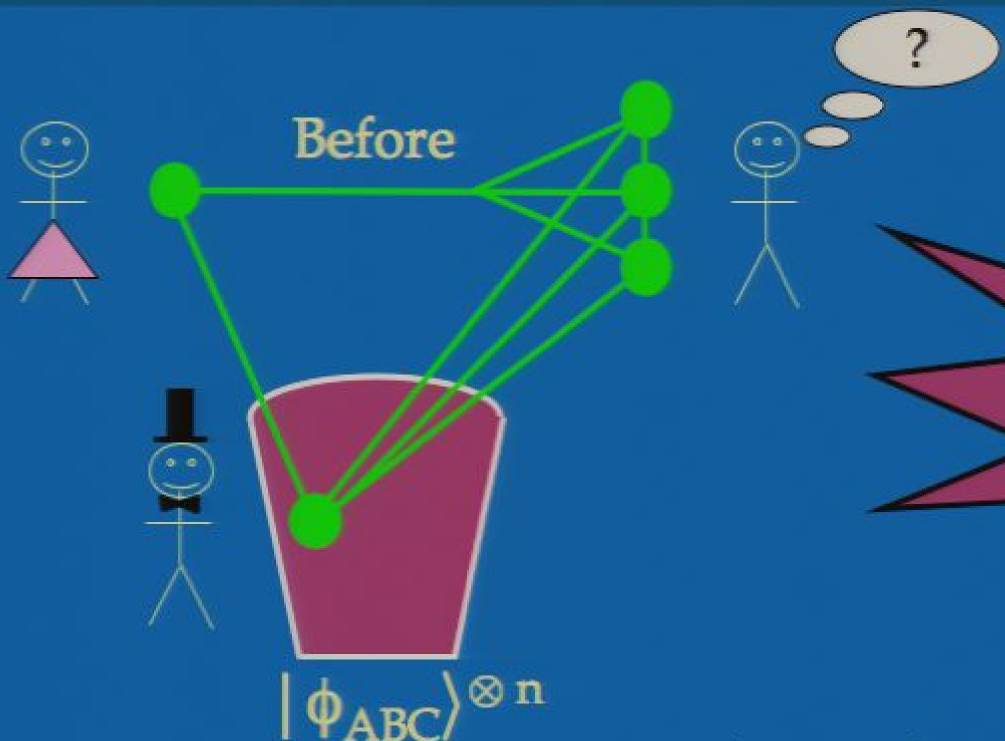

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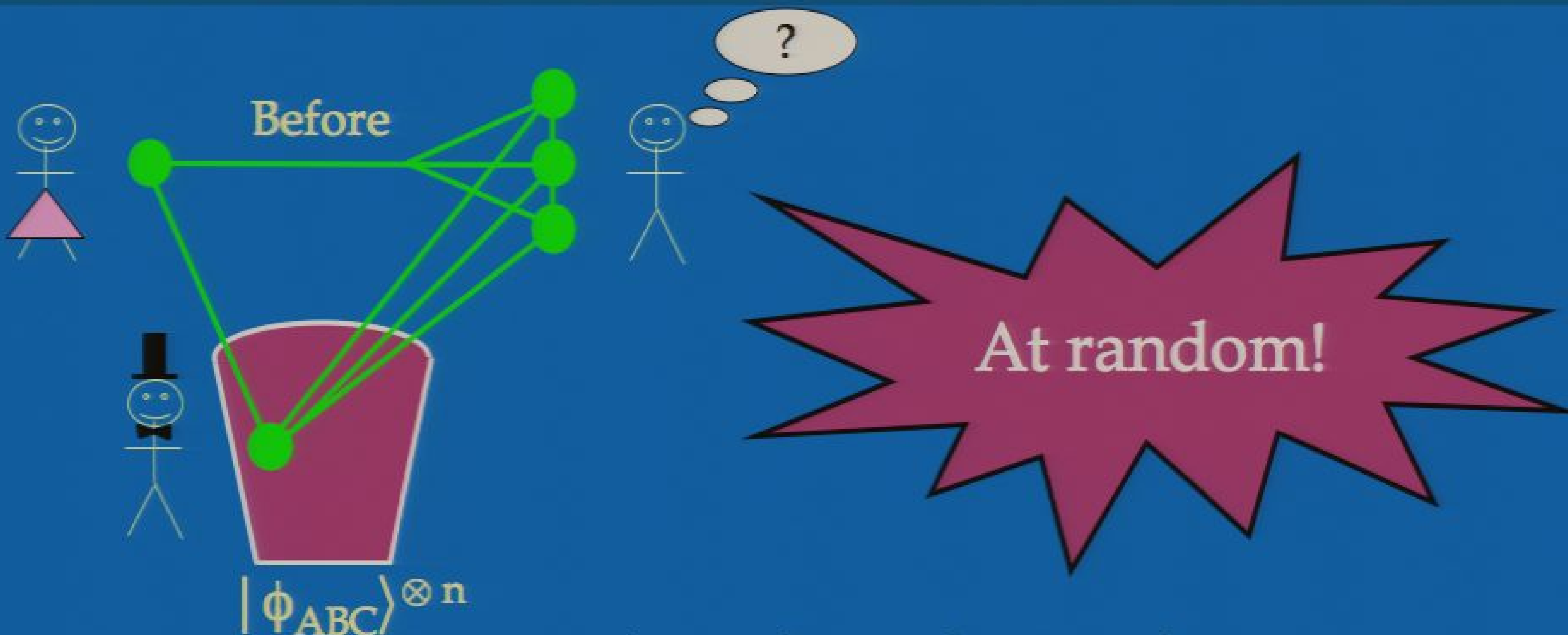


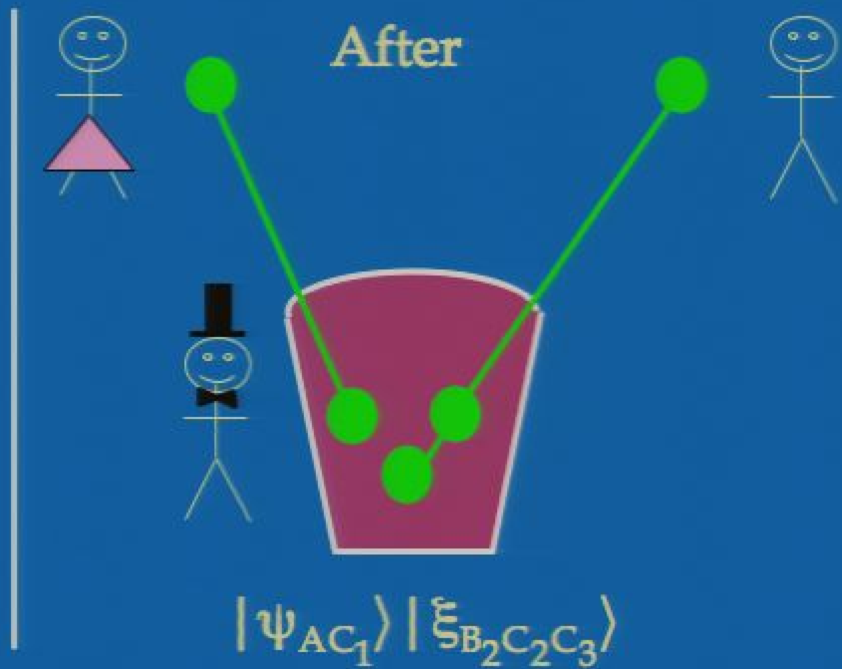
(According to the unitarily invariant measure on the high-probability subspace of $B^{\otimes n}$.)

Bob can ignore the correlation structure of his state!

Final accounting

Investment:

Bob sends Charlie ~n[I(A;B)$_\phi$]/2 qubits



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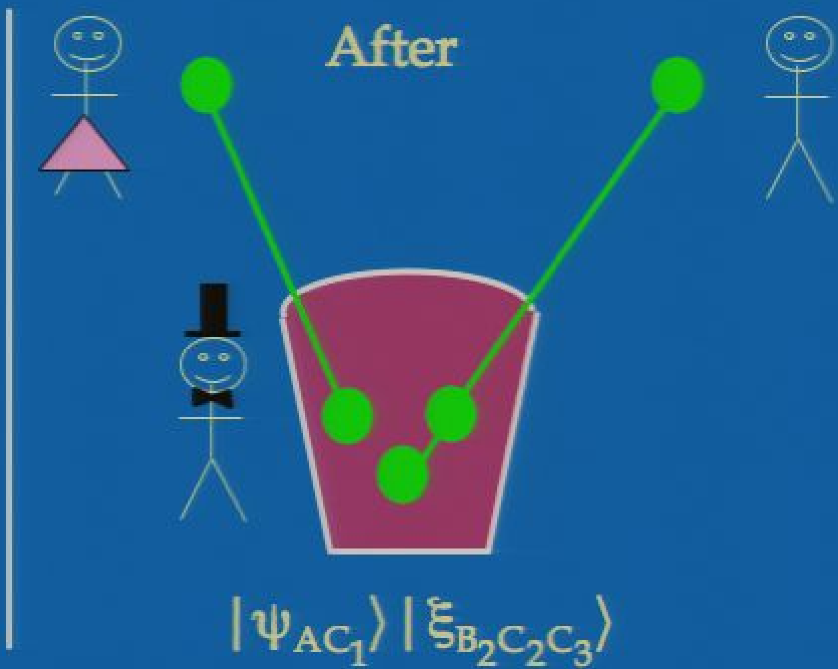
Investment:
Bob sends Charlie ~n[I(A;B)$_\phi$]/2 qubits

Rewards:
1) Charlie holds Alice's purification
2) B and C establish ~n[I(B;C)$_\phi$]/2 ebits



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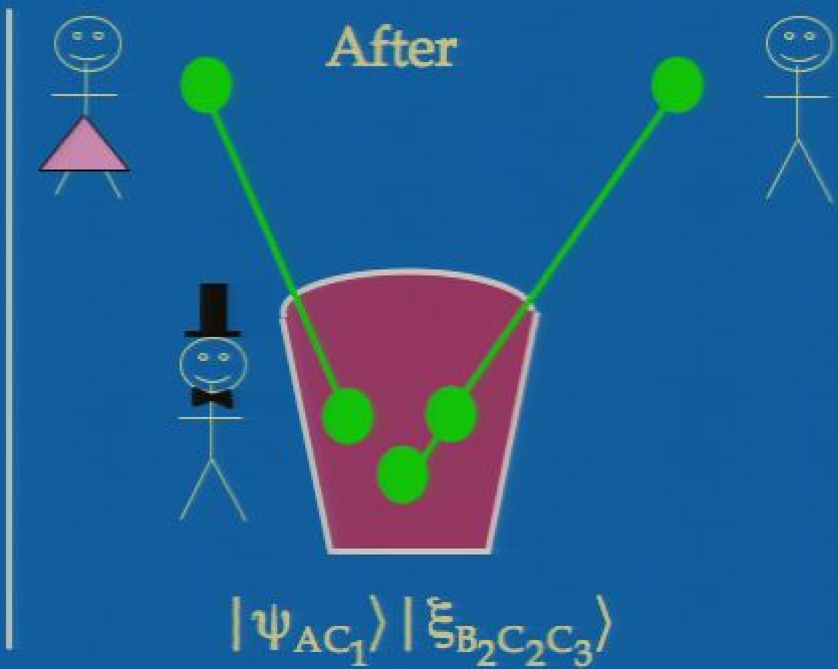
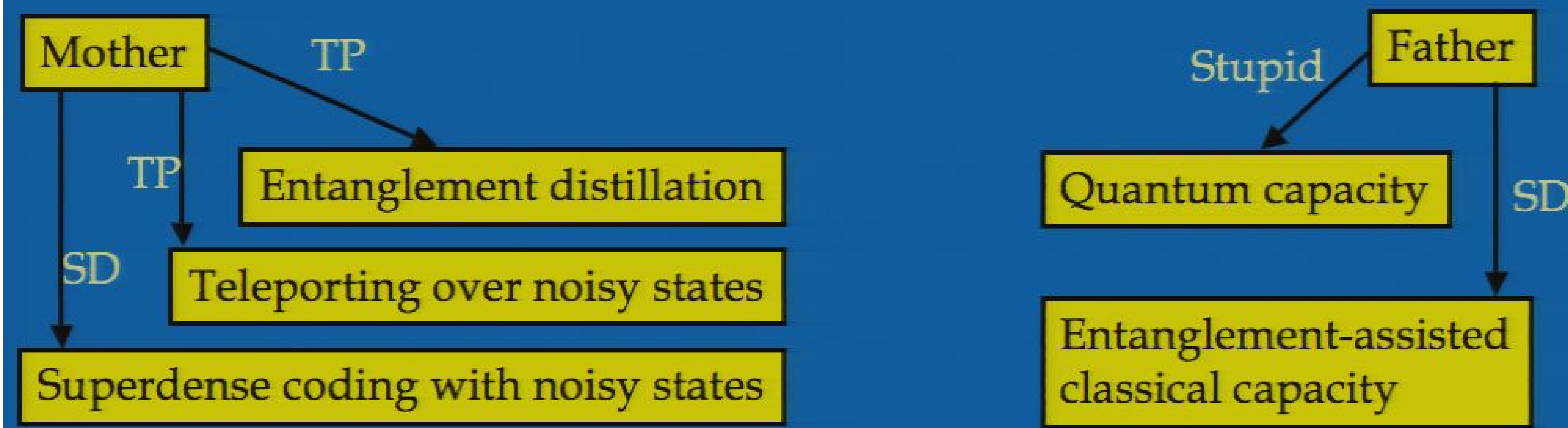


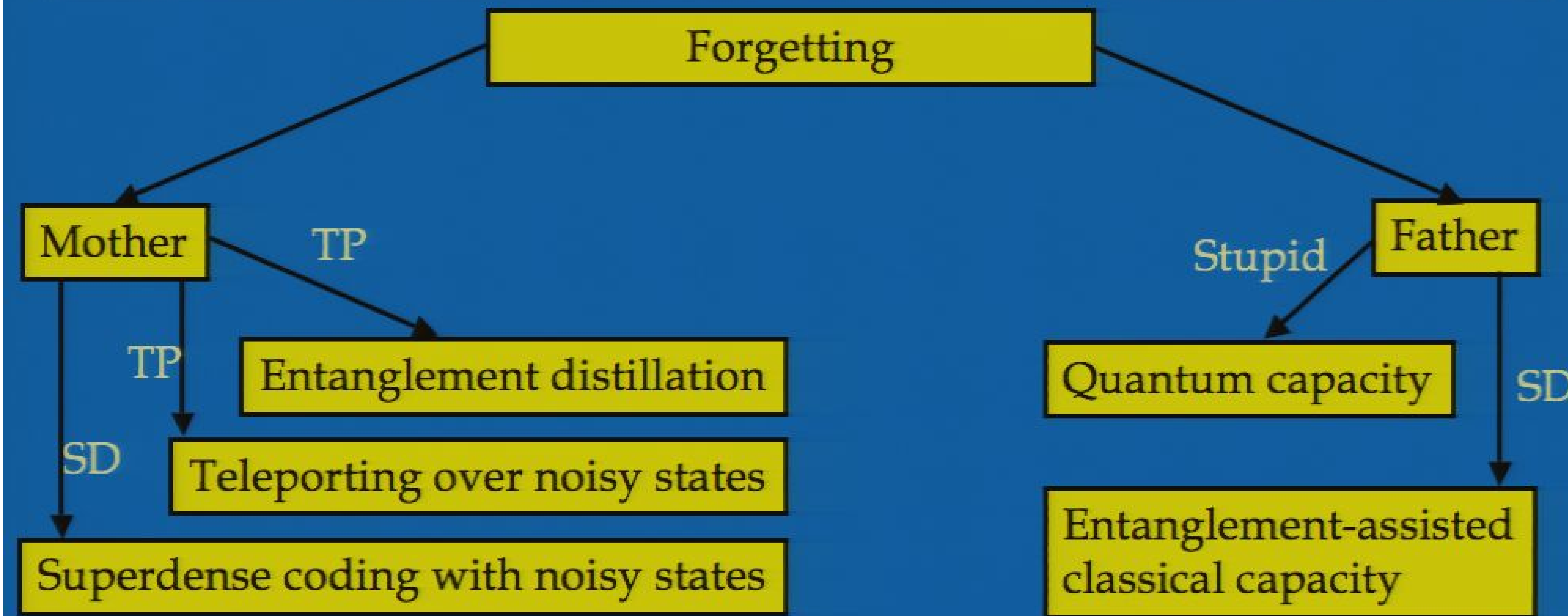
OK – but what good is it?

Mother of all protocols



Devetak, Harrow, Winter [2003]

Mother of all protocols



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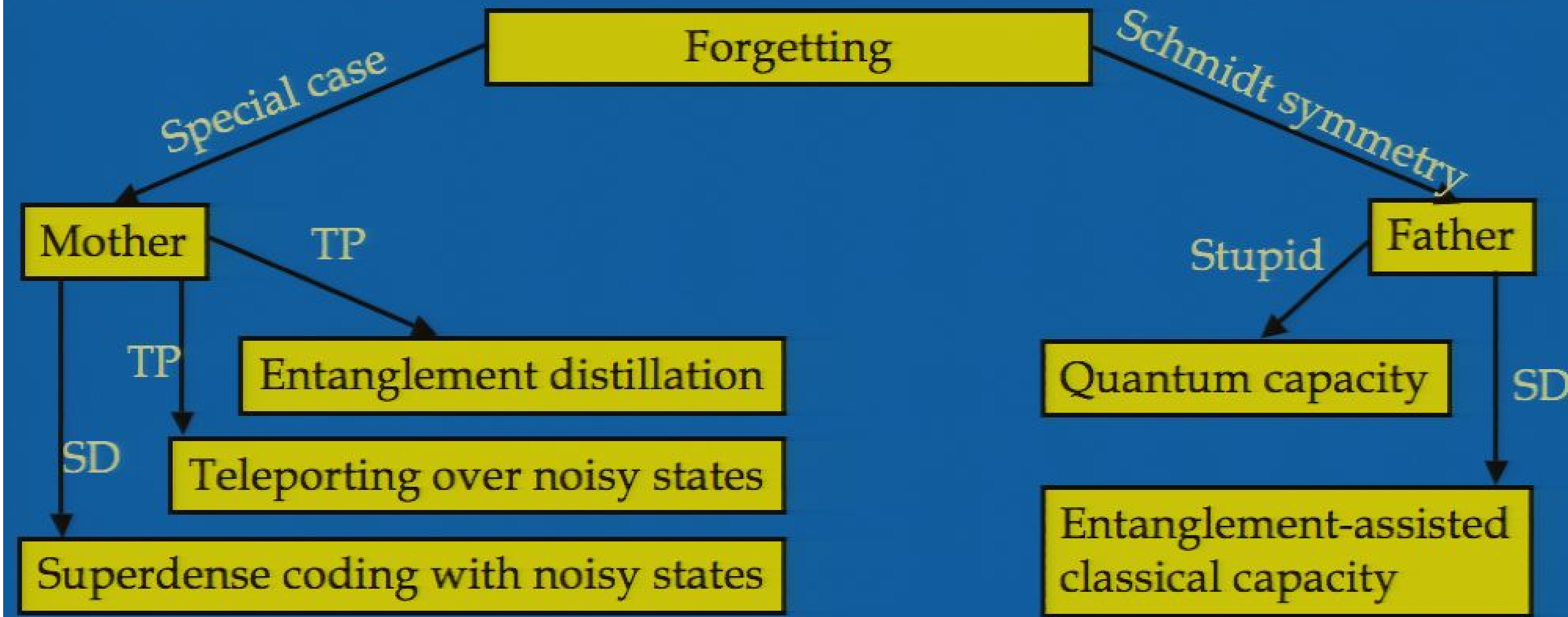

