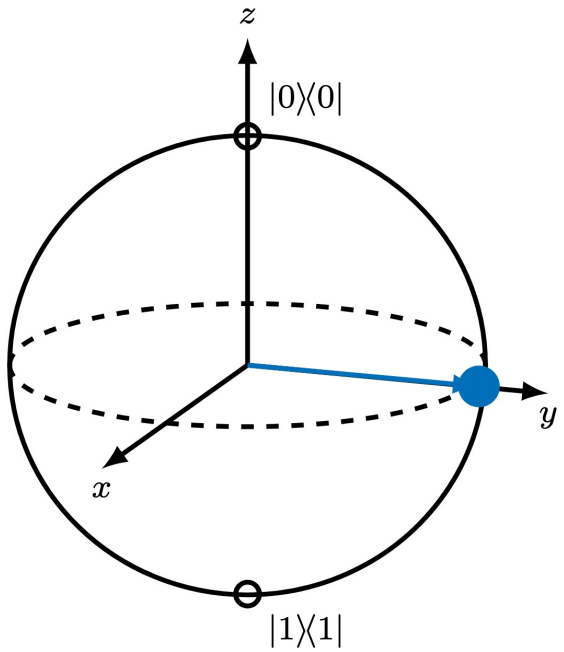
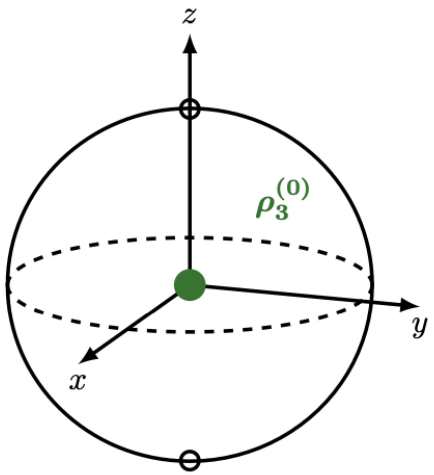
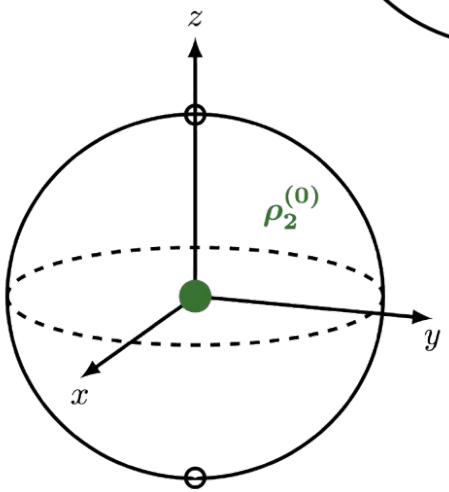
Decoherence, Predictability, and Robustness: Investigating the Preferred Division of a Quantum System into Subsystems





