Quantum Mechanics

from an Information Theory Perspective

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Introduction

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  - unitary evolution - time reversible
  - wavefunction collapse - non reversible

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  - wavefunction collapse - non reversible
- avoid wavefunction collapse? (see [Garret, 2016])
- measurement $\approx$ entanglement

Outline

Motivation

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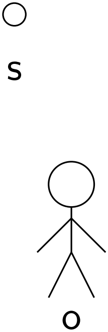
- three participants: system, observer and environment (no-deletion [Arun Kumar Pati, 2000])
- system, observer and environment form a closed system
- system and observer entangled, environment absorbs observer state

Motivation (A Schematic)



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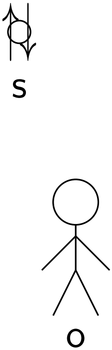

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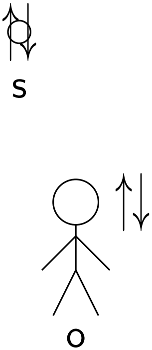

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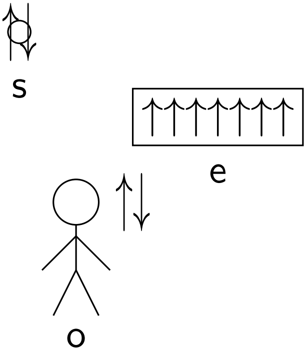

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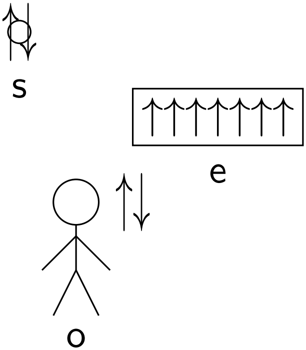
$$|\psi\rangle_{\mathrm{s}} = \psi_0 |0\rangle_{\mathrm{s}} + \psi_1 |1\rangle_{\mathrm{s}}$$



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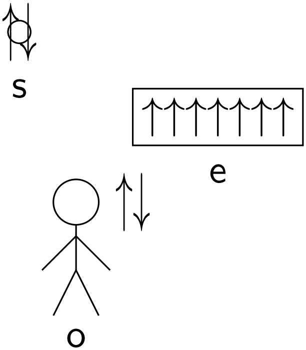

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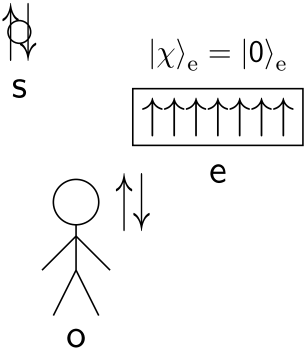

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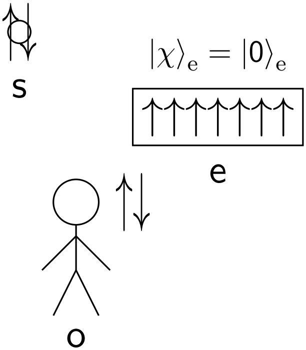

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$$|\psi\rangle_{\mathrm{s}}, |\phi\rangle_{\mathrm{o}}, |\chi\rangle_{\mathrm{e}} \in \mathcal{H} = \mathrm{span}\{|0\rangle, |1\rangle\}$$

Motivation (The Measurement Procedure)

overall measurement procedure:

$$|\psi\rangle_{\mathrm{s}} |\phi\rangle_{\mathrm{o}} |\chi\rangle_{\mathrm{e}} = (\psi_0 |0\rangle + \psi_1 |1\rangle)_{\mathrm{s}} (\phi_0 |0\rangle + \phi_1 |1\rangle)_{\mathrm{o}} |0\rangle_{\mathrm{e}}$$

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|000\rangle_{\rm soe} &\rightarrow |000\rangle_{\rm soe} \\
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\end{aligned}
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Motivation (Extension to Basis)

a natural unitary extension:

$$\begin{aligned} |001\rangle_{\mathrm{soe}} &\to |010\rangle_{\mathrm{soe}} \\ |011\rangle_{\mathrm{soe}} &\to |011\rangle_{\mathrm{soe}} \\ |101\rangle_{\mathrm{soe}} &\to |100\rangle_{\mathrm{soe}} \\ |111\rangle_{\mathrm{soe}} &\to |101\rangle_{\mathrm{soe}} \end{aligned}$$