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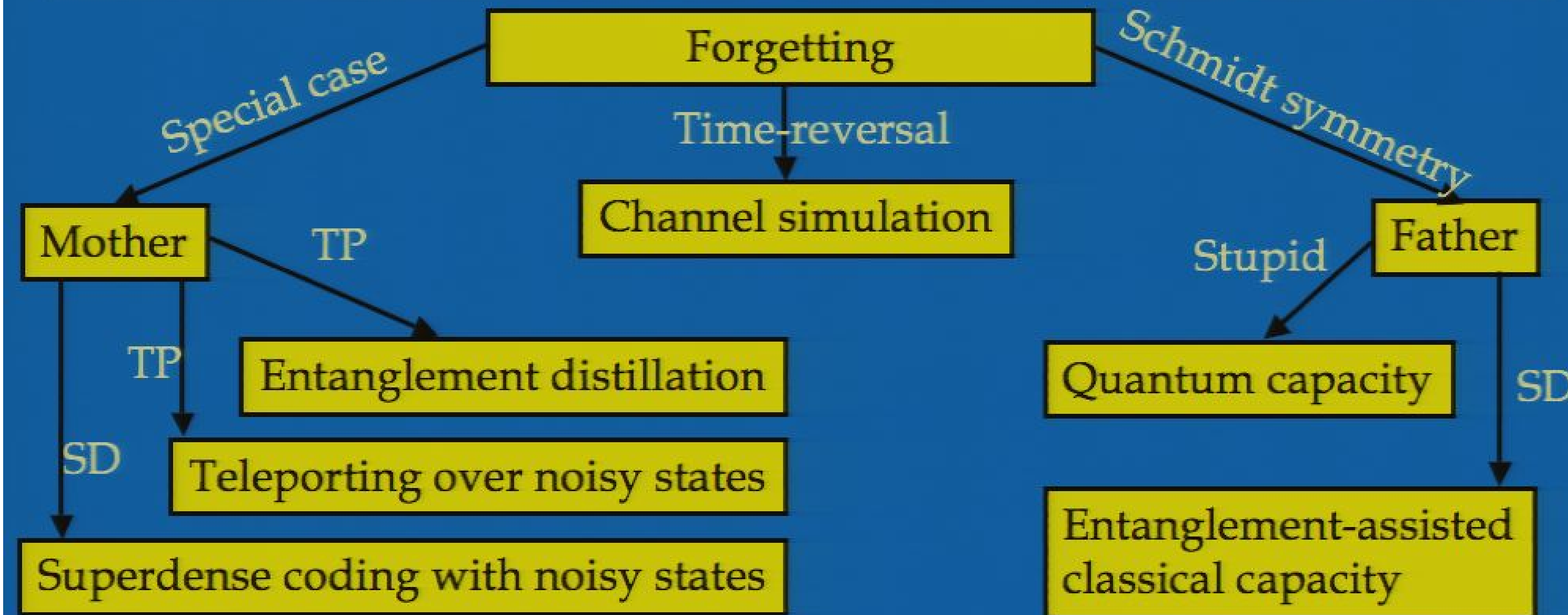

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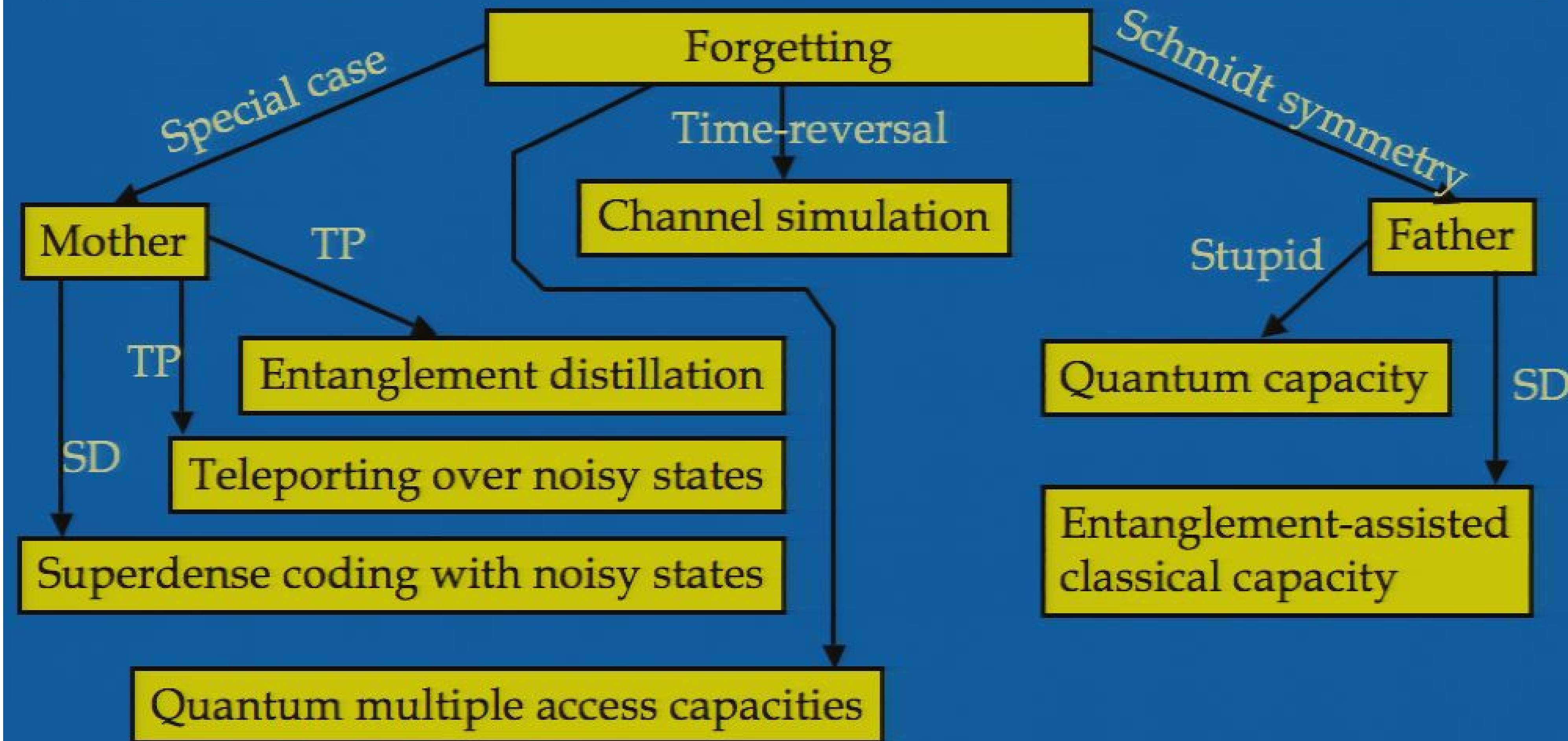

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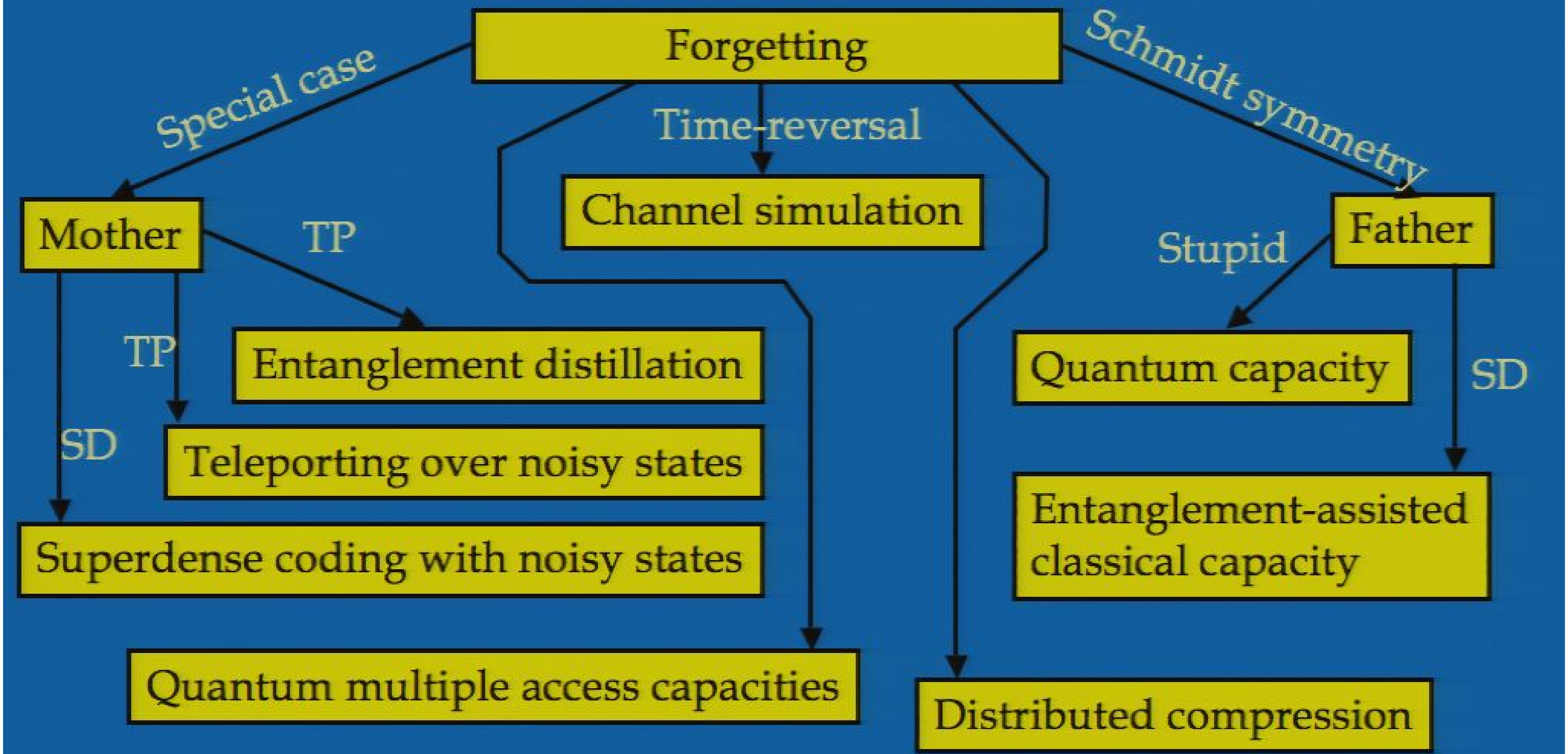

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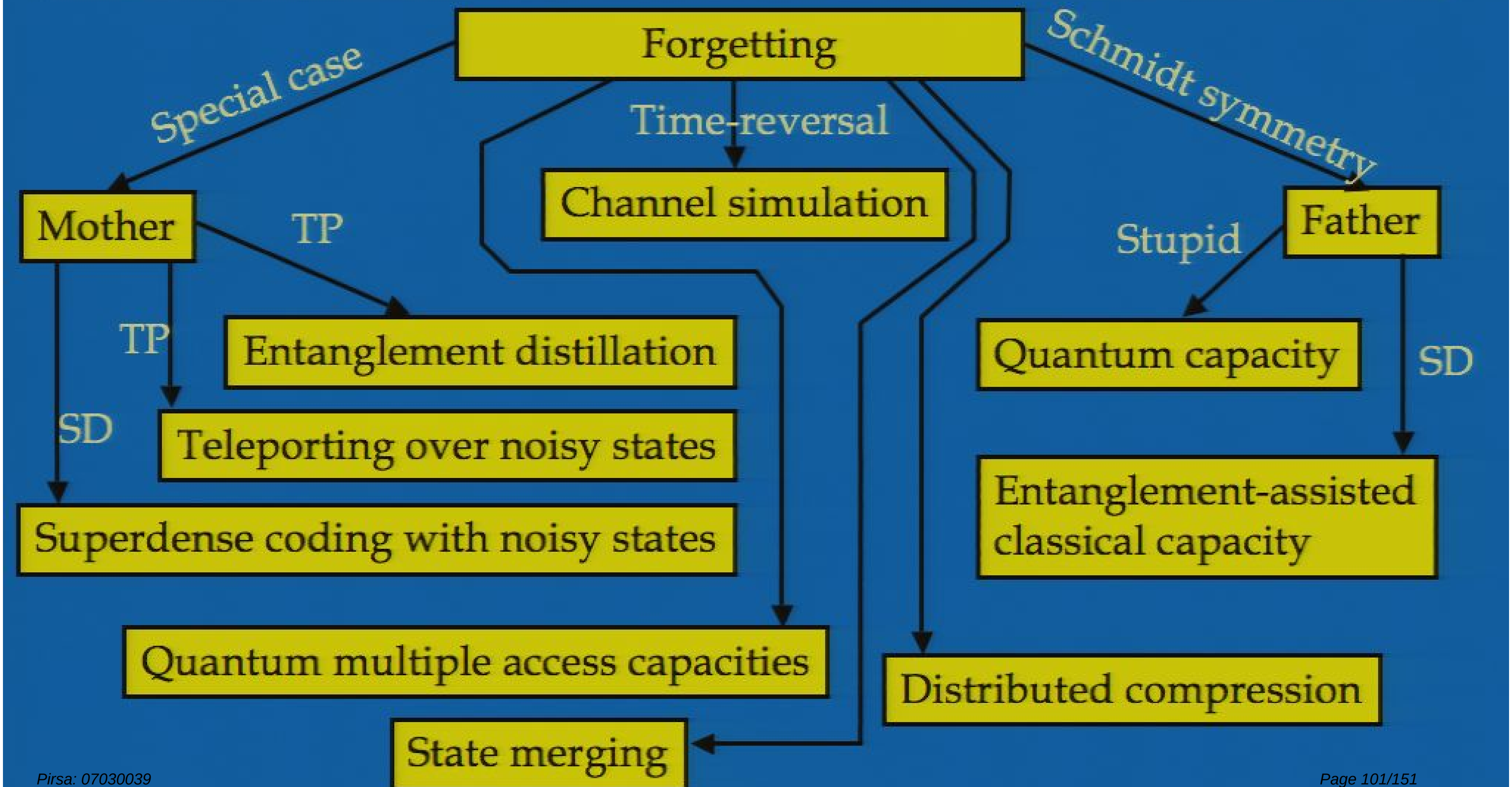

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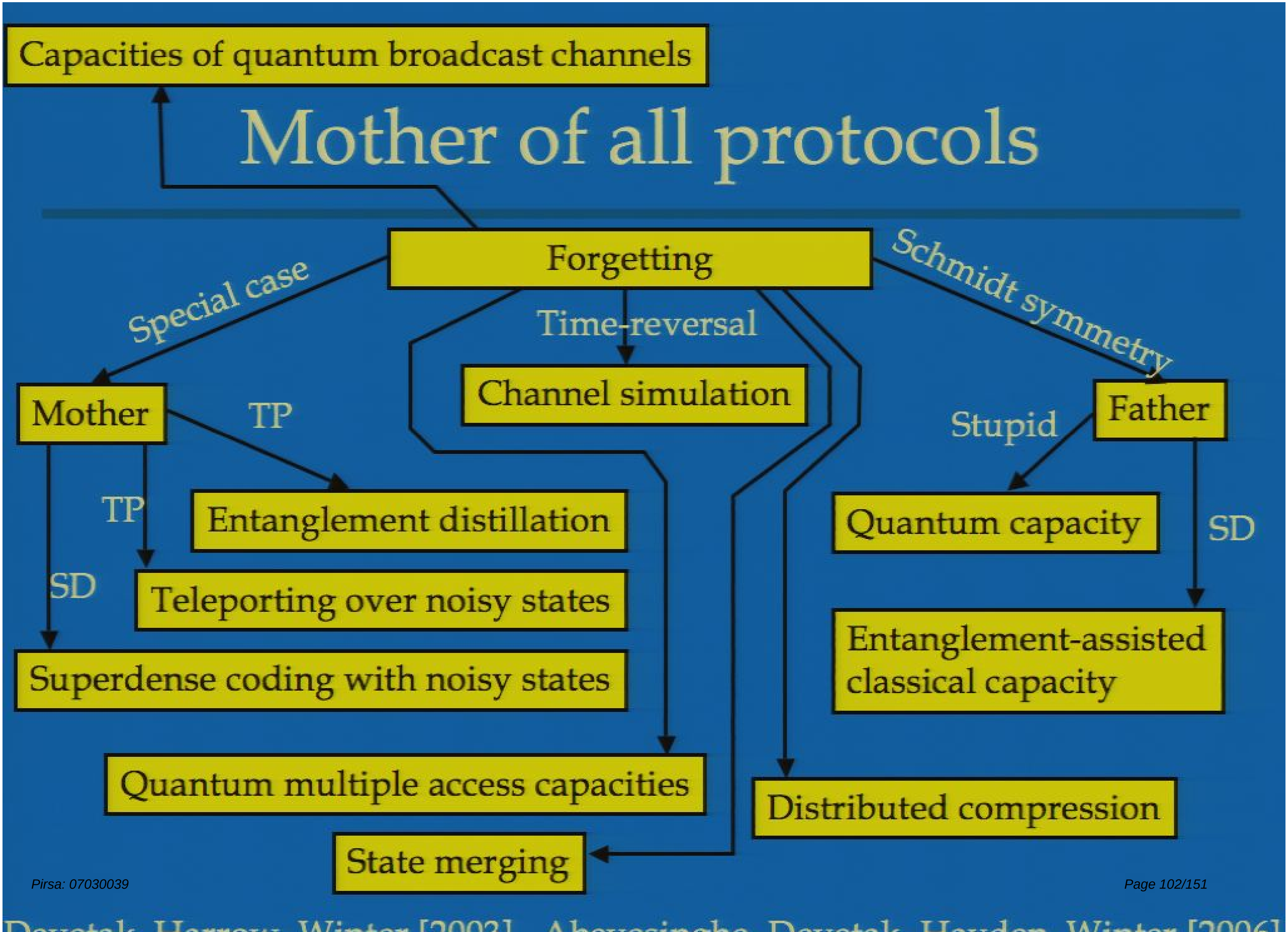
Capacities of quantum broadcast channels
Mother of all protocols
Forgetting
Special case
Time-reversal
Schmidt symmetry
Channel simulation
Mother
TP
Father
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Superdense coding with noisy states
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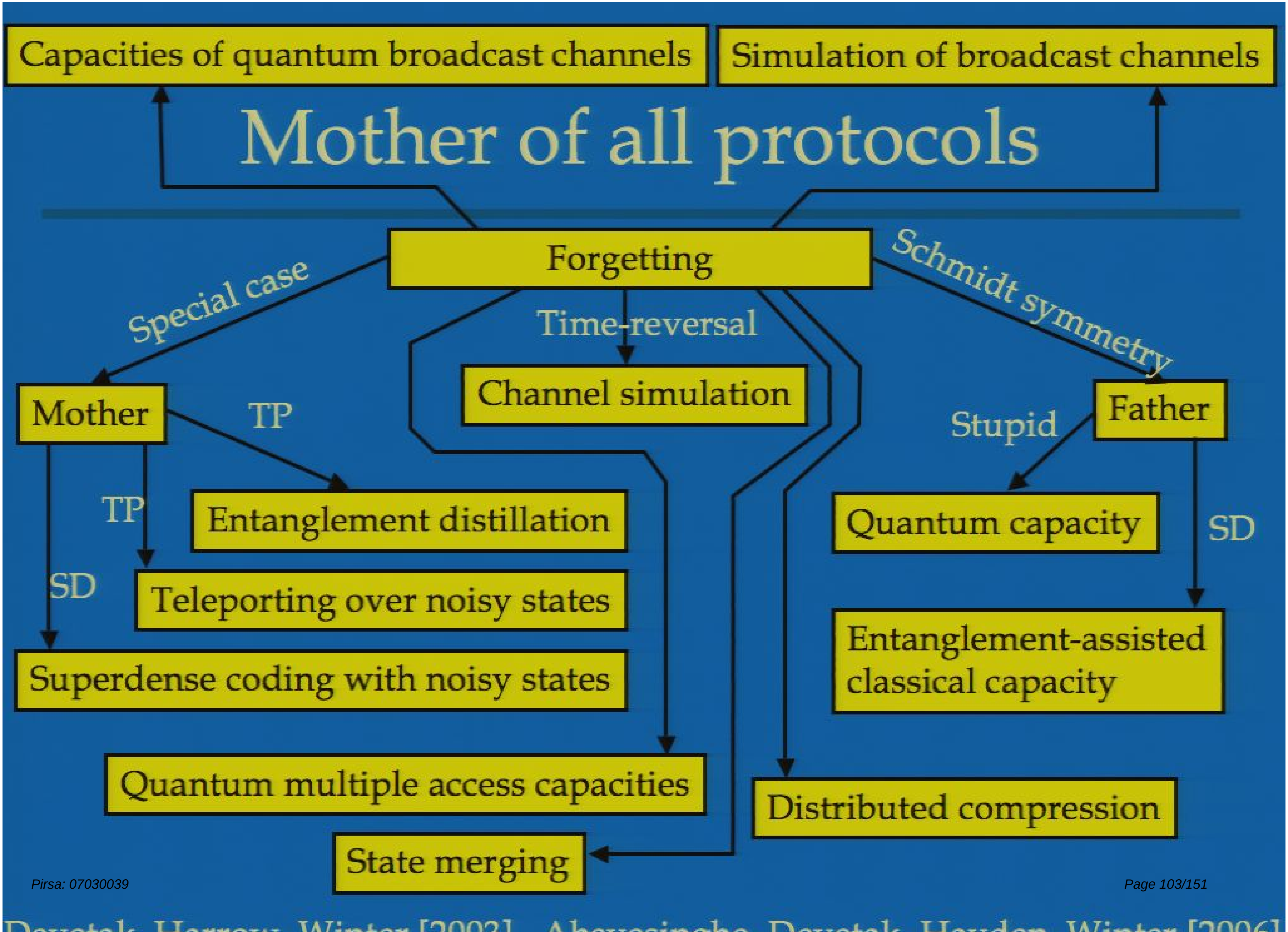
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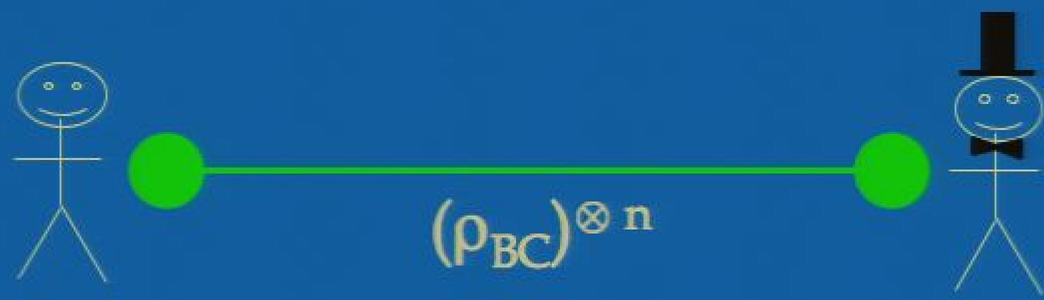
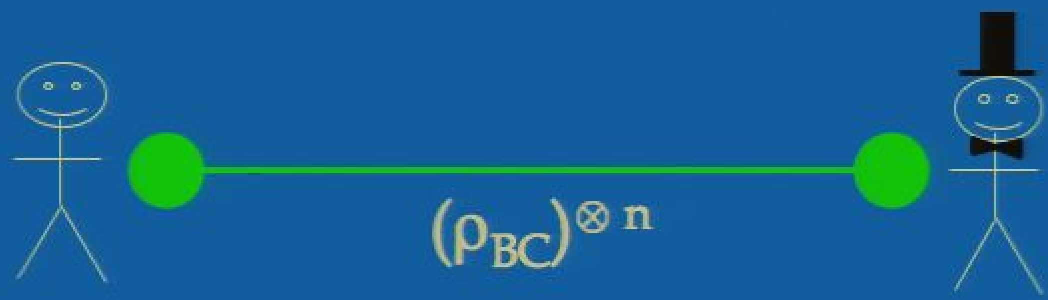
Entanglement distillation