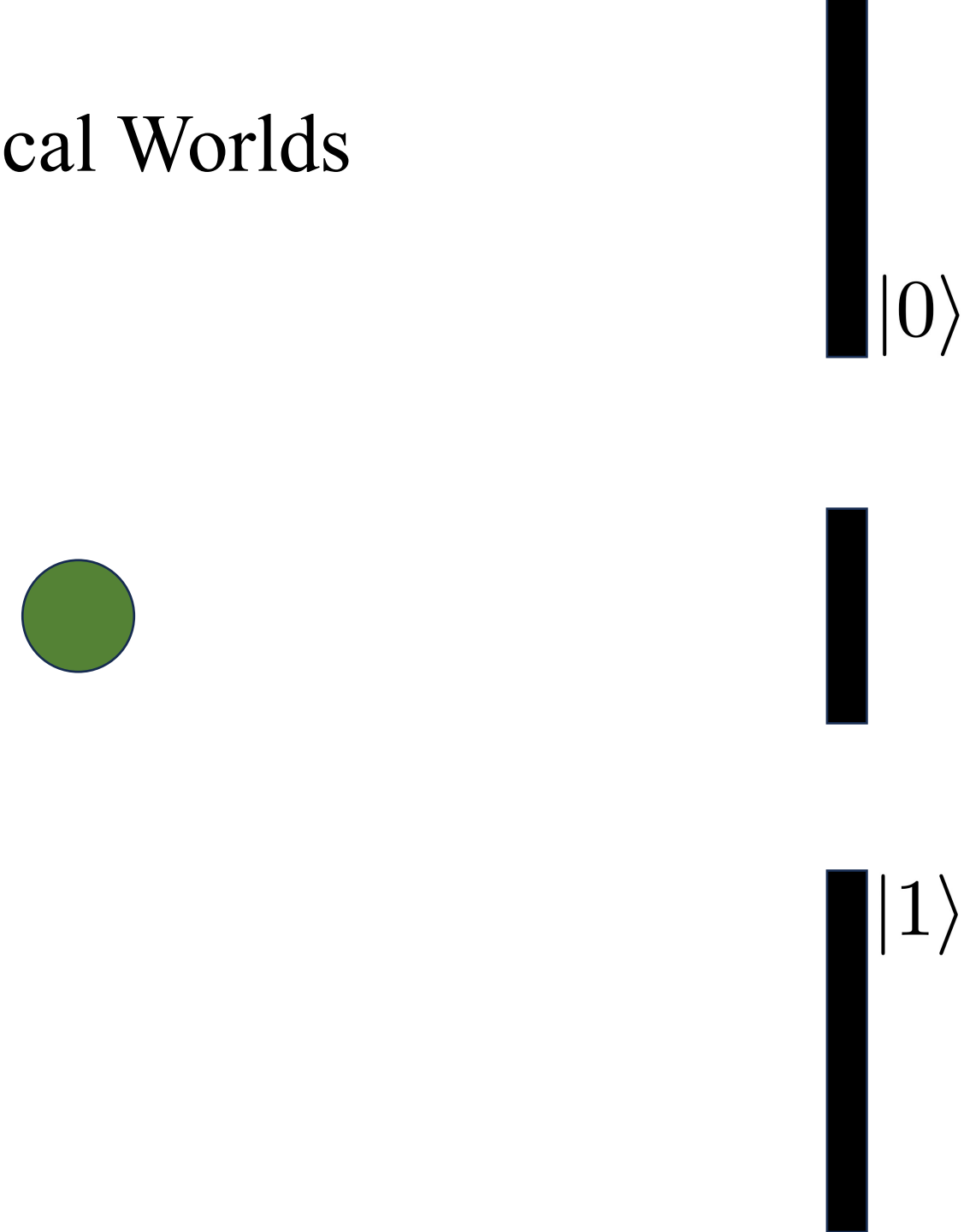


Aiden Karpf
Advised by Prof. Kevin Setter
Pomona College Thesis Presentation 2025