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$$

$$
|\psi\rangle_{\mathrm{s}} |\phi\rangle_{\mathrm{o}} |1\rangle_{\mathrm{e}} \to (\psi_0 |01\rangle + \psi_1 |10\rangle)_{\mathrm{so}} |\phi\rangle_{\mathrm{e}} =: \left|\bar{\Psi}\right\rangle_{\mathrm{so}} |\phi\rangle_{\mathrm{e}}
$$

Motivation (Generic State)

generic environment state:

$$|\psi\rangle_{\rm s} |\phi\rangle_{\rm o} |\chi\rangle_{\rm e} \quad = \quad (\psi_0 |0\rangle + \psi_1 |1\rangle)_{\rm s}(\phi_0 |0\rangle + \phi_1 |1\rangle)_{\rm o}(\chi_0 |0\rangle + \chi_1 |1\rangle)_{\rm e}$$

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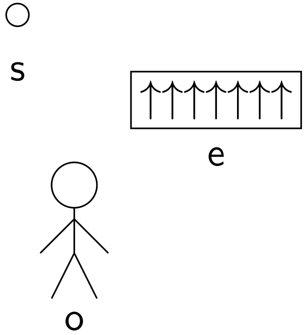
Motivation (Summarising)



North points up

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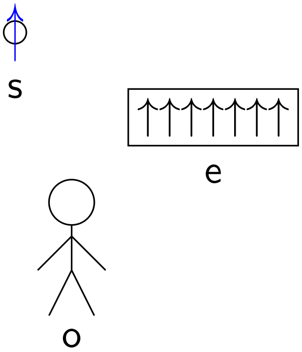

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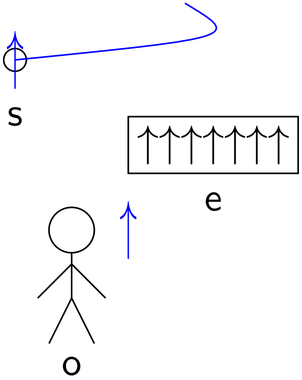

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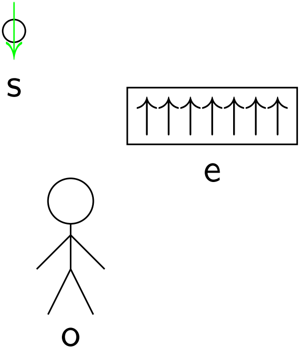

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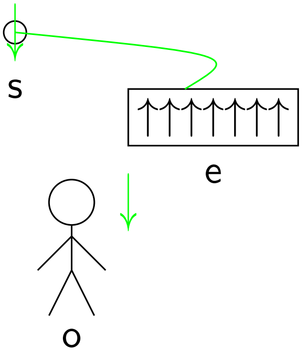

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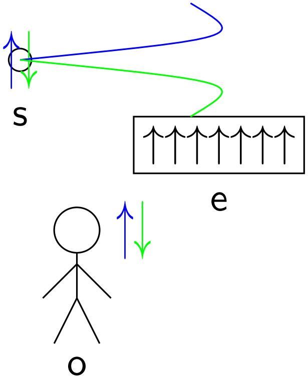

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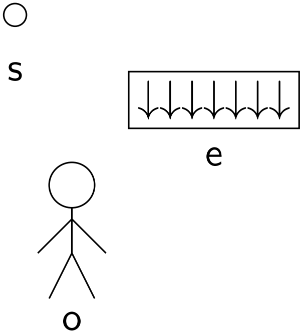

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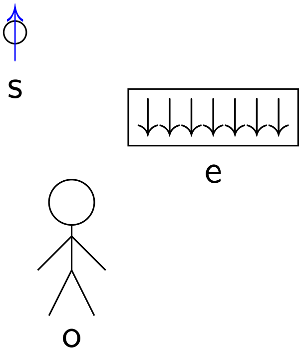

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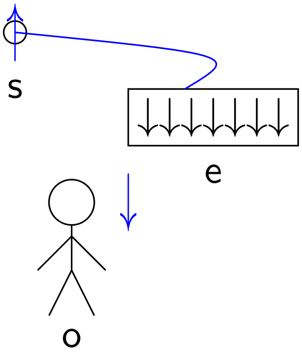

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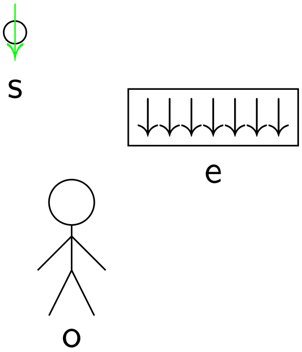