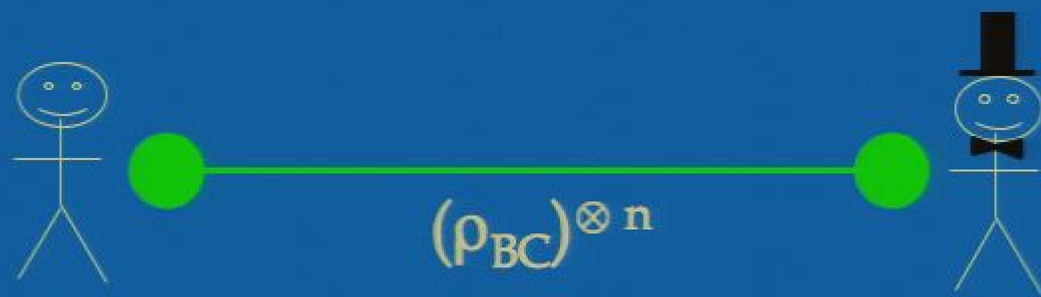
Entanglement distillation



Bob and Charlie share many copies of a noisy entangled state and would like to convert it to ebits.

Only local operations and *classical communication* are allowed. Forgetting protocol good but uses *quantum communication*

Entanglement distillation



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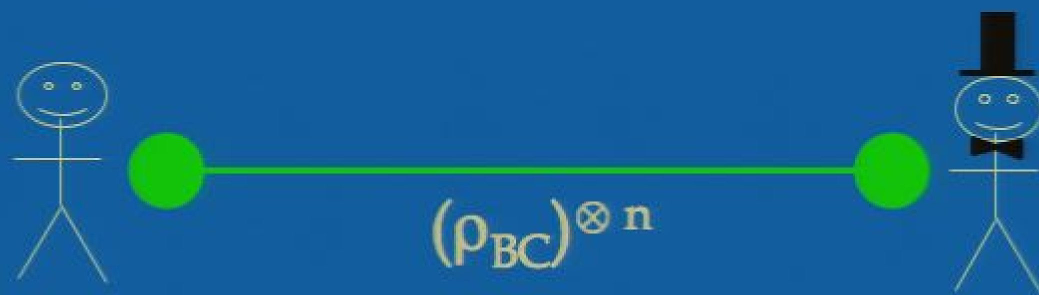

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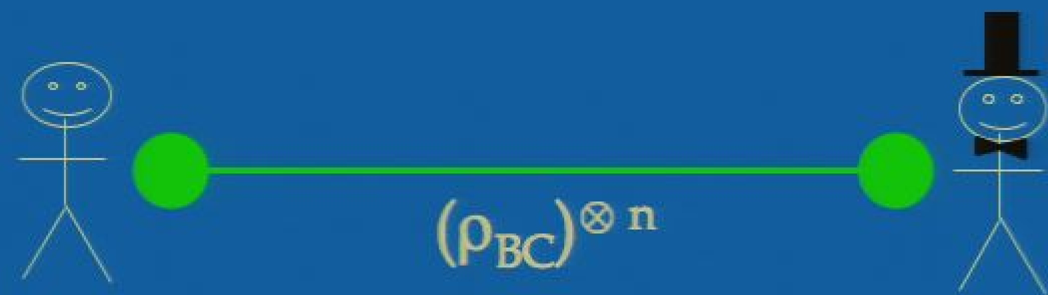

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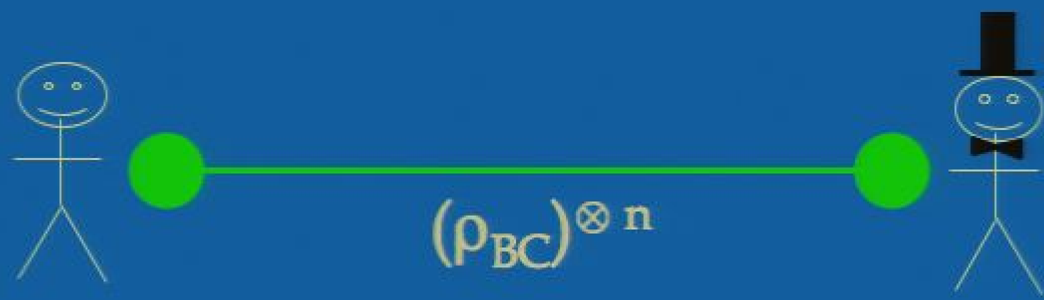

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Bristol Evening Post

Friday, August 5, 2005

Scientist knows less than nothing

A MATHEMATICS expert from Bristol has come up with a baffling theory to help explain the complex world of quantum physics.

by Ian Turner
i.turner@bepp.co.uk

Dr Andreas Winter of Bristol University said it was possible to know "less than nothing" and discovered that "negative knowledge" does exist in the quantum world of extremely small things.

But while the breakthrough may make sense to experts in quantum physics, it will leave the man in the street completely baffled.

Dr Winter, a lecturer at the university's department of mathematics, has been scratching his head to come up with an explanation of his theory.

And his example will still leave most people wondering why he bothered.

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Dr Winter worked with two other experts, Jonathan Oppenheim from Cambridge University and Michal Horodecki from the Institute for Theoretical Physics in Gdansk, Poland, to develop the theory. Their work has now been published in the leading science journal *Nature*.

Quantum physics tries to explain the behaviour of particles, such as electrons, protons, and neutrons, which are smaller than an atom.

Scientists claim that in the quantum world, there are things we just cannot know, no matter how clever we are.

But confusingly, they also say there are situations where someone can know more than everything. This is known as quantum entanglement, and when two people share entanglement, there can be negative information.

Mr Horodecki said the idea of negative information can be put on a rigorous scientific footing.

He said: "We can quantify information in terms of how much stuff I need to send you before you get to know something. In the case of negative quantum information, you can get to know something without me sending you any quantum particles [illegible] will gain the potential to learn more quantum information in the future."

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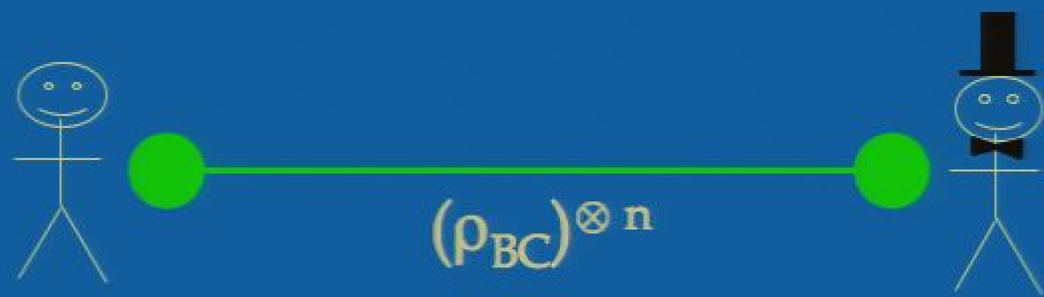

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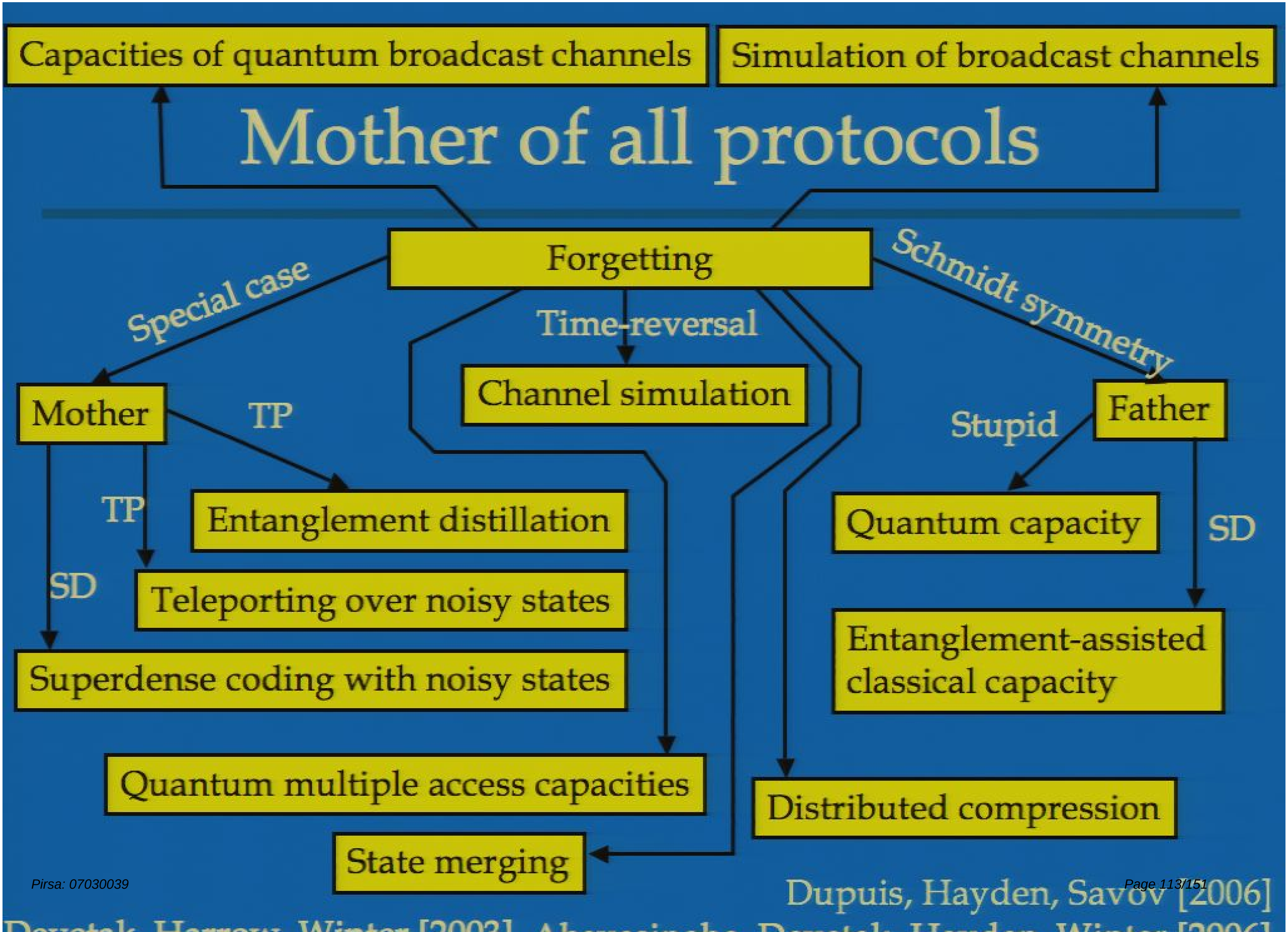
Capacities of quantum broadcast channels
Simulation of broadcast channels
Mother of all protocols
Forgetting
Special case
Time-reversal
Schmidt symmetry
Mother
Channel simulation
Father
TP
Stupid
TP
Entanglement distillation
Quantum capacity
SD
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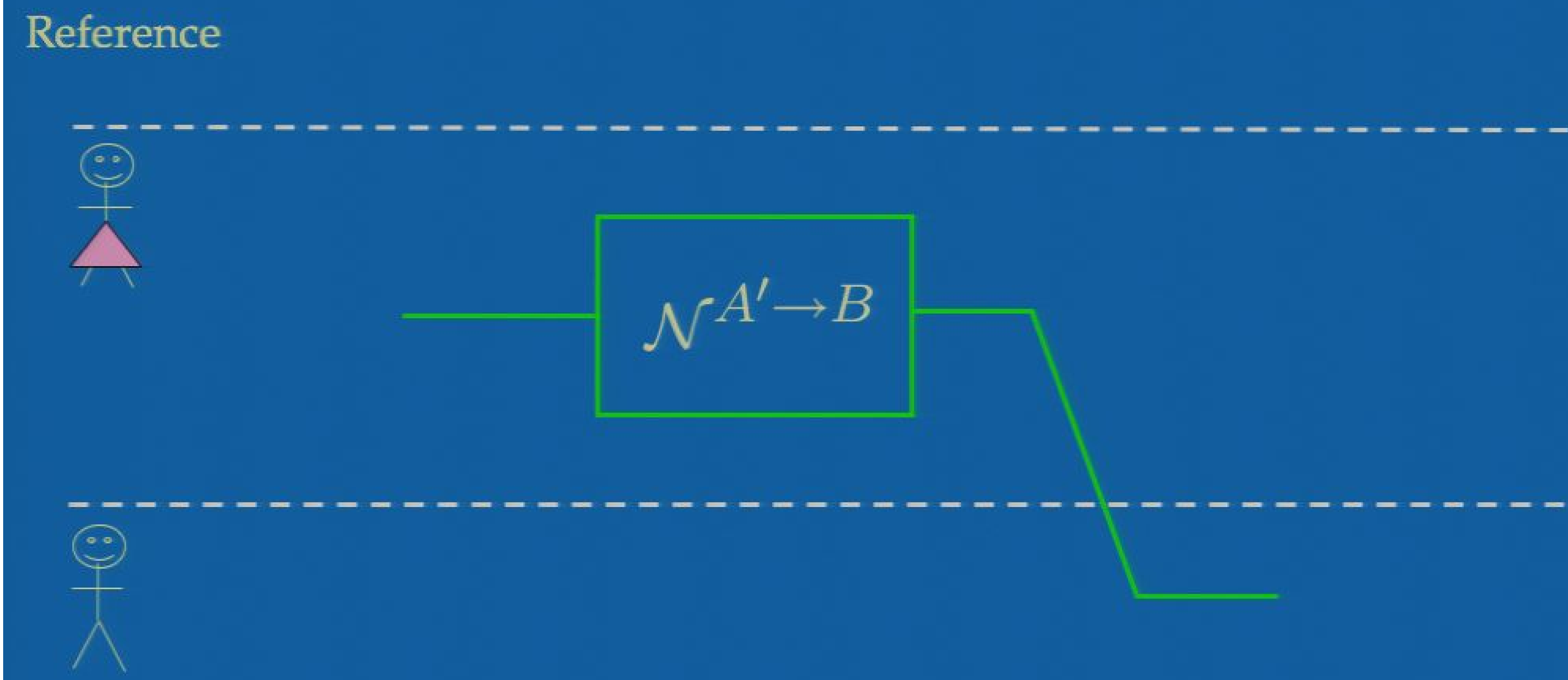
Teleporting over noisy states
Entanglement-assisted classical capacity
Superdense coding with noisy states
Quantum multiple access capacities
Distributed compression
State merging
Dupuis, Hayden, Savov [2006]