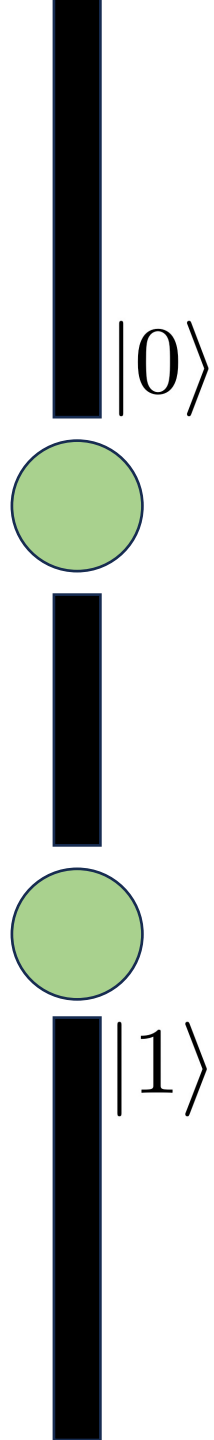
Quantum vs Classical Worlds

electron

Quantum vs Classical Worlds

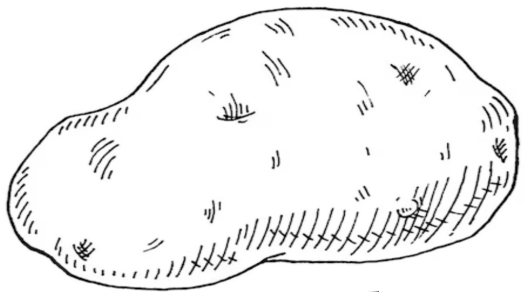


Quantum vs Classical Worlds



Quantum vs Classical Worlds

Quantum vs Classical Worlds

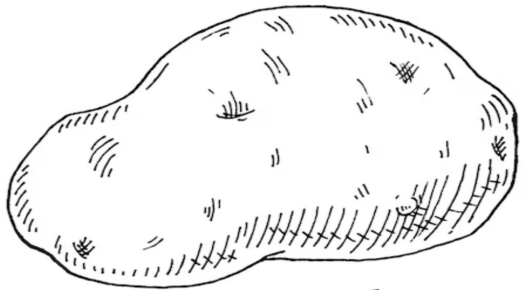


potato

$|0\rangle$

$|1\rangle$

Quantum vs Classical Worlds



$|0\rangle$

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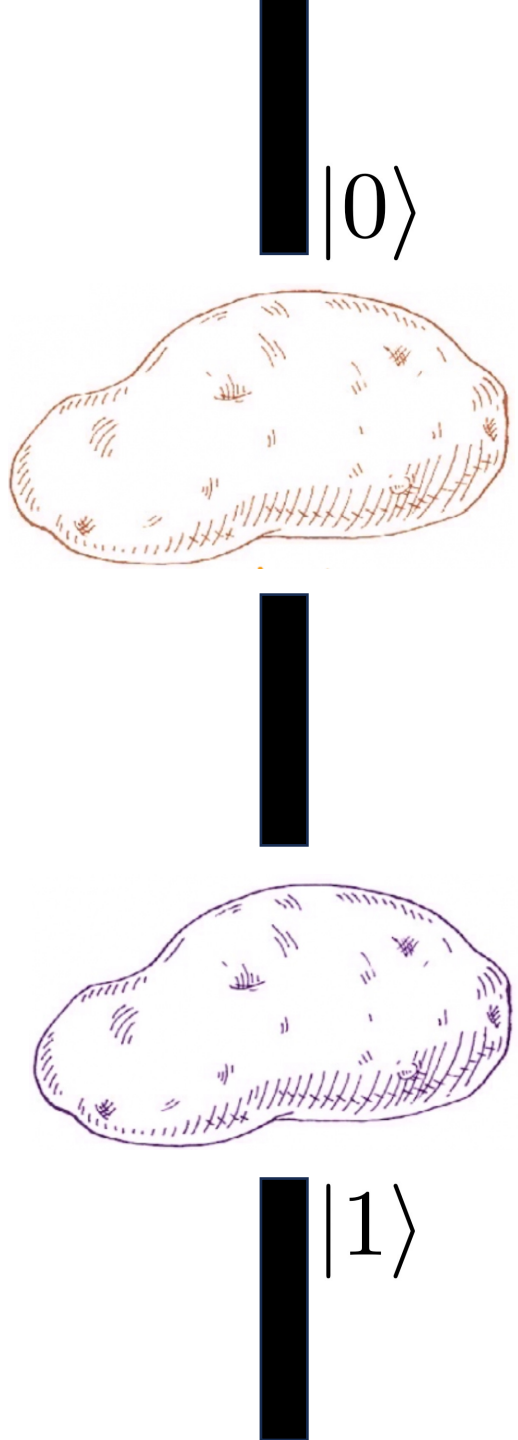
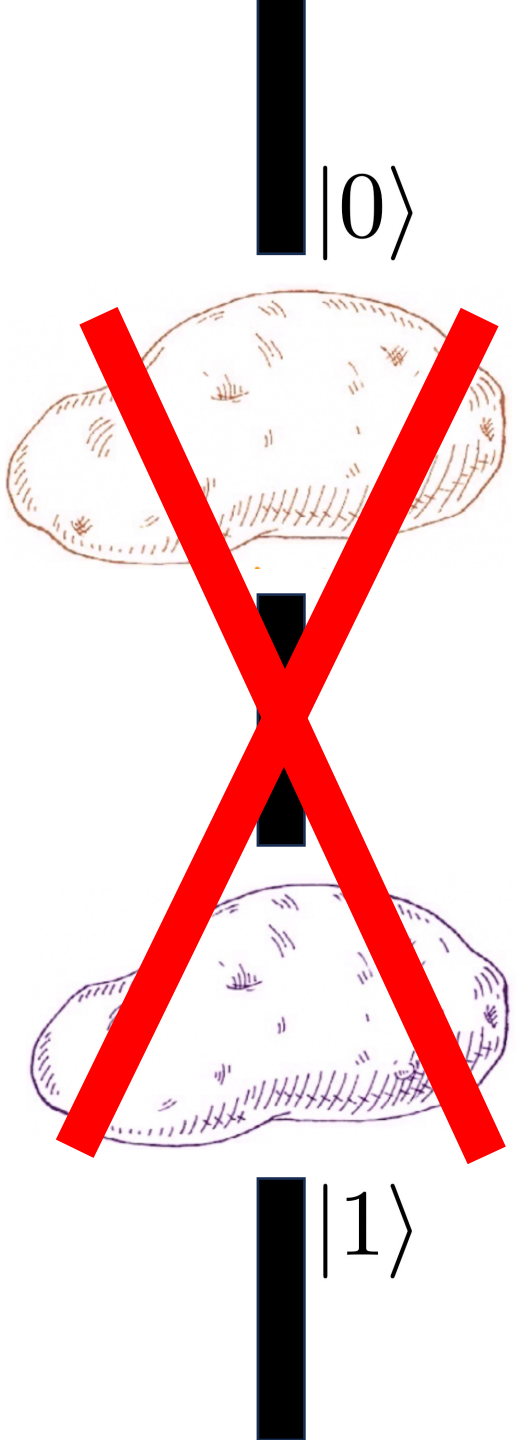
Quantum vs Classical Worlds