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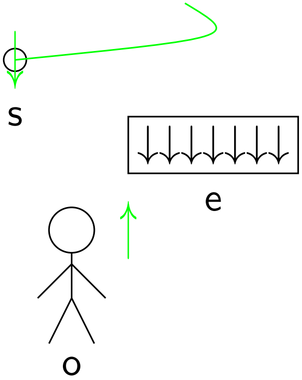

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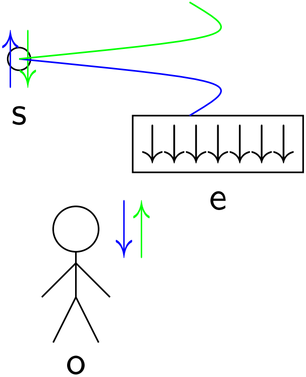

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Local Operators

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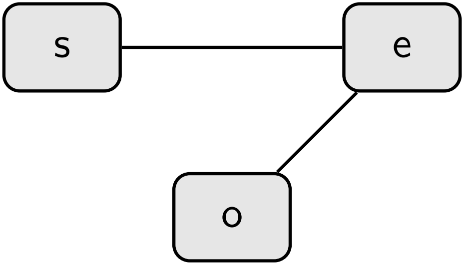

Local Operators (Imprint)

$\mathcal{I}_{\mathrm{a}\to\mathrm{b}}$:

$$\begin{aligned}
\mathcal{I}_{\mathrm{a}\to\mathrm{b}} \left|00\right\rangle_{\mathrm{ab}} &= \left|00\right\rangle_{\mathrm{ab}} \\
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$\equiv$ CNOT gate

Local Operators (Swap)

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$\equiv$ SWAP gate

Local Operators

$$
\begin{array}{ccccc}
 & \mathcal{I}_{s\to e} & & \mathcal{S}_{o\leftrightarrow e} & \\
|000\rangle_{\mathrm{soe}} & \longrightarrow & |000\rangle_{\mathrm{soe}} & \longrightarrow & |000\rangle_{\mathrm{soe}} \\
|010\rangle_{\mathrm{soe}} & \longrightarrow & |010\rangle_{\mathrm{soe}} & \longrightarrow & |001\rangle_{\mathrm{soe}} \\
|100\rangle_{\mathrm{soe}} & \longrightarrow & |101\rangle_{\mathrm{soe}} & \longrightarrow & |110\rangle_{\mathrm{soe}} \\
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generalised imprint:

$$\mathcal{I}_{\mathrm{a}\to\mathrm{b}} |i\rangle_{\mathrm{a}} |j\rangle_{\mathrm{b}} = |i\rangle_{\mathrm{a}} |j+i\rangle_{\mathrm{b}}$$

'$+$' defined appropriately

Generalisation (The Procedure)

$$|\zeta\rangle_{\mathrm{soe}} = |\psi\rangle_{\mathrm{s}} |\phi\rangle_{\mathrm{o}} |\chi\rangle_{\mathrm{e}} \quad = \quad \left(\sum_i \psi_i |i\rangle_{\mathrm{s}}\right) \left(\sum_j \phi_j |j\rangle_{\mathrm{o}}\right) \left(\sum_k \chi_k |k\rangle_{\mathrm{e}}\right)$$

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&= \sum_k \chi_k \left(\sum_i \psi_i |i\rangle |i+k\rangle\right)_{\mathrm{so}} |\phi\rangle_{\mathrm{e}} \\
&=: \left(\sum_k \chi_{\mathrm{k}} |\Psi_k\rangle_{\mathrm{so}}\right) |\phi\rangle_{\mathrm{e}}
\end{aligned}
$$

Learning the Environment

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starting with "classical" environment:

$$|\chi\rangle_{\mathrm{e}} = \sum_k \chi_k |k\rangle_{\mathrm{e}_1} |k\rangle_{\mathrm{e}_2} |k\rangle_{\mathrm{e}_3} \dots |k\rangle_{\mathrm{e}_\mathrm{N}}$$

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perfect entanglement obtained

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perfect entanglement obtained