Entanglement-assisted communication



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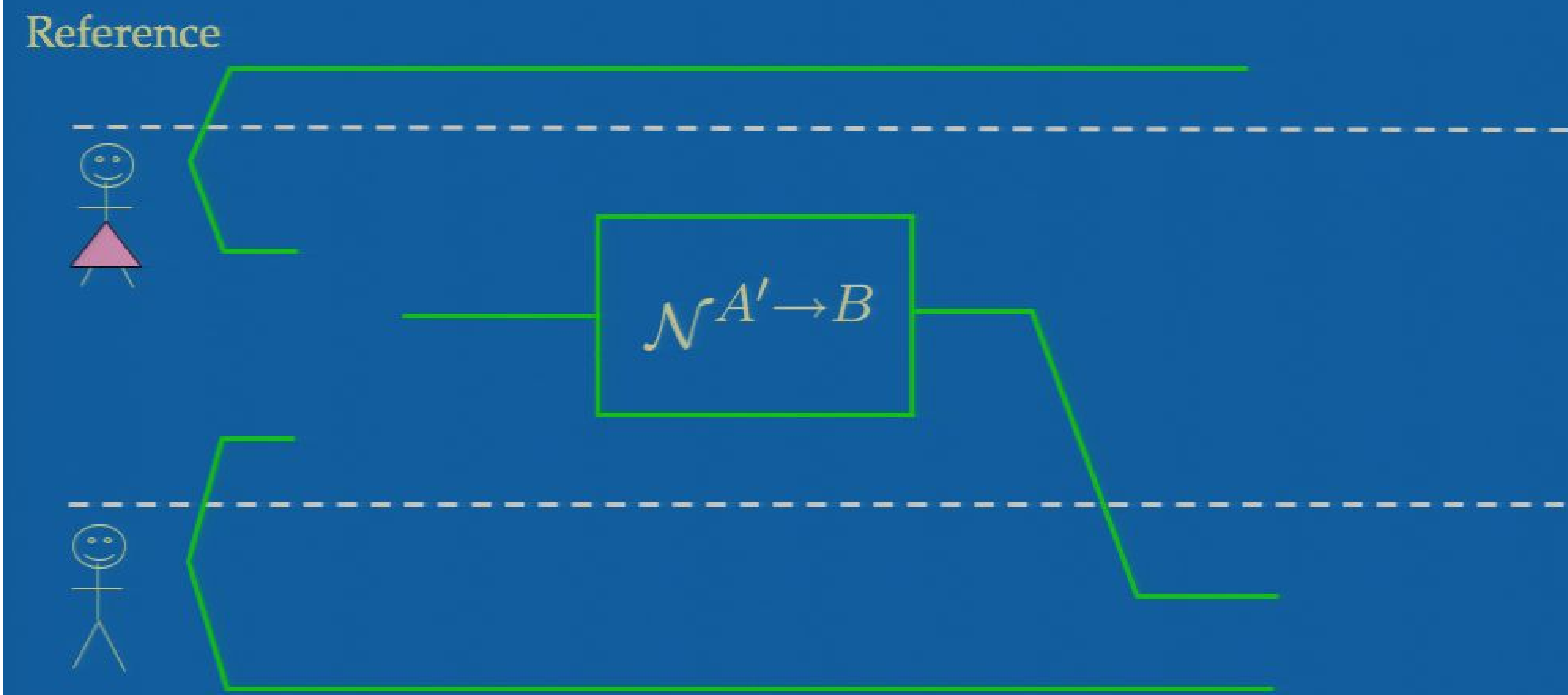
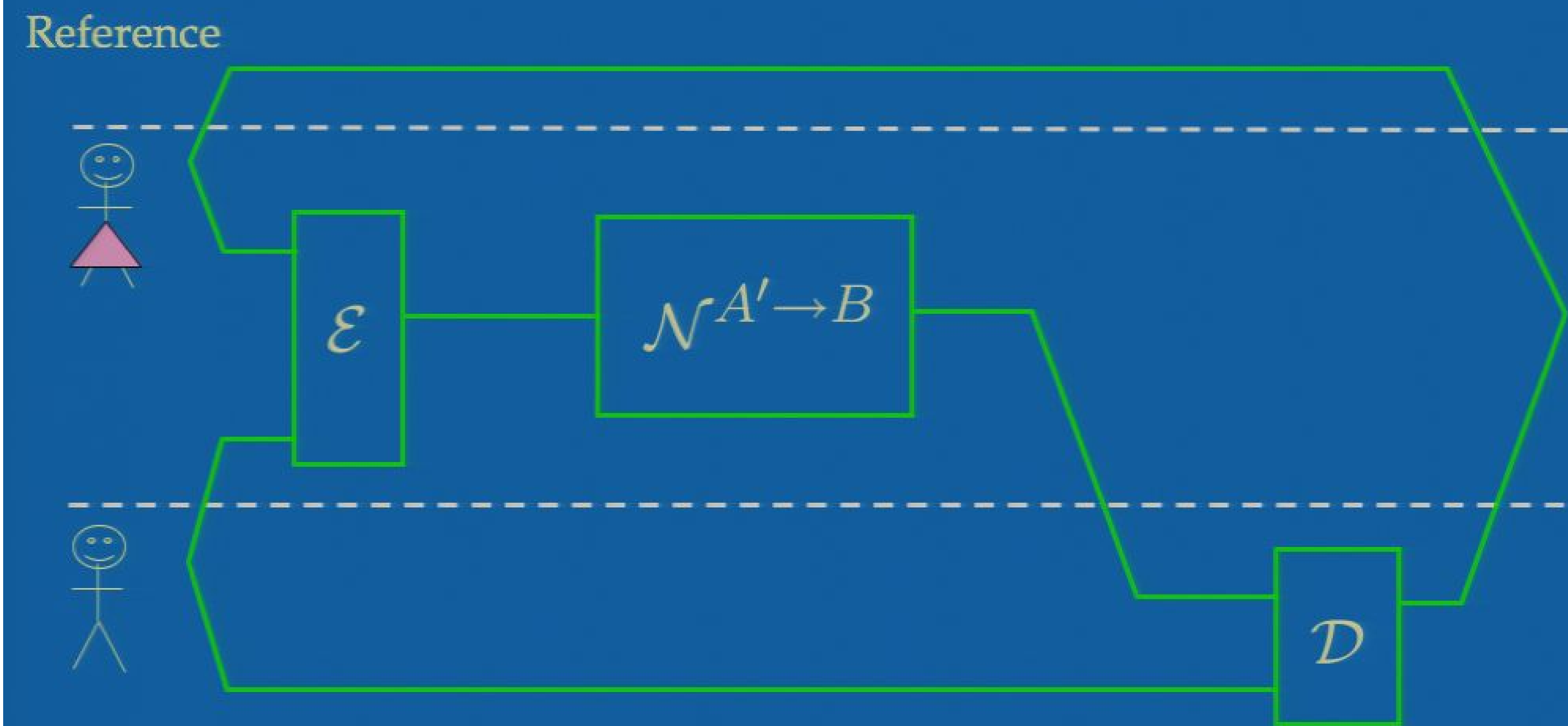


Objective is to transfer Alice's reference entanglement to Bob

Entanglement-assisted communication



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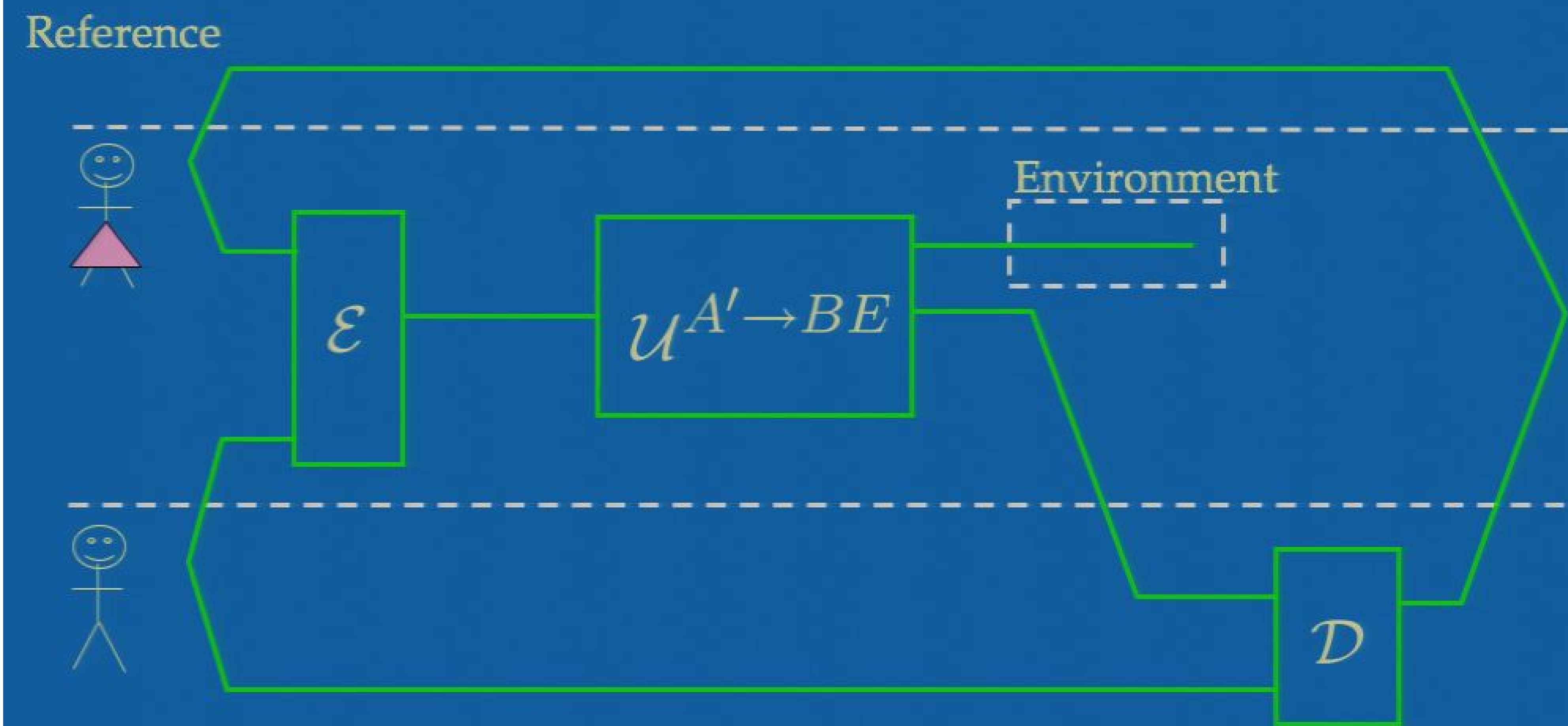

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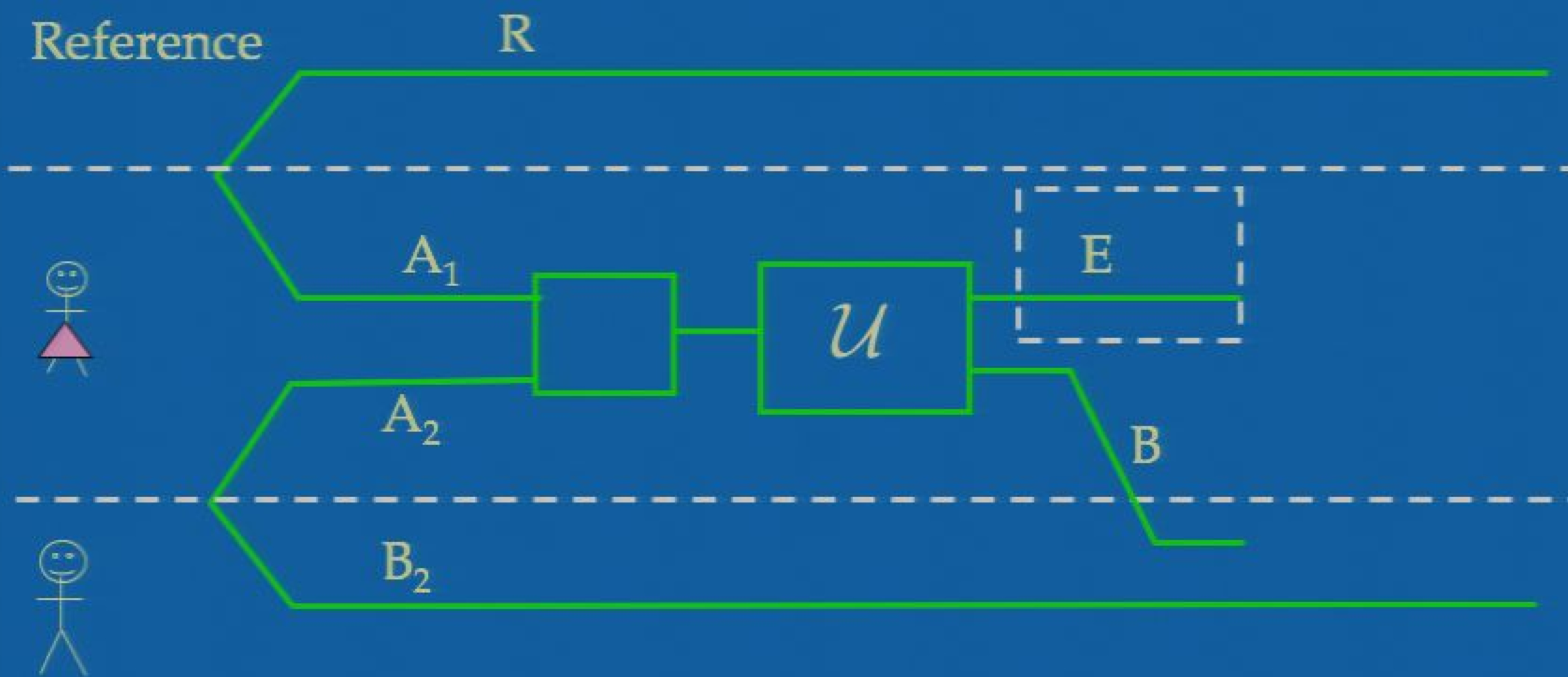
Reduction to forgetting



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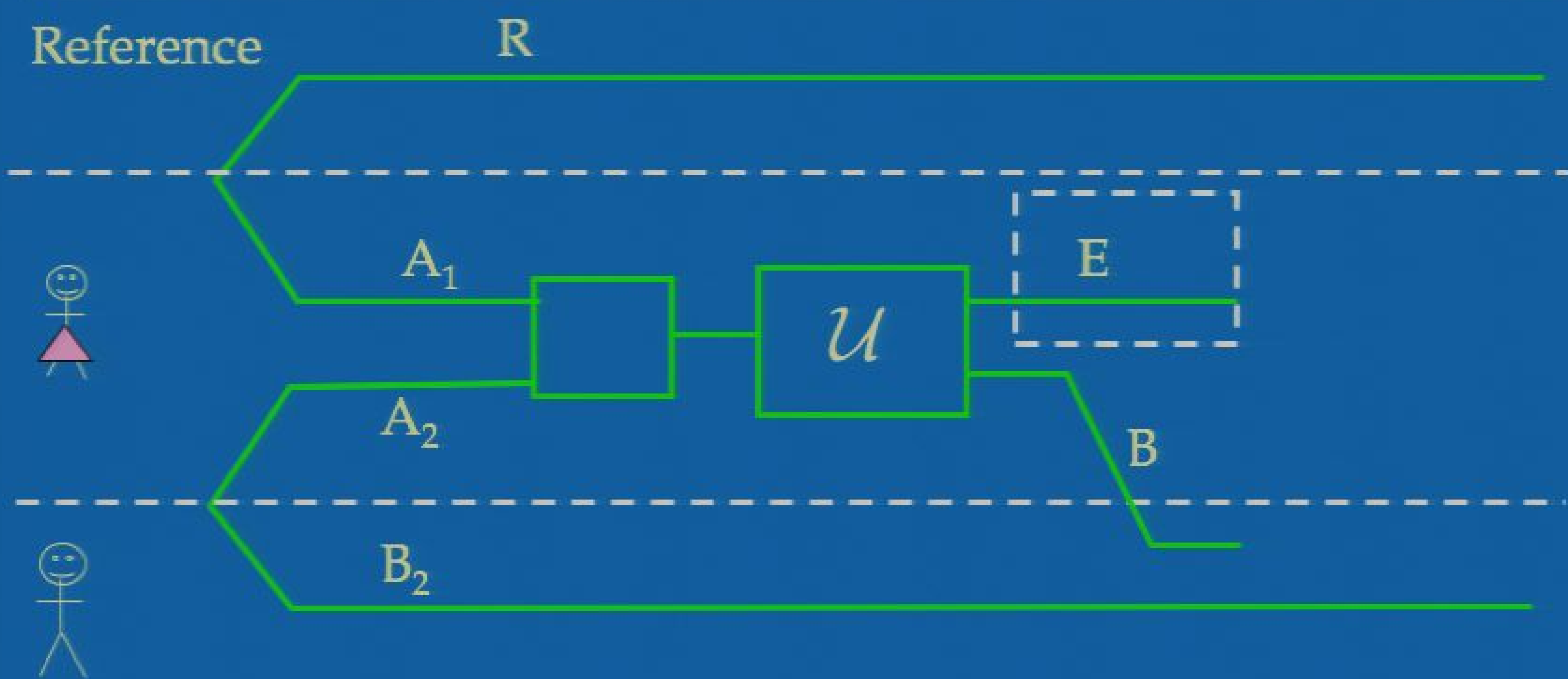

Who needs to do the forgetting?