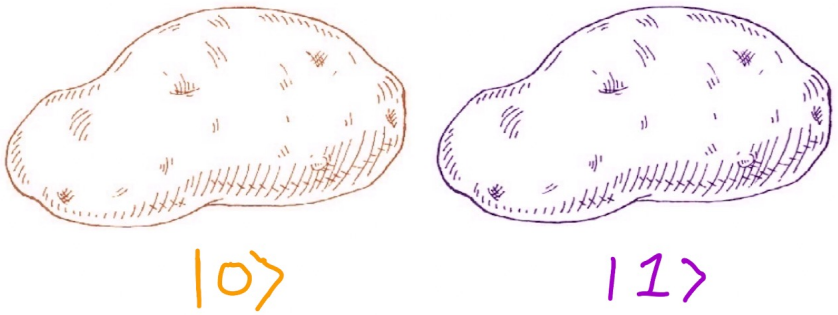
Quantum vs Classical Worlds



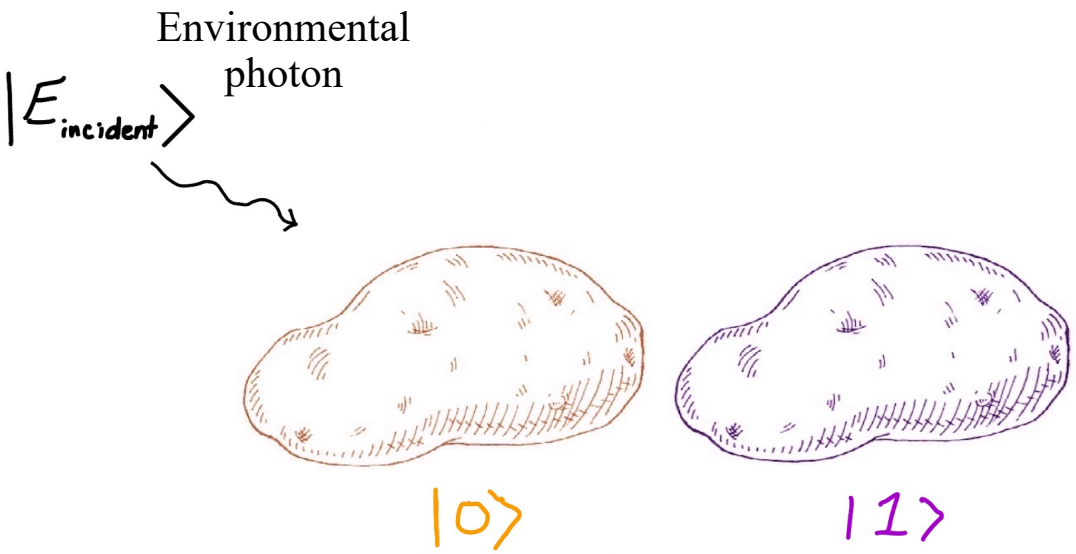
Quantum vs Classical Worlds

WHY NOT??