$|i\rangle$

$|\phi\rangle$

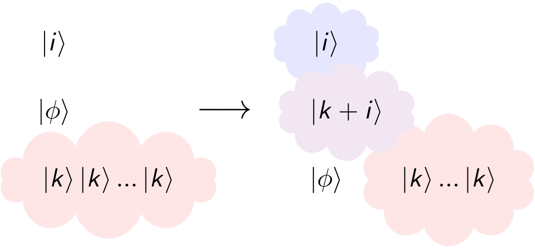
$|k\rangle\,|k\rangle \dots |k\rangle$

Learning the Environment

starting with "classical" environment:

$$|\chi\rangle_{\mathrm{e}} = \sum_k \chi_k \, |k\rangle_{\mathrm{e_1}} \, |k\rangle_{\mathrm{e_2}} \, |k\rangle_{\mathrm{e_3}} \ldots |k\rangle_{\mathrm{e_N}}$$

perfect entanglement obtained

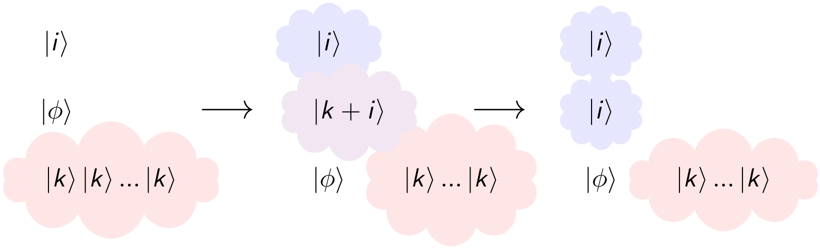


Learning the Environment

starting with "classical" environment:

$$|\chi\rangle_{\mathrm{e}} = \sum_k \chi_k \, |k\rangle_{\mathrm{e}_1} |k\rangle_{\mathrm{e}_2} |k\rangle_{\mathrm{e}_3} \ldots |k\rangle_{\mathrm{e}_\mathrm{N}}$$

perfect entanglement obtained



Learning the Environment (The Procedure)

$$\mathcal{S}_{o\leftrightarrow e_1} \circ \mathcal{I}_{s\rightarrow e_1} \qquad \begin{aligned} \mathrm{s} &: |i\rangle_{\mathrm{s}} \\ \mathrm{o} &: |\phi\rangle_{\mathrm{o}} \\ \mathrm{e} &: |k\rangle_{\mathrm{e_1}} \, |k\rangle_{\mathrm{e_2}} \ldots |k\rangle_{\mathrm{e_N}} \end{aligned}$$

$$\hookrightarrow \qquad \begin{aligned} \mathrm{s} &: |i\rangle_{\mathrm{s}} \\ \mathrm{o} &: |k+i\rangle_{\mathrm{o}} \\ \mathrm{e} &: |\phi\rangle_{\mathrm{e_1}} \, |k\rangle_{\mathrm{e_2}} \ldots |k\rangle_{\mathrm{e_N}} \end{aligned}$$

Learning the Environment (The Procedure)

$$\mathcal{I}^{-1}_{e_2 \to o} \qquad \begin{aligned} &\mathrm{s}: |i\rangle_{\mathrm{s}} \\ &\mathrm{o}: |k+i\rangle_{\mathrm{o}} \\ &\mathrm{e}: |\phi\rangle_{\mathrm{e_1}} \, |k\rangle_{\mathrm{e_2}} \ldots |k\rangle_{\mathrm{e_N}} \end{aligned}$$

$$\hookrightarrow \qquad \begin{aligned} &\mathrm{s}: |i\rangle_{\mathrm{s}} \\ &\mathrm{o}: |k+i-k\rangle_{\mathrm{o}} \\ &\mathrm{e}: |\phi\rangle_{\mathrm{e_1}} \, |k\rangle_{\mathrm{e_2}} \ldots |k\rangle_{\mathrm{e_N}} \end{aligned}$$

$$= \qquad \begin{aligned} &\mathrm{s}: |i\rangle_{\mathrm{s}} \\ &\mathrm{o}: |i\rangle_{\mathrm{o}} \\ &\mathrm{e}: |\phi\rangle_{\mathrm{e_1}} \, |k\rangle_{\mathrm{e_2}} \ldots |k\rangle_{\mathrm{e_N}} \end{aligned}$$

Summary

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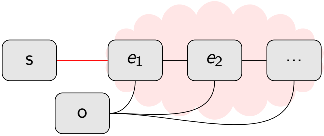
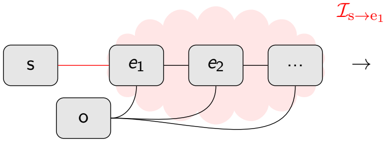