It is sufficient to ensure that there is a product state on $R \otimes E$

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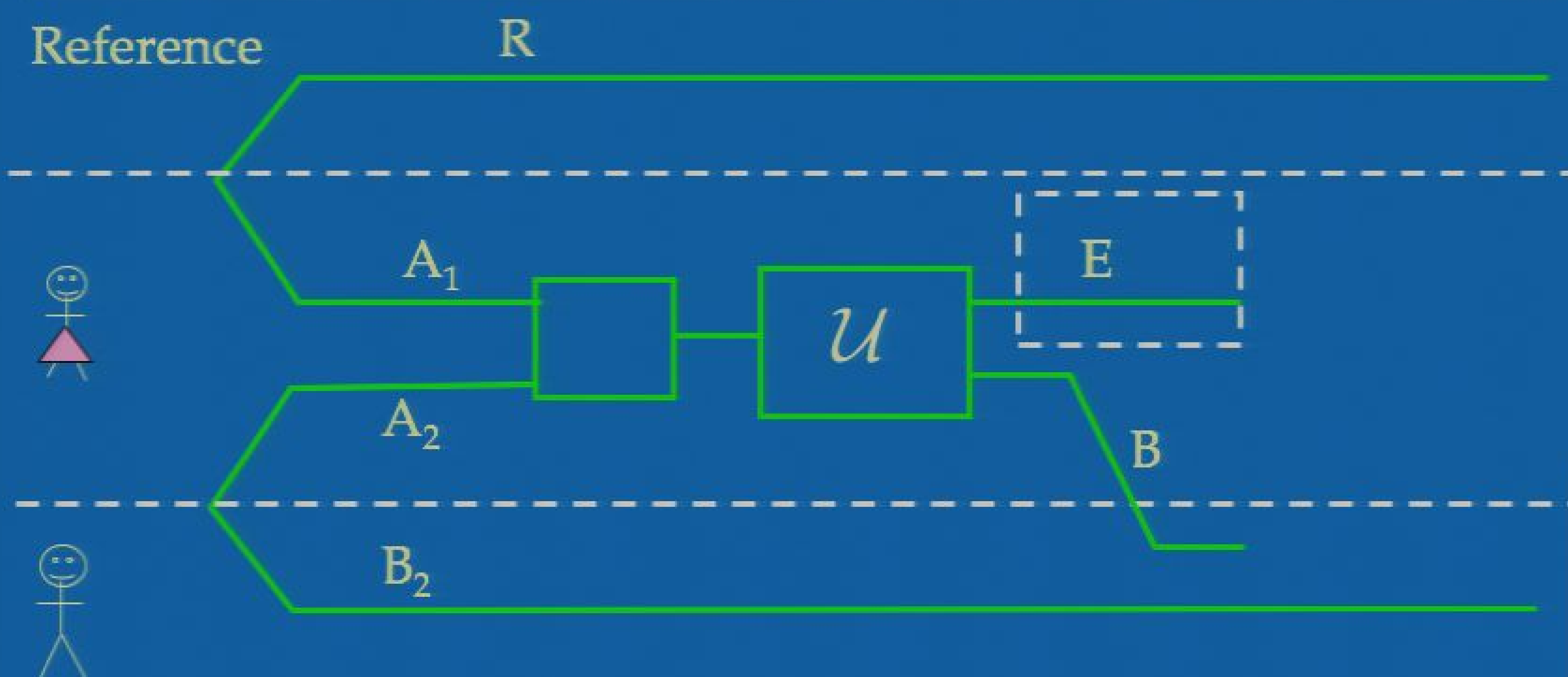

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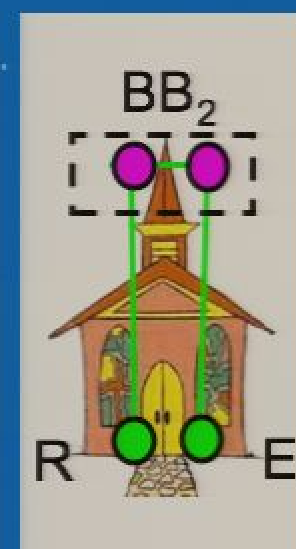

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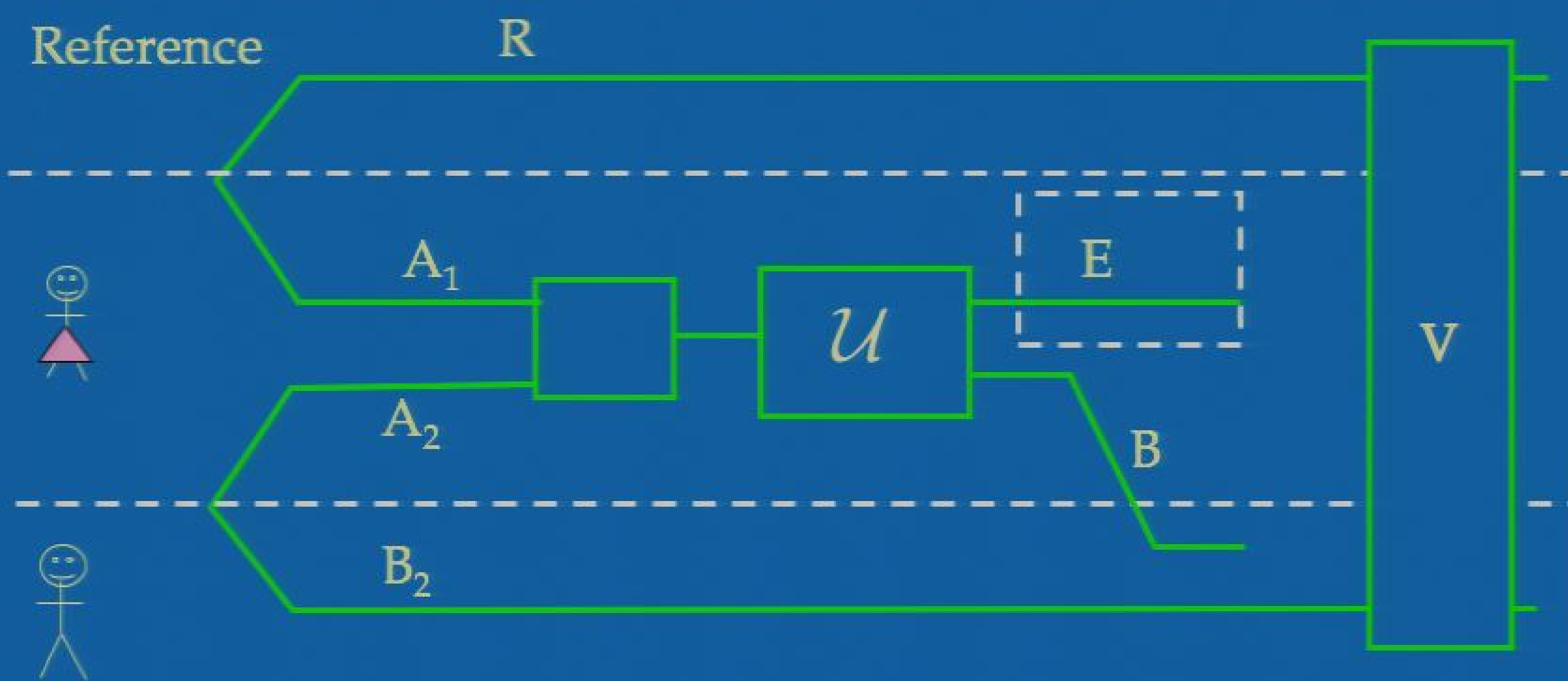

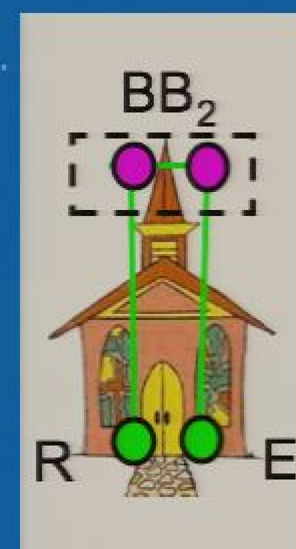

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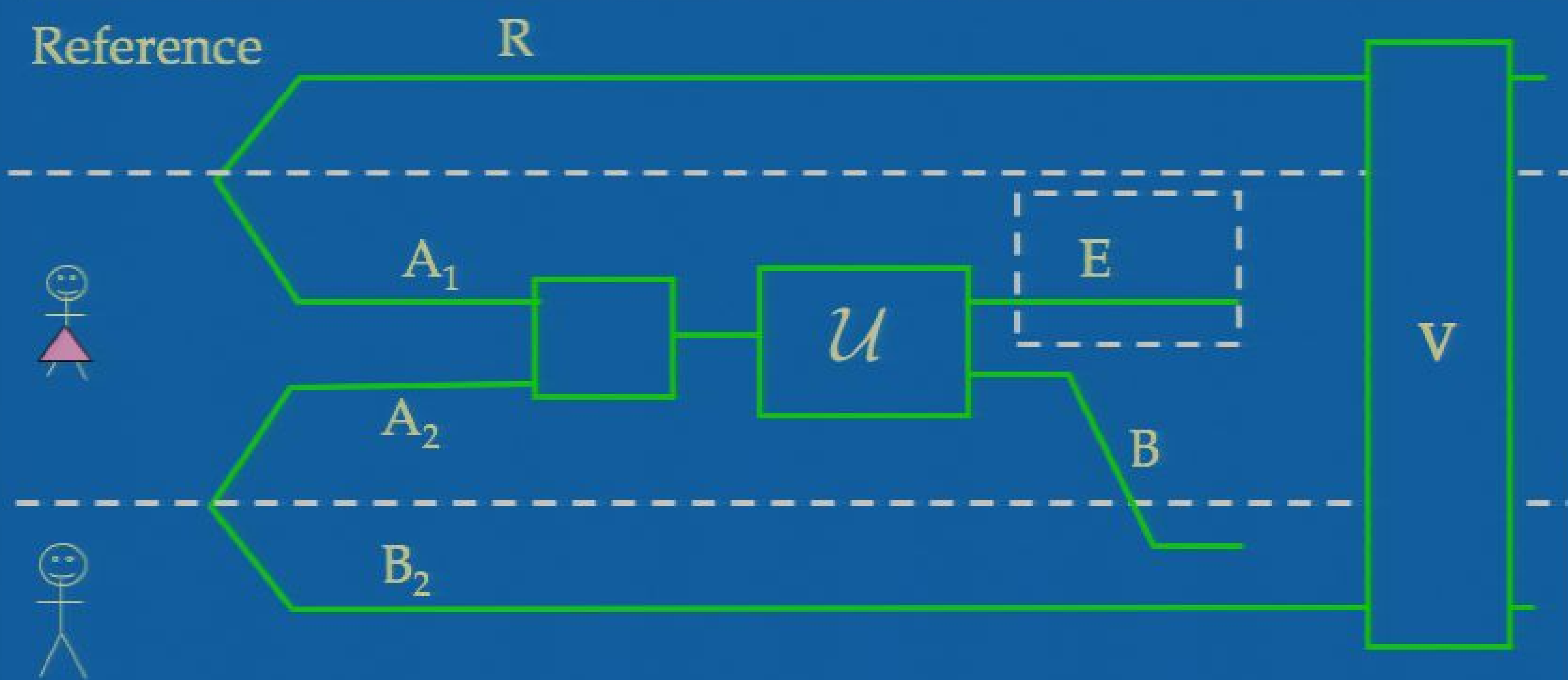
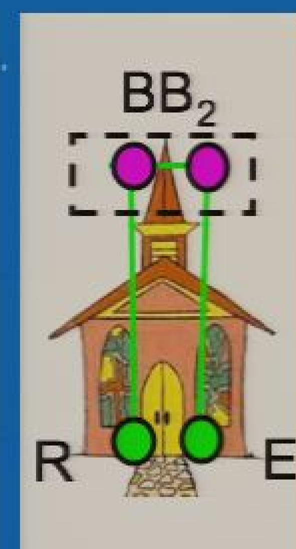
Imagine: apply a random unitary V to RB_2.
Result: For sufficiently large B_2, product state on $R \otimes E$!

$$|\Phi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle^A|0\rangle^B + |1\rangle^A|1\rangle^B\right)$$

$$(A\otimes I)|\Phi\rangle = (I\otimes A^T)|\Phi\rangle$$

Reduction to forgetting





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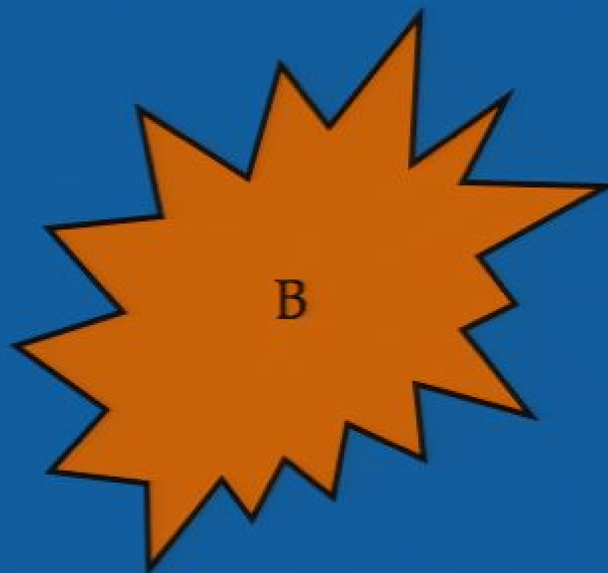

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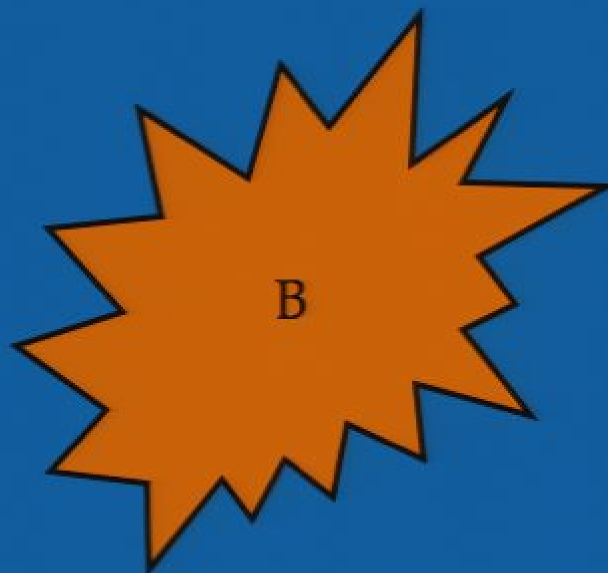

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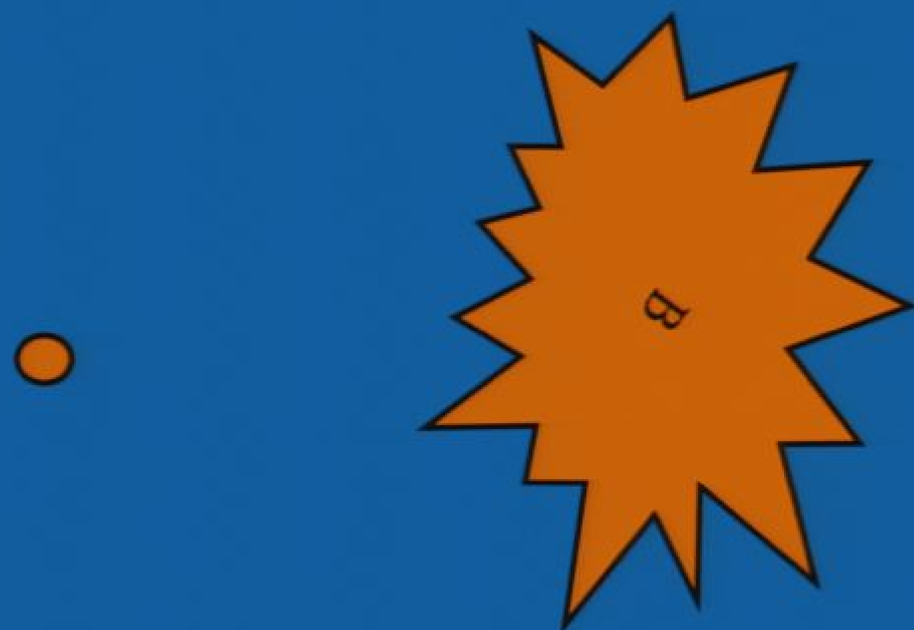

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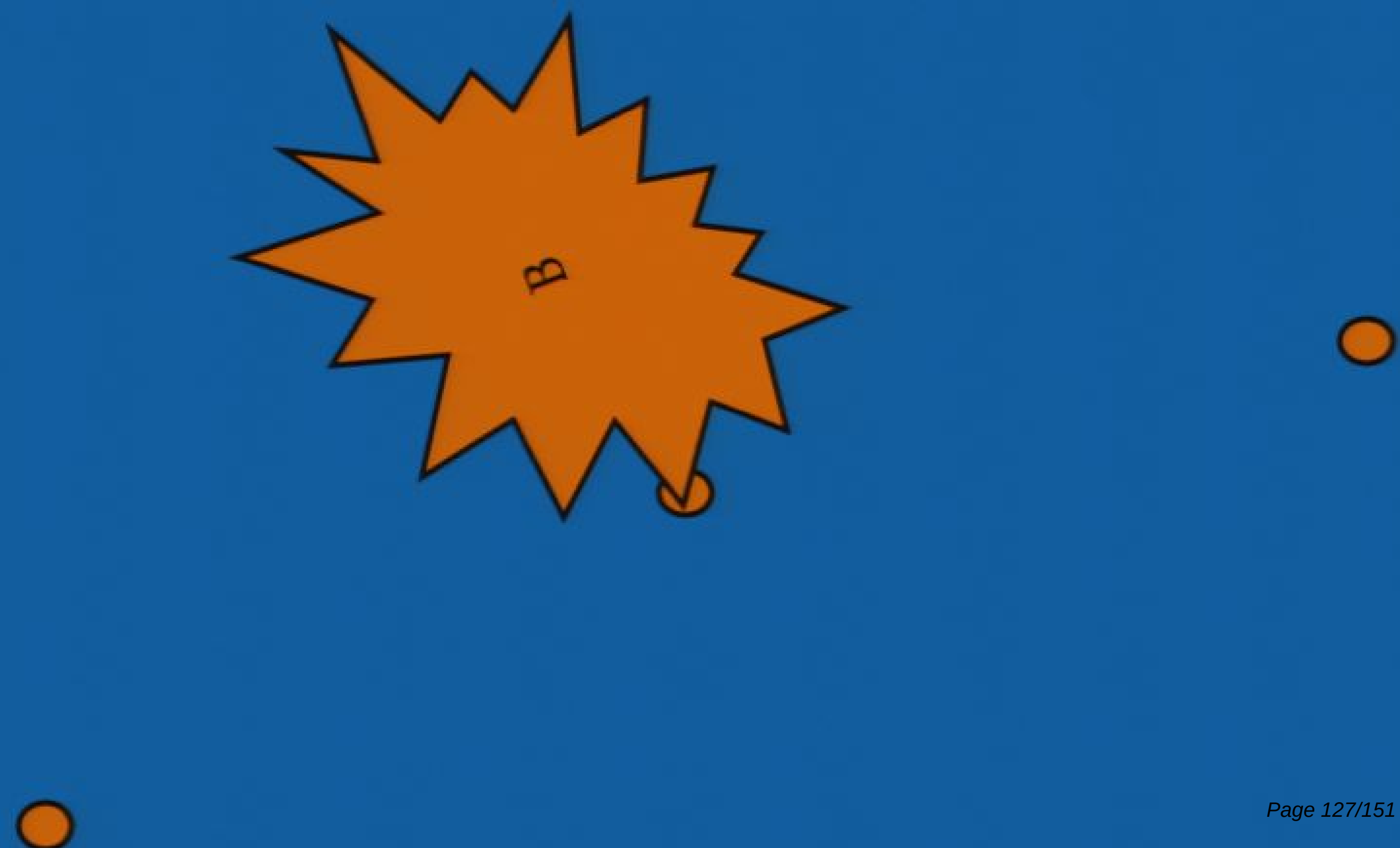

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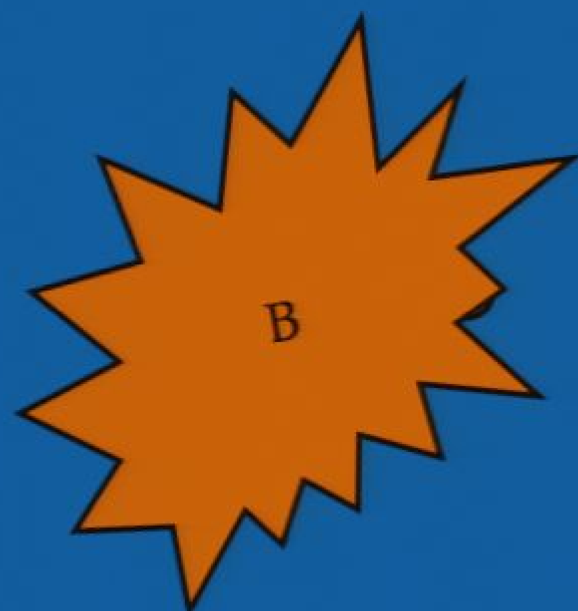