Potato in a Superposition State



Potato in a Superposition State



Potato in a Superposition State

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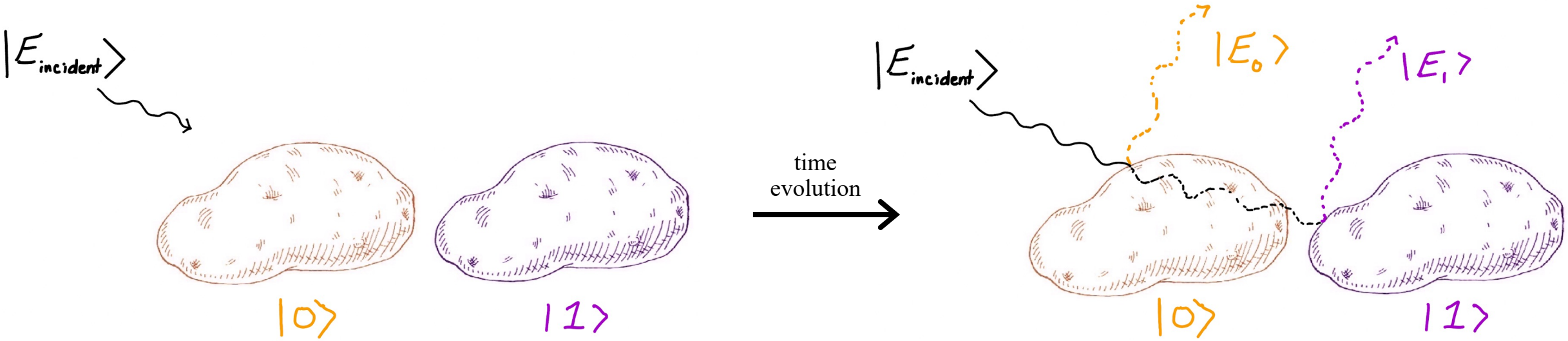
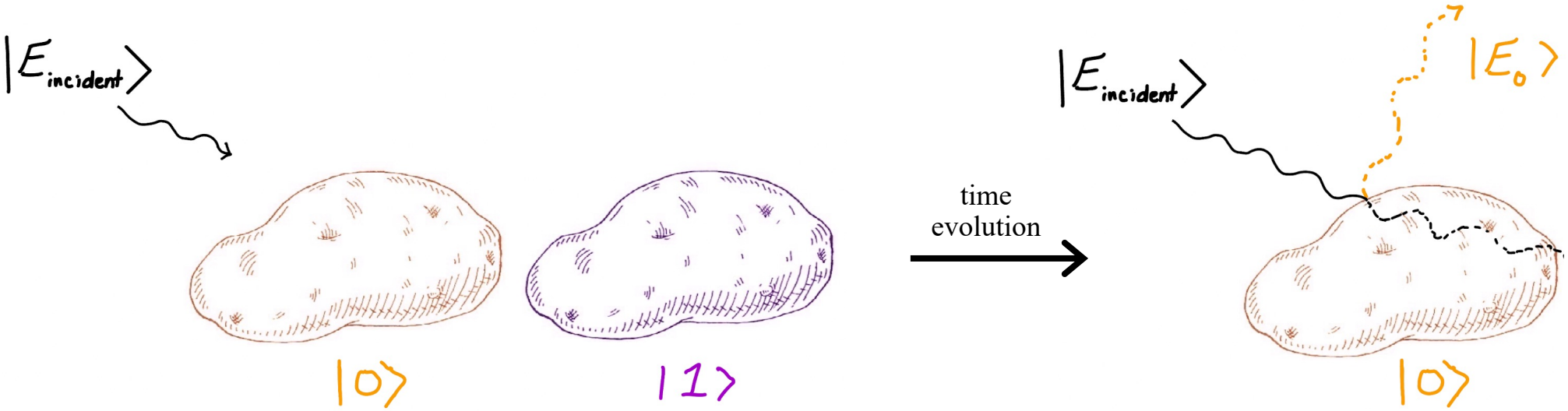
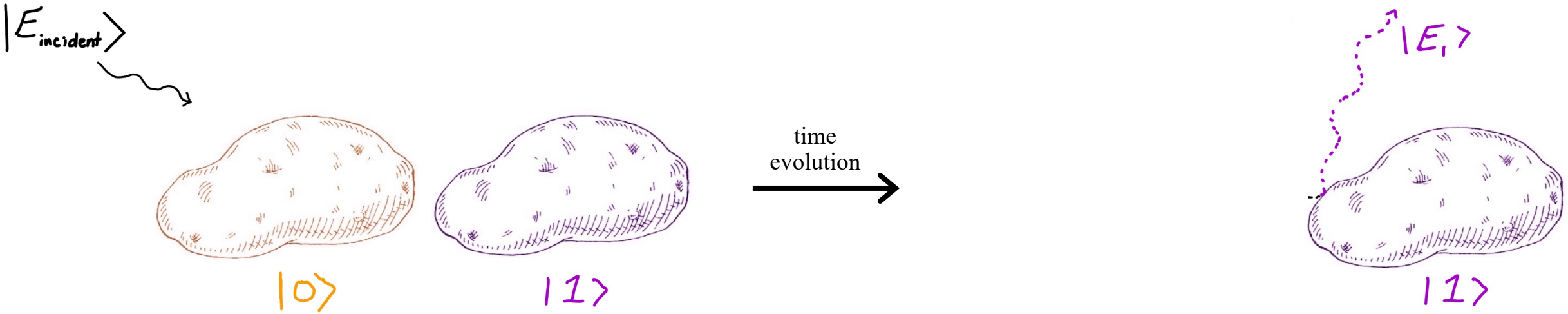