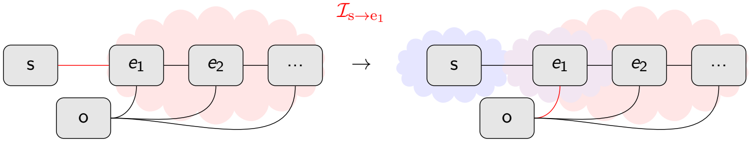
process of entangling system and observer to achieve measurement

Summary



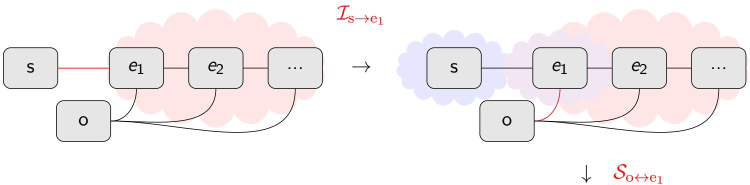
process of entangling system and observer to achieve measurement

Summary



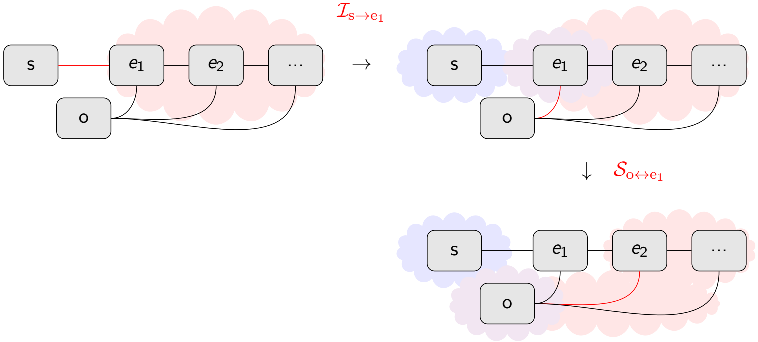
process of entangling system and observer to achieve measurement

Summary



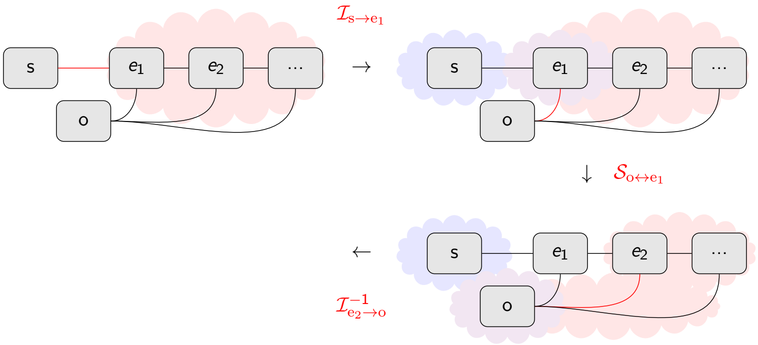
process of entangling system and observer to achieve measurement

Summary



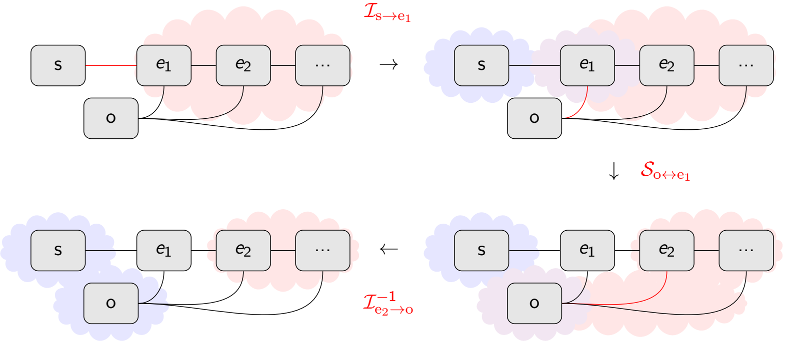
process of entangling system and observer to achieve measurement

Summary



process of entangling system and observer to achieve measurement

Summary



process of entangling system and observer to achieve measurement

Summary

Summary

- perfect entanglement between system and observer

Summary

- perfect entanglement between system and observer
- classical environment required for entanglement

Summary

- perfect entanglement between system and observer
- classical environment required for entanglement
- wavefunction also contains counterfactual branches!

Bibliography

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Thanks

Firstly, thanks to Torsten Enßlin for the all the guidance.

And thanks for listening!