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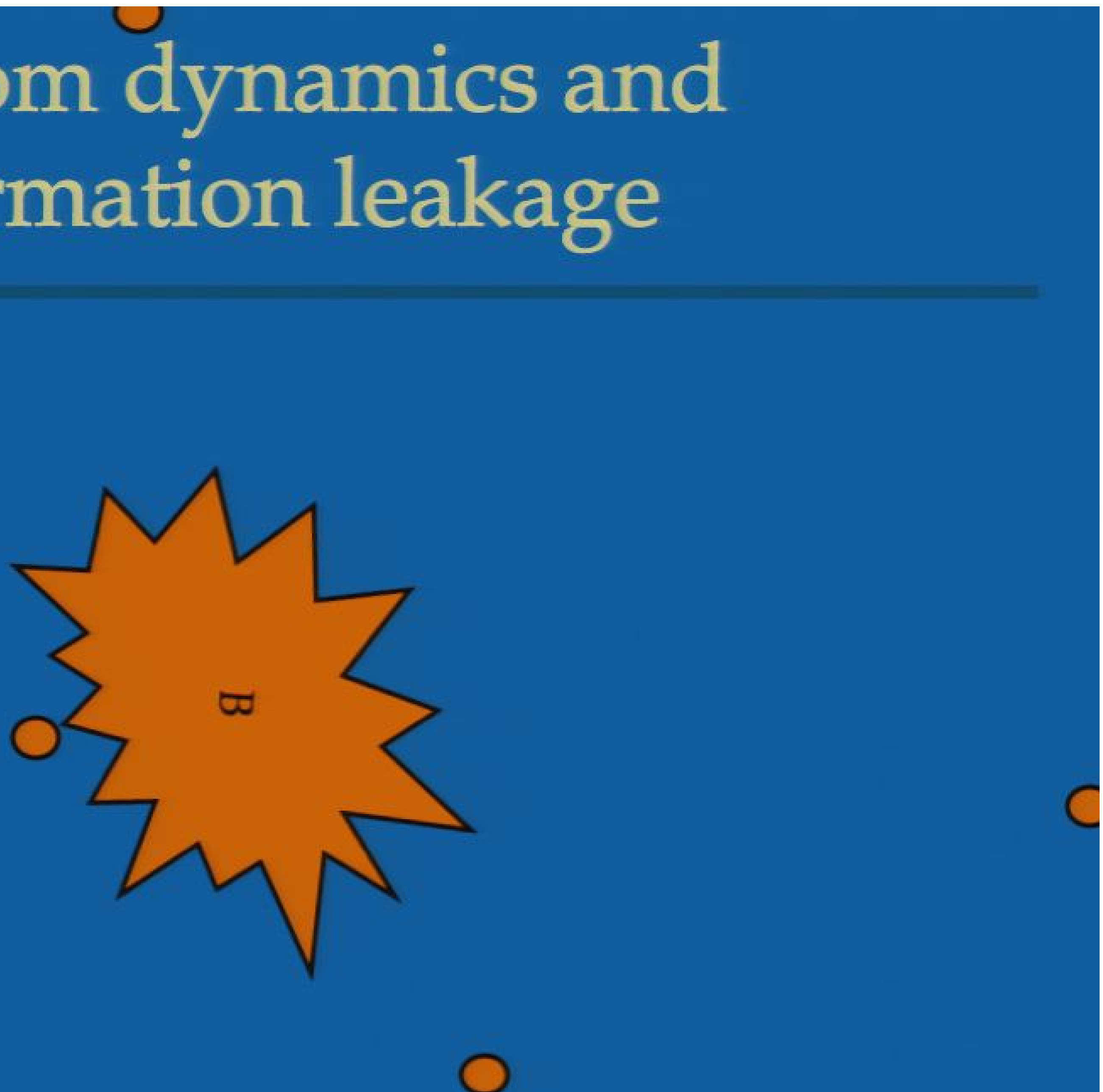

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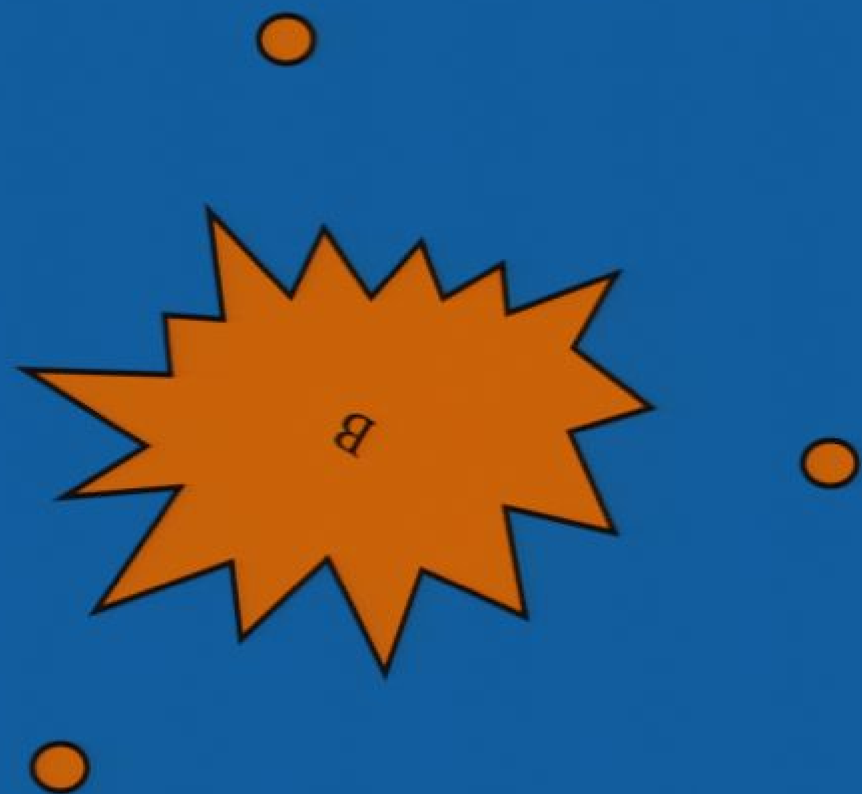

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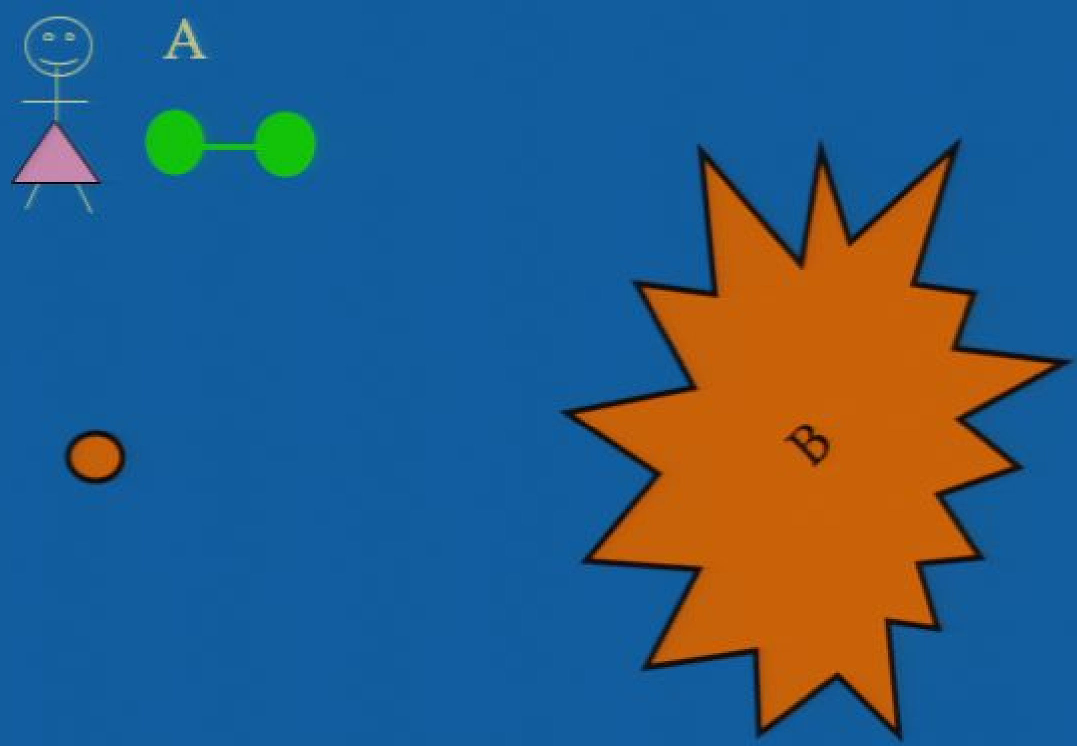

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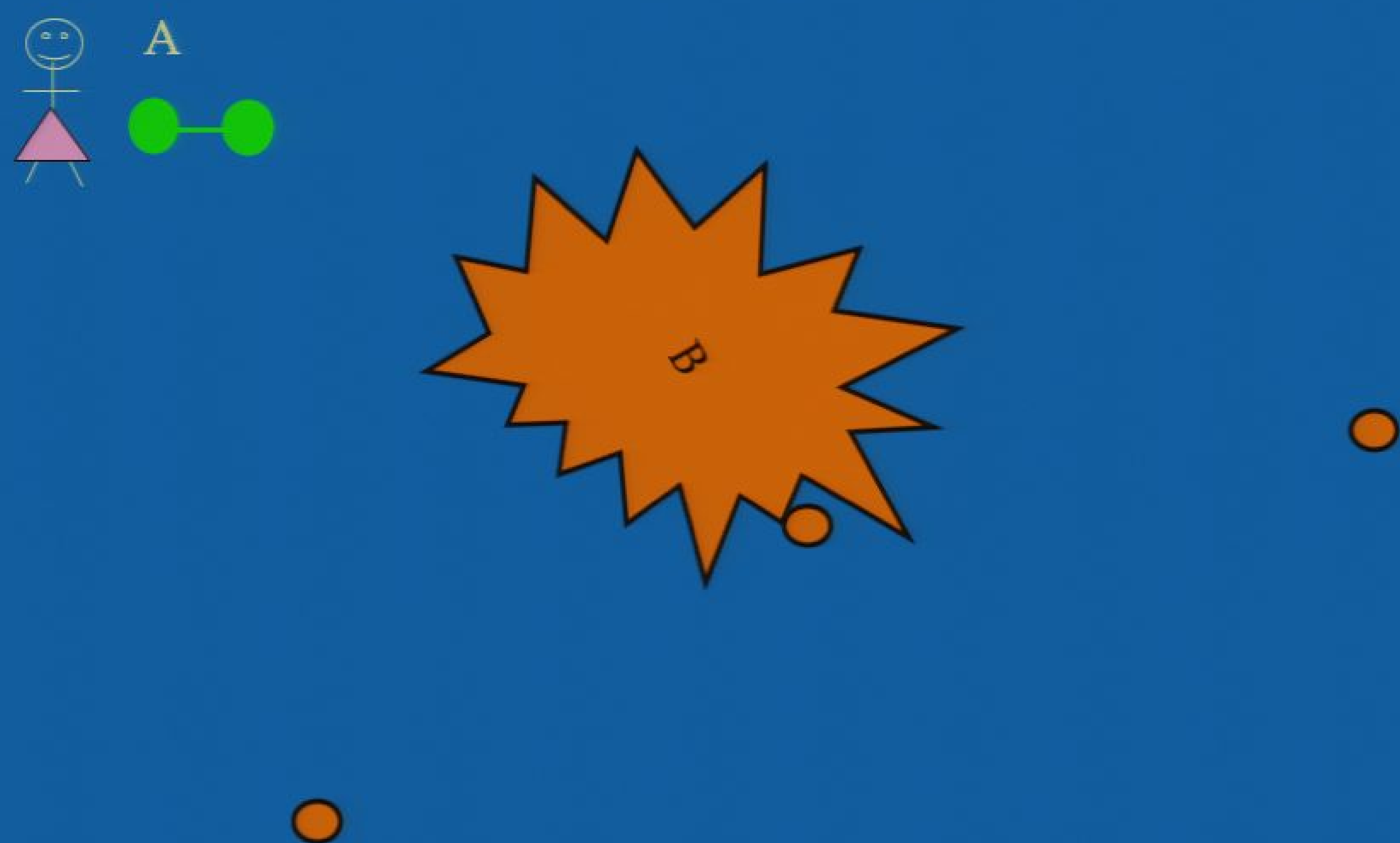

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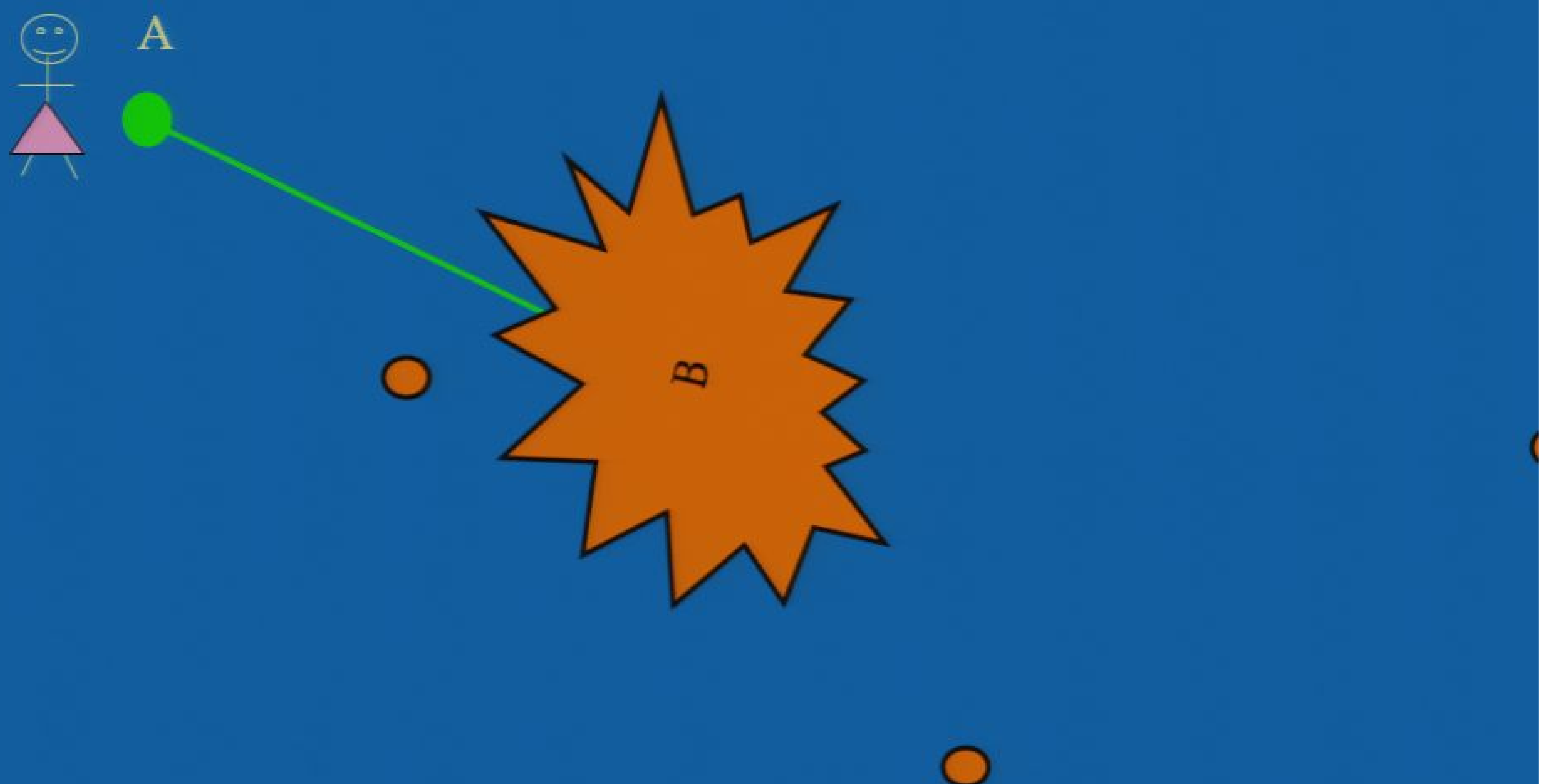

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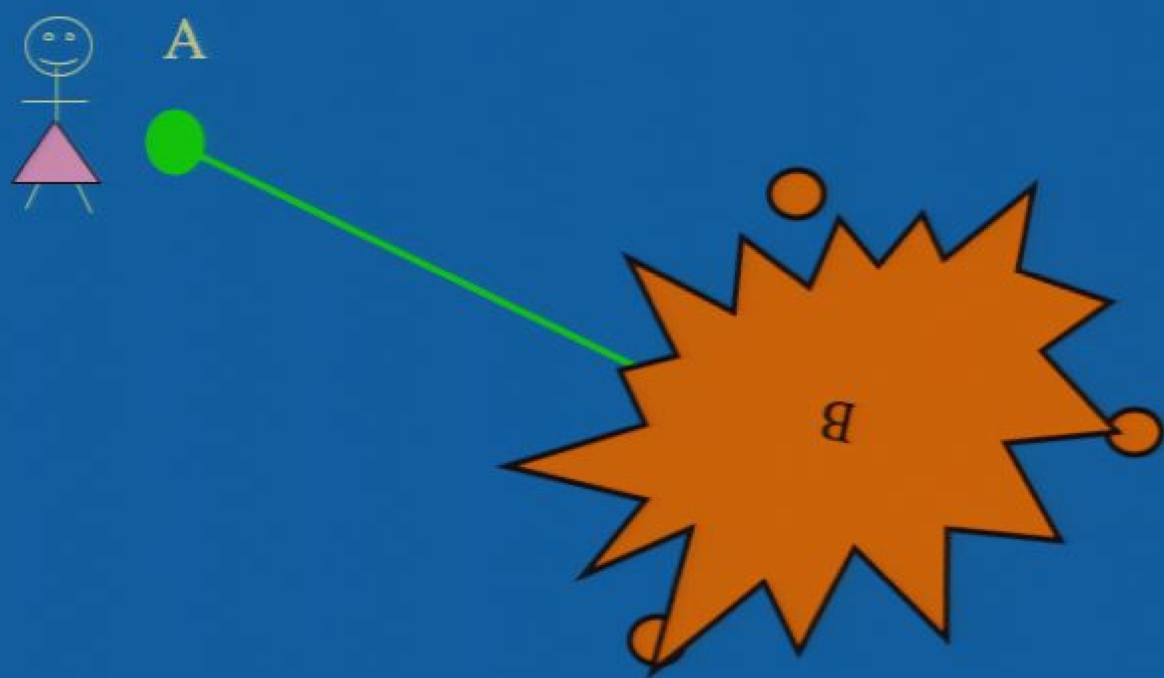

How long must Alice wait until the "information about A" gets radiated?