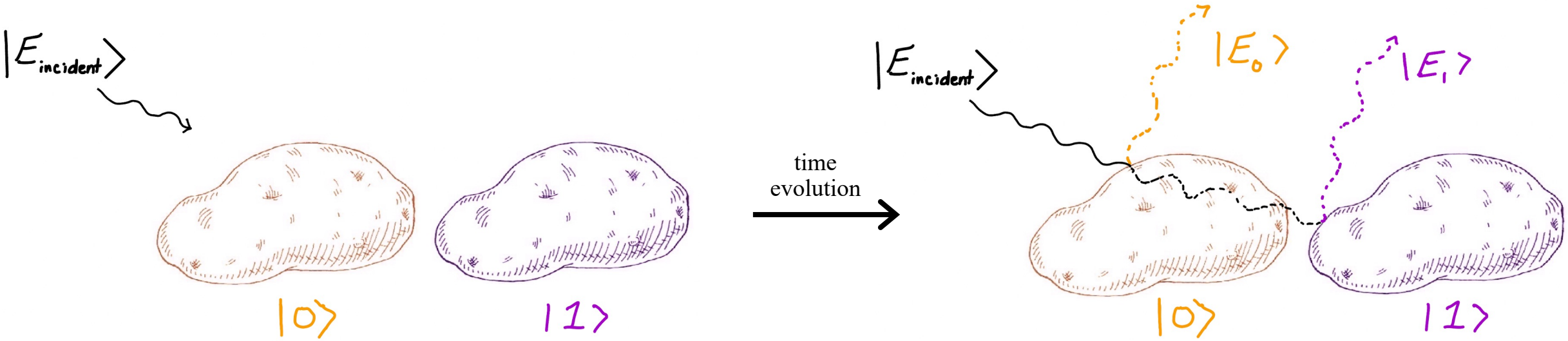
Potato in a Superposition State



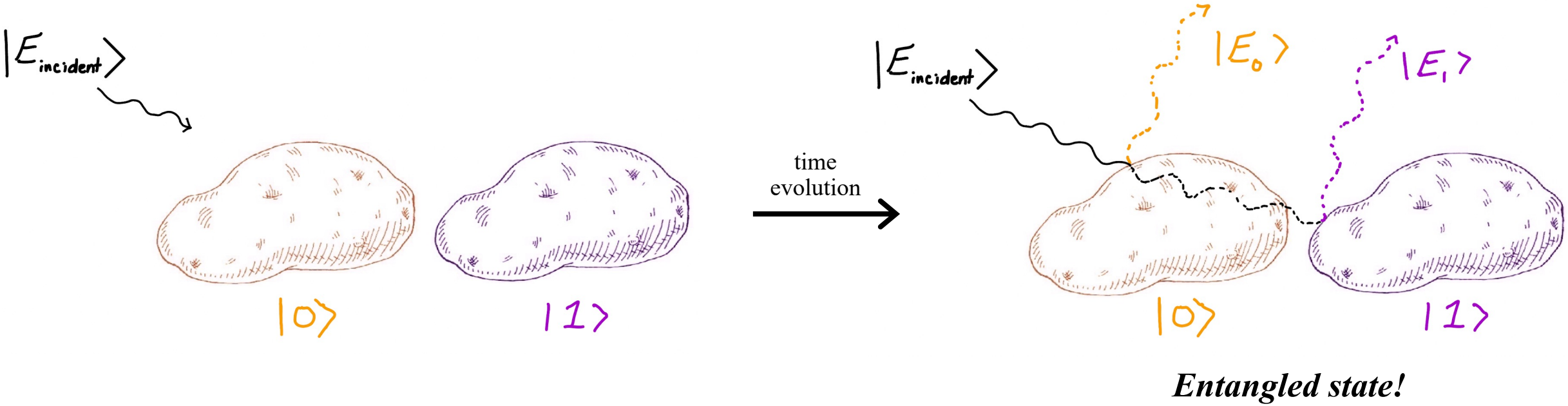
Potato in a Superposition State