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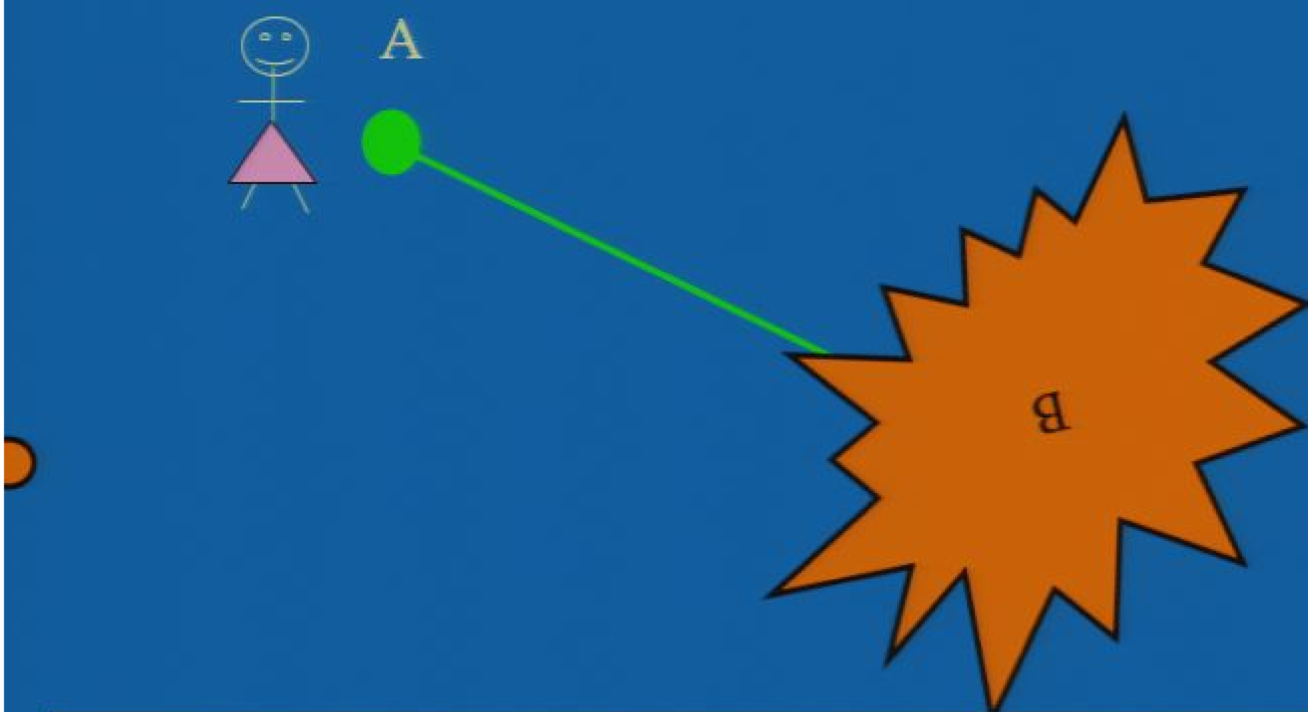

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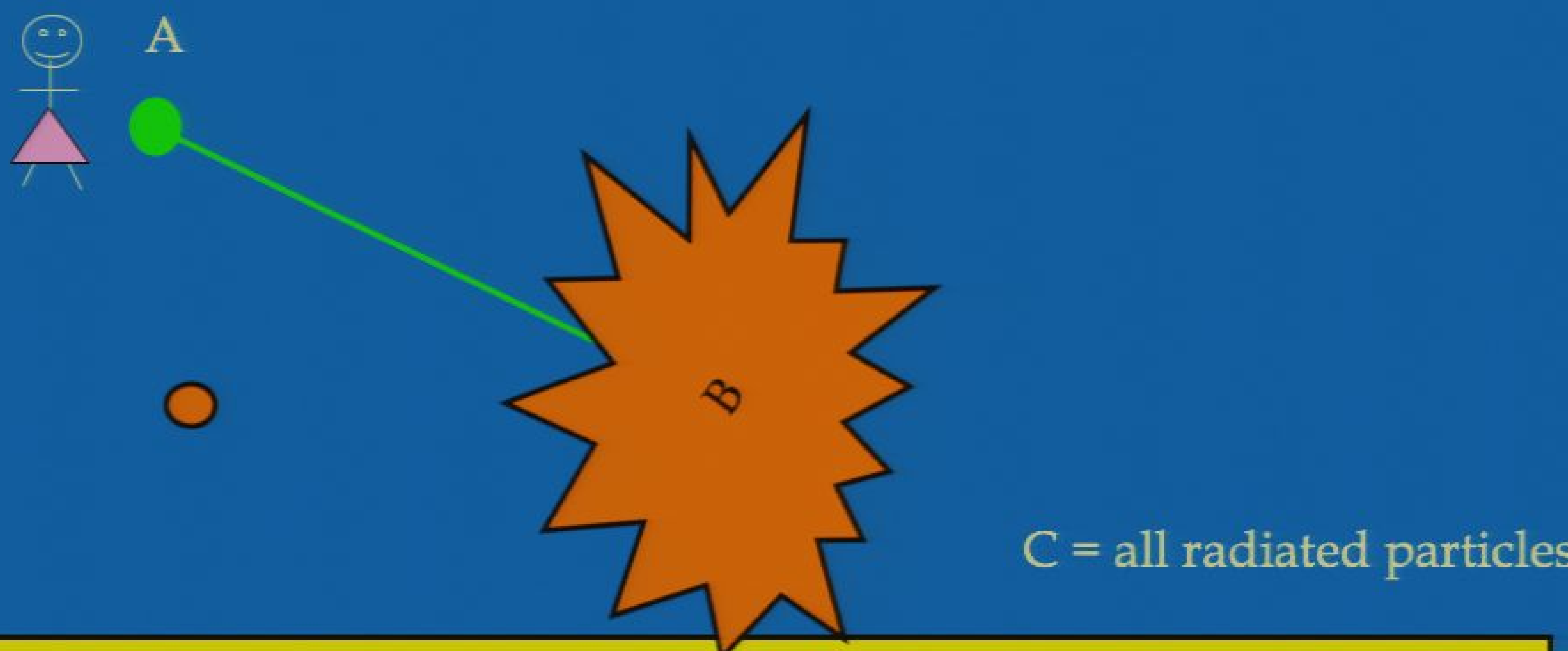

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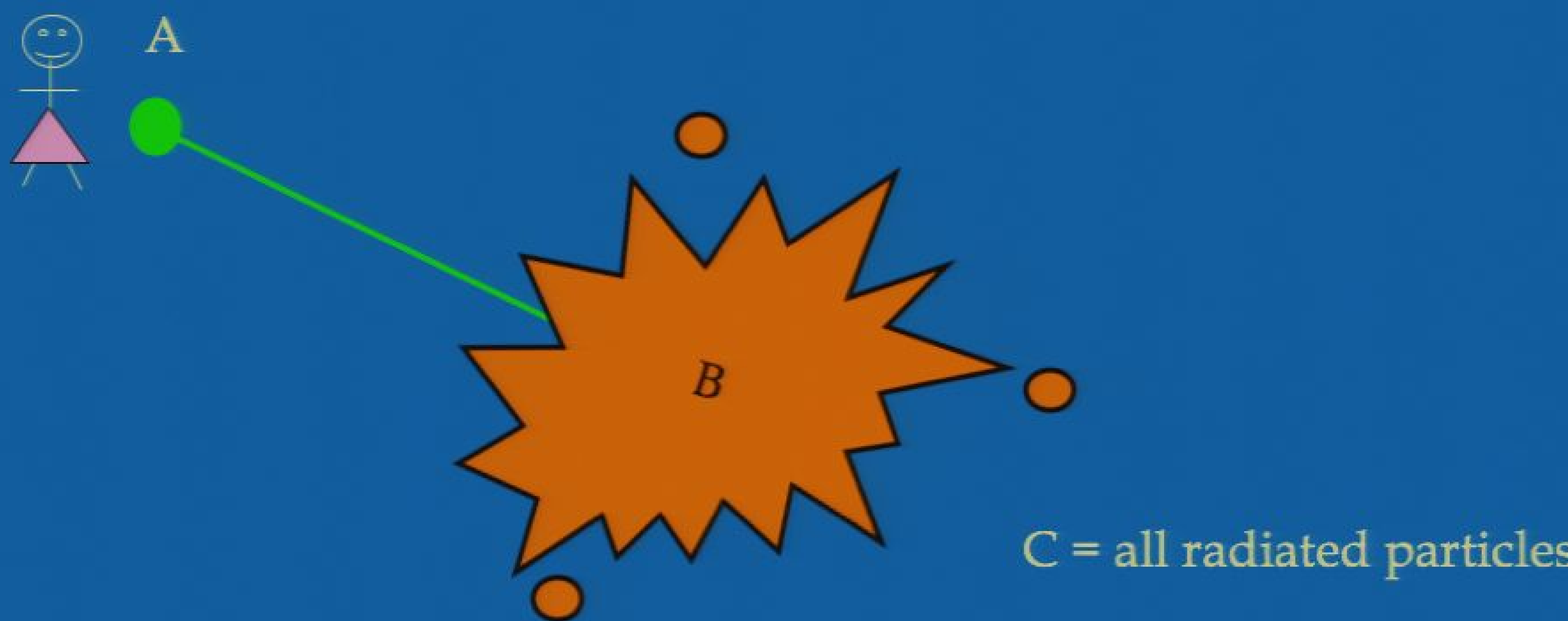

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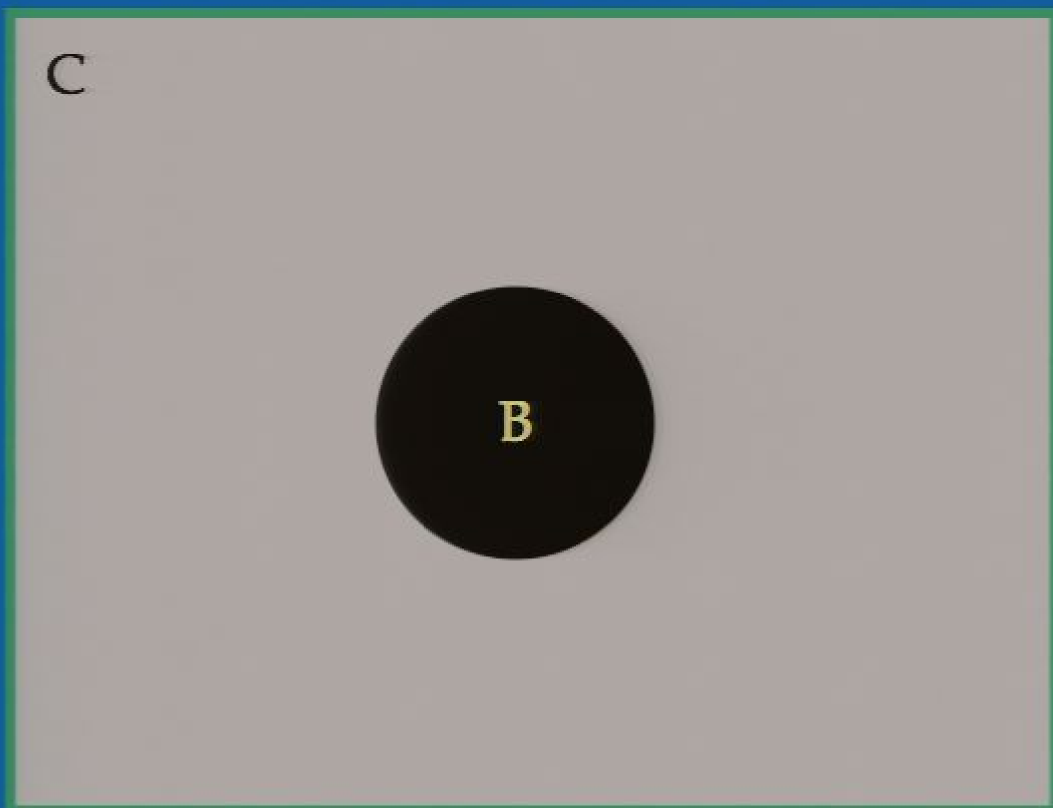
For sufficiently mixing dynamics,
information about A is released *almost immediately*

Lessons for black hole information loss?



t_0: Pure state:

B: Black hole

C: Rest of universe

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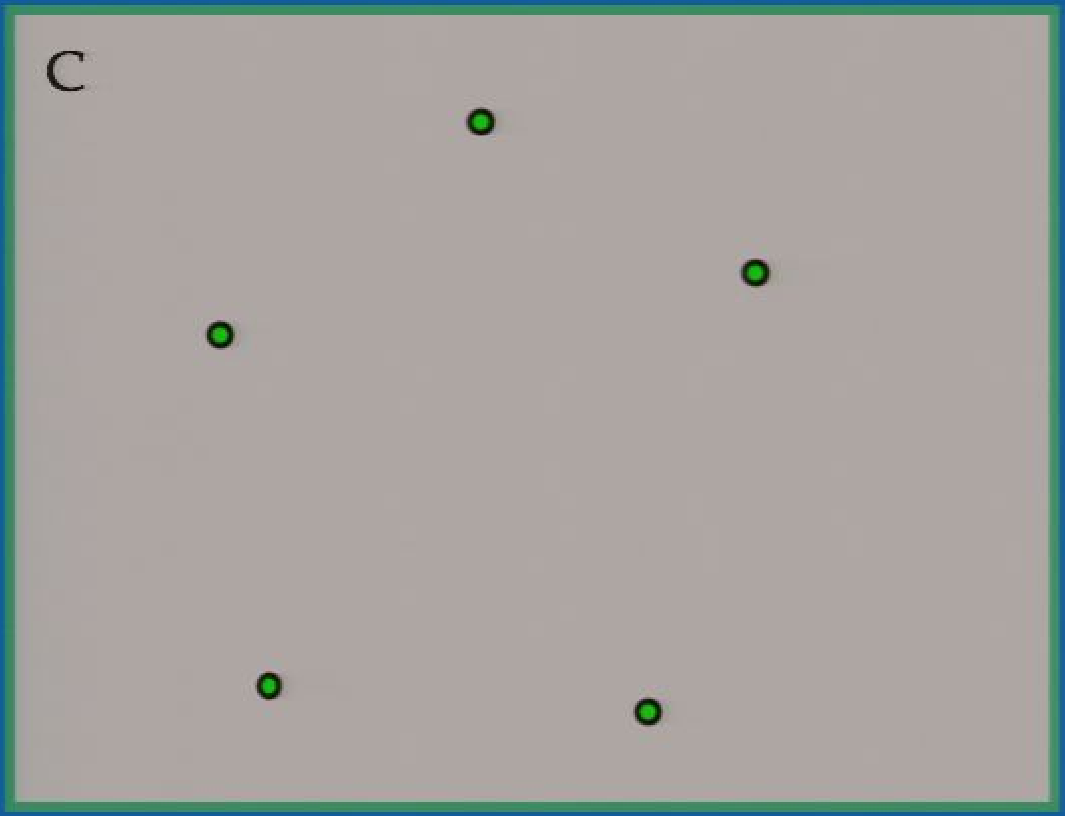

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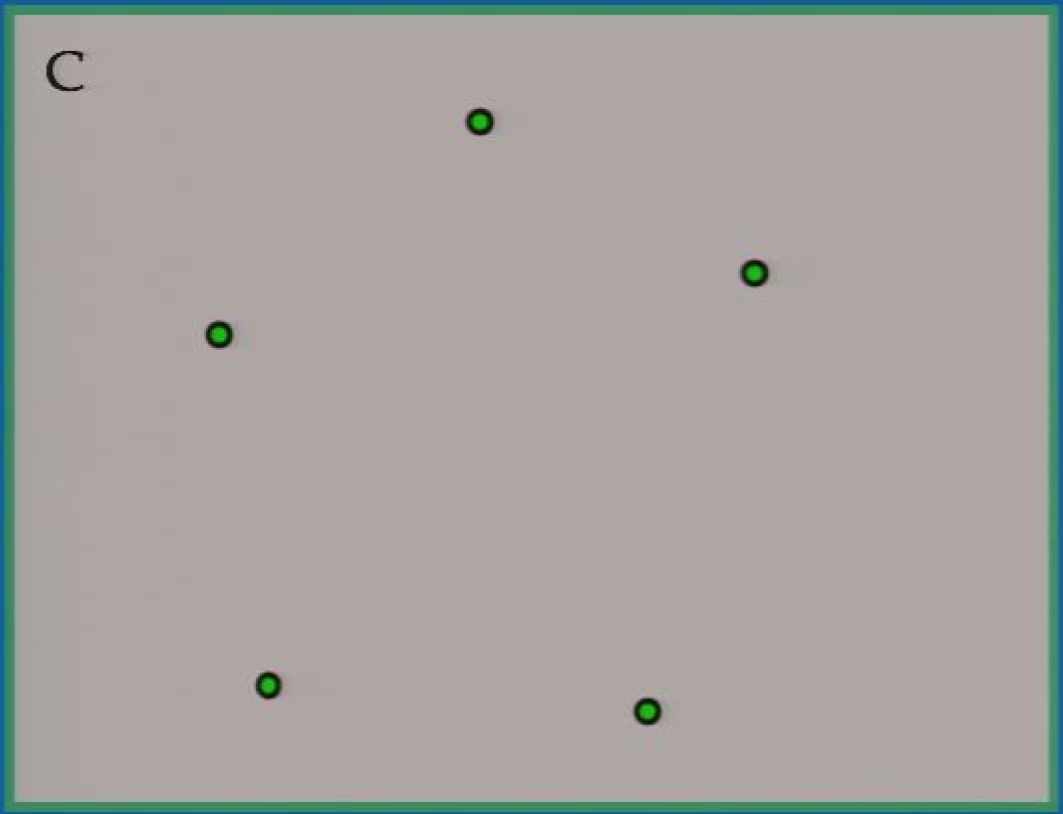

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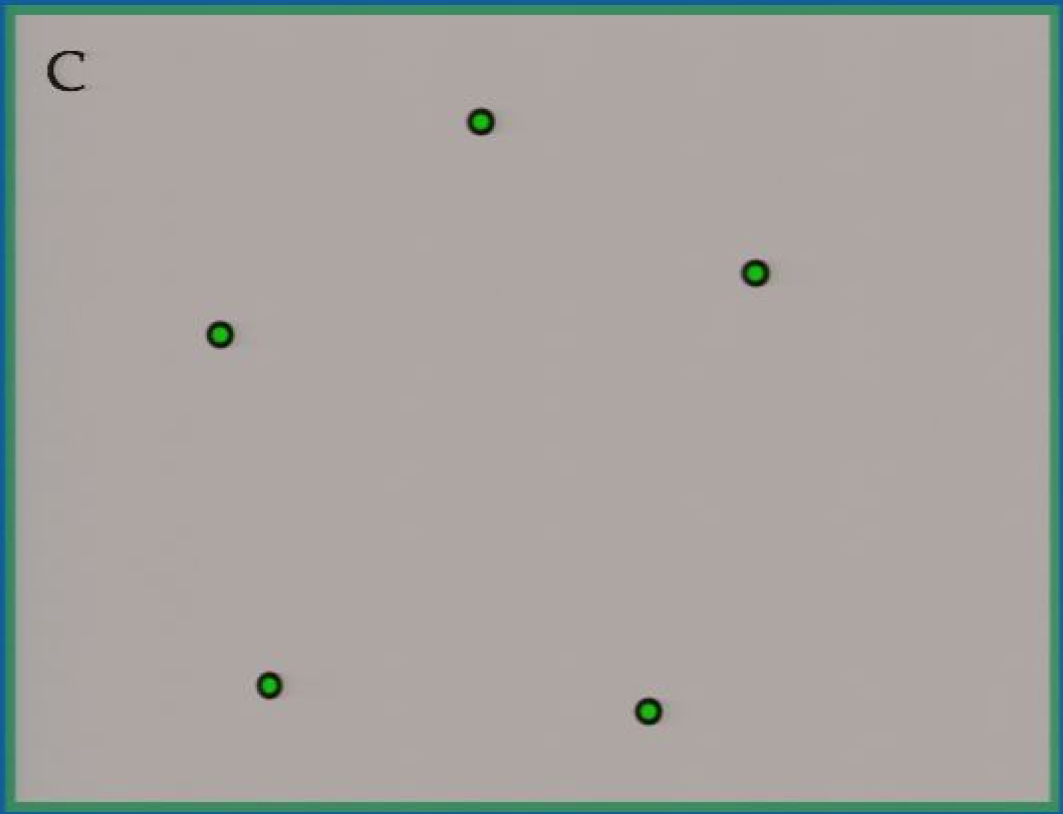

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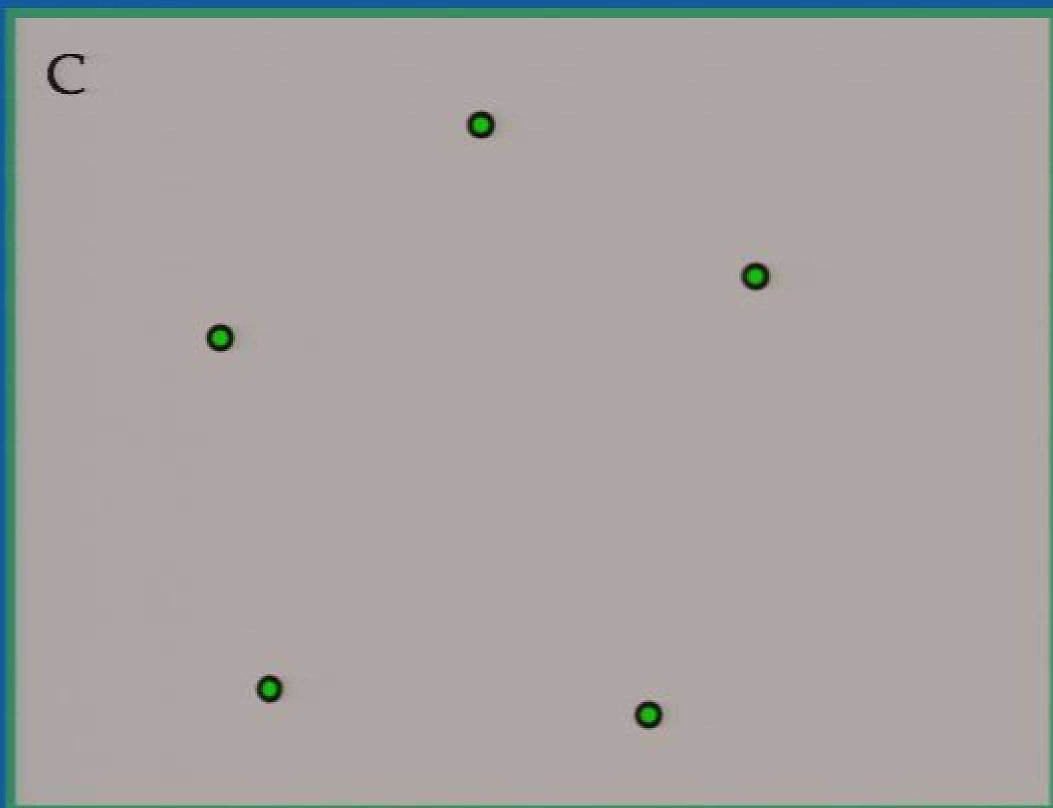

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Standard question: Is final state mixed or pure?