Potato in a Superposition State

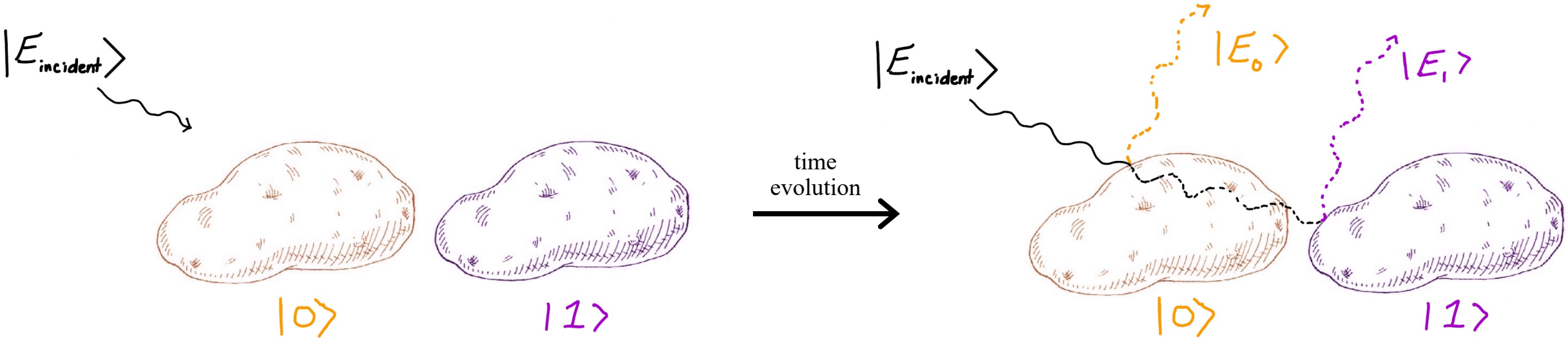


Potato in a Superposition State



Entangled state!

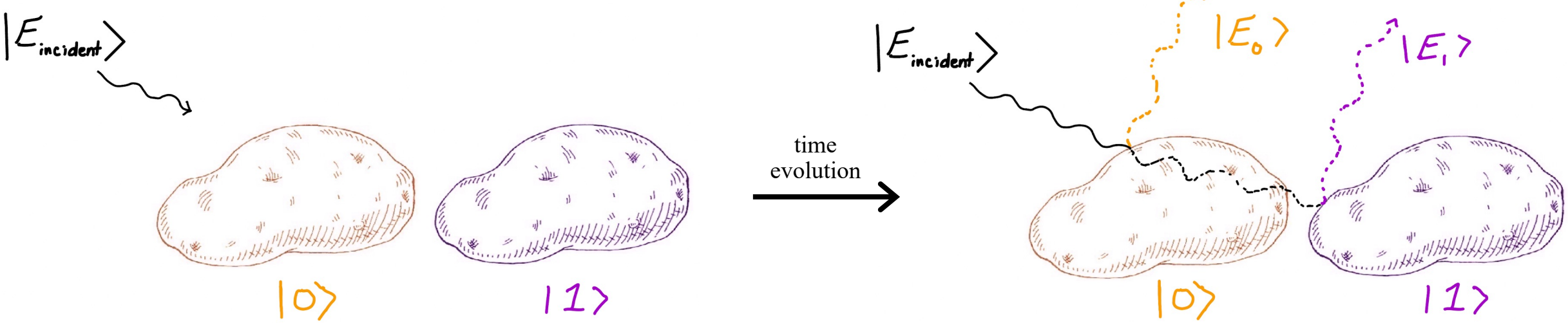
Potato in