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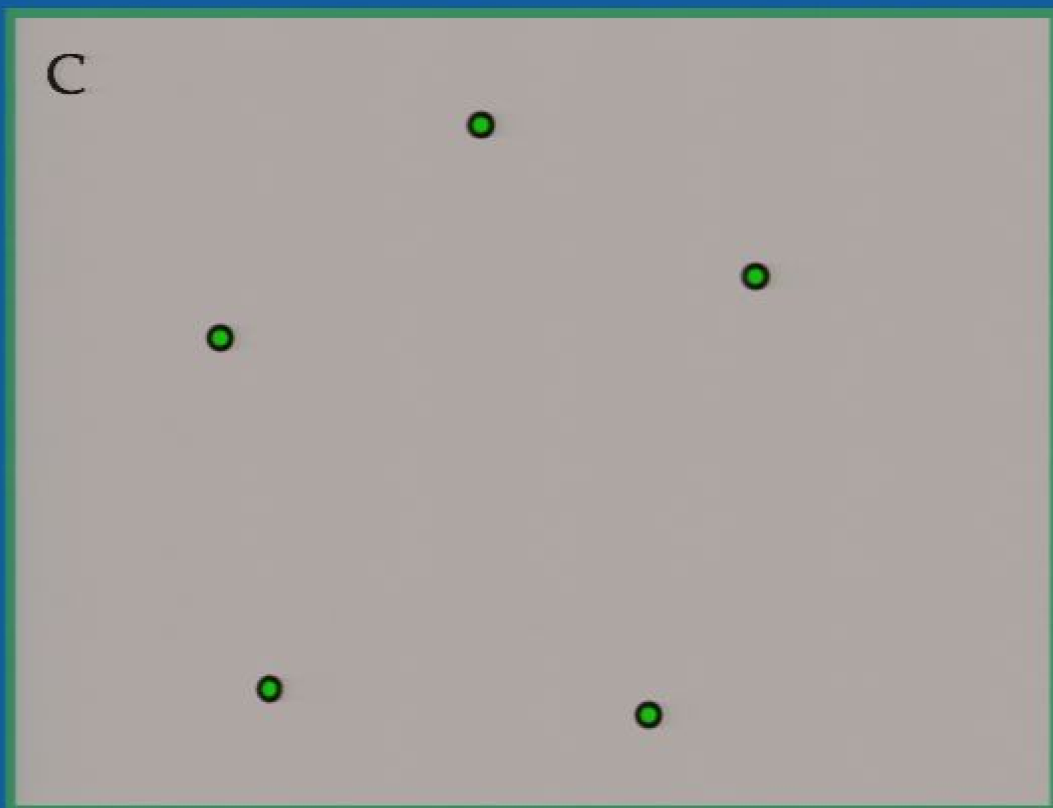

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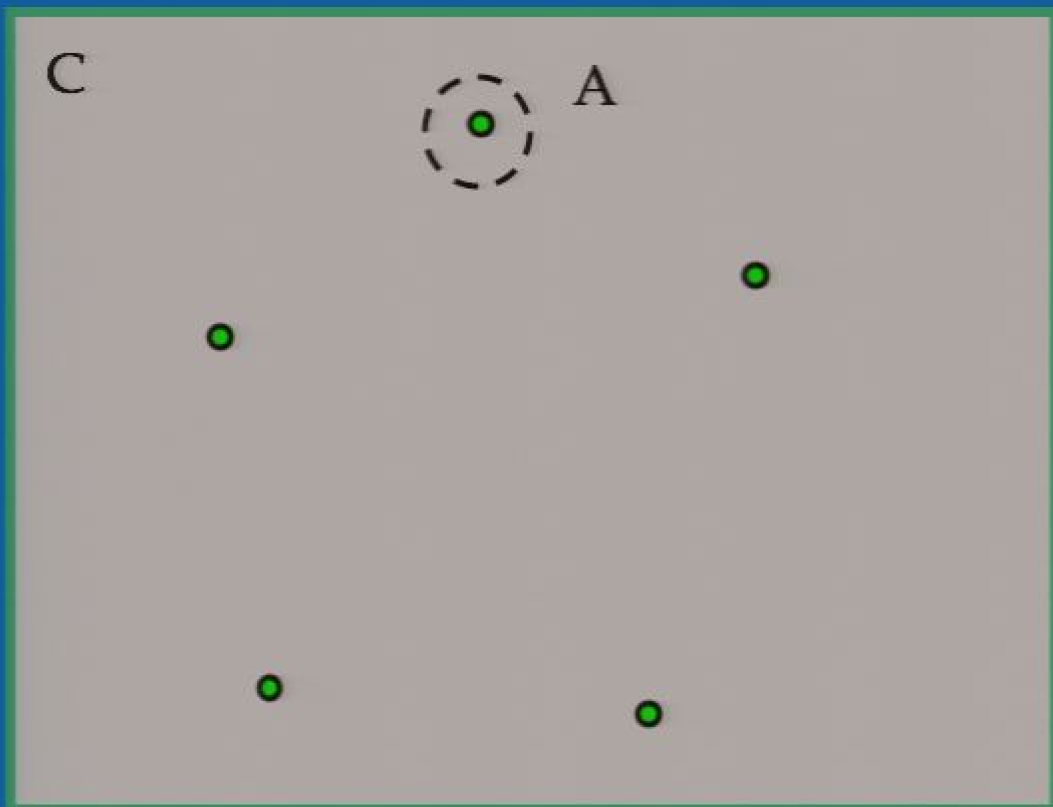

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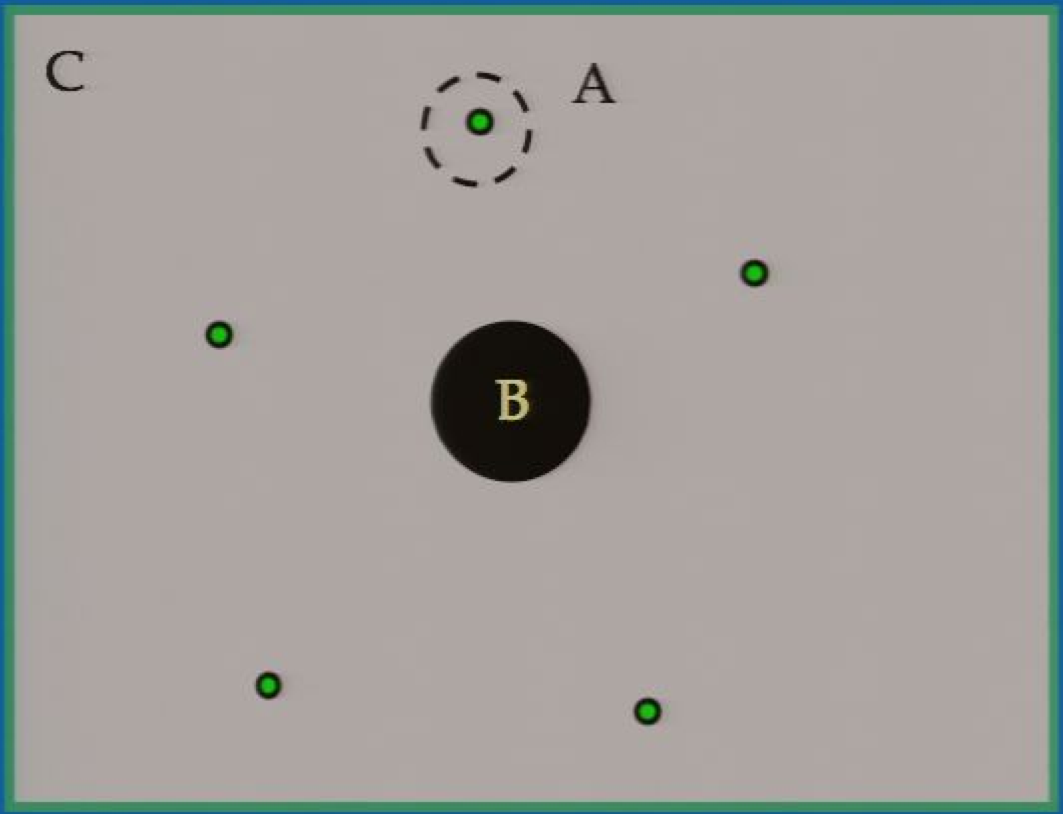

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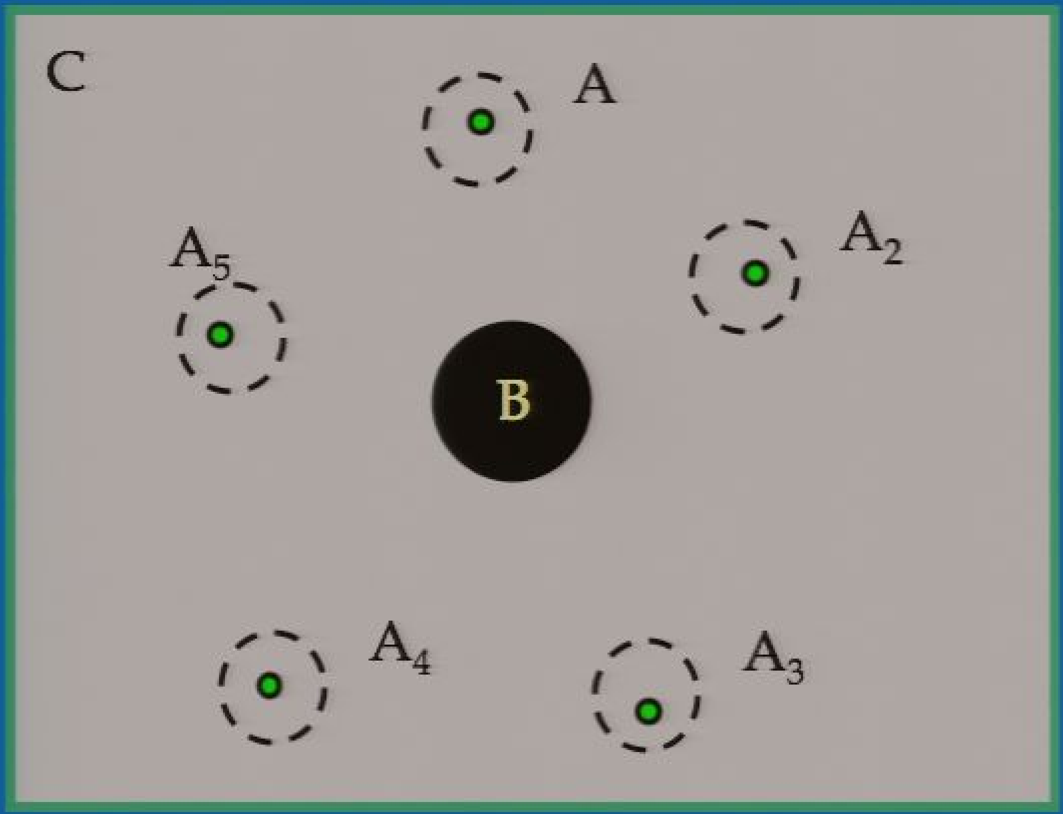

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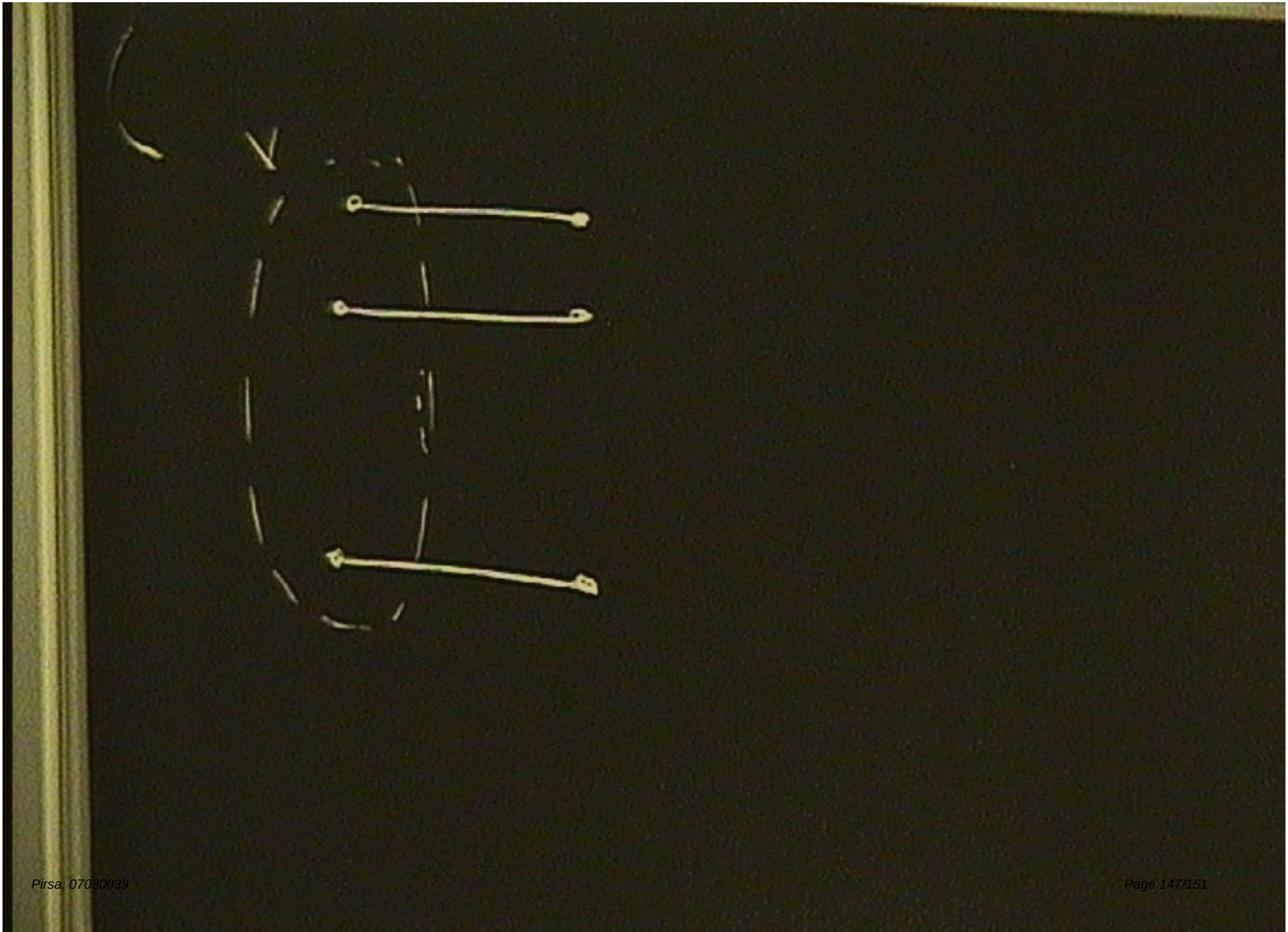

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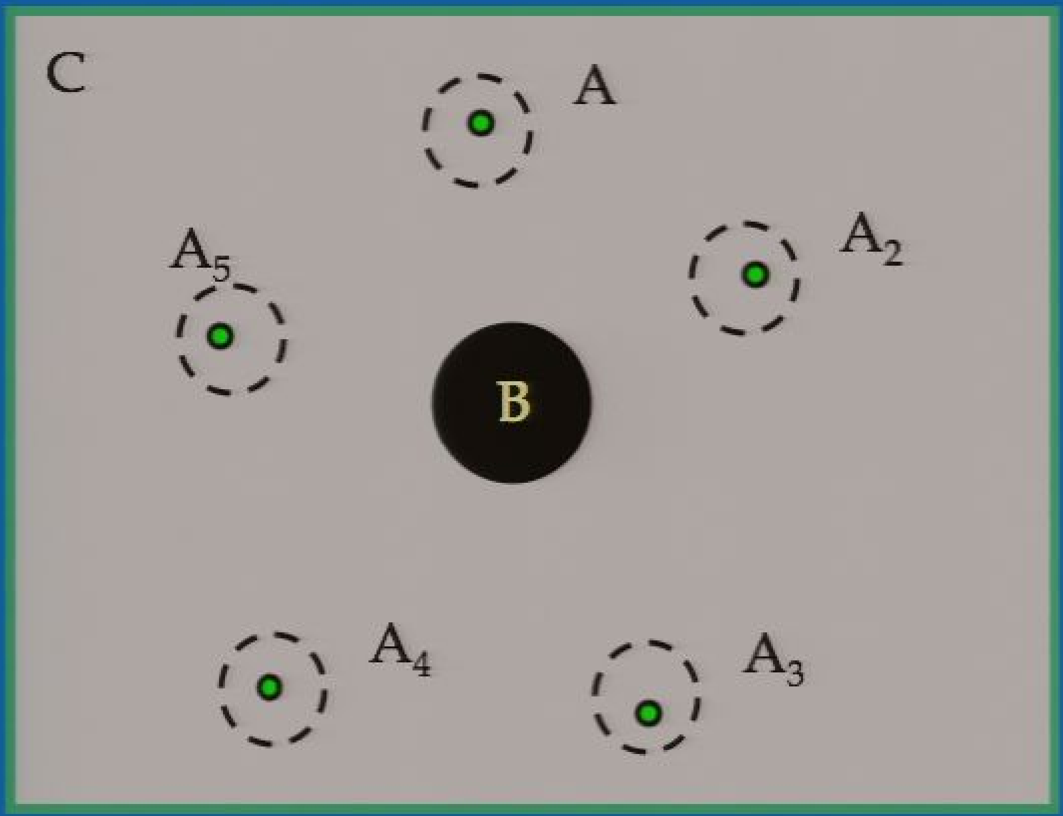

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Summary

- Forgetting is a basic primitive for quantum information theory
- Detailed understanding of how to do it most efficiently
- These methods are generated by generic unitary transformations: could be useful for understanding real physics

http://arxiv.org/abs/quant-ph/0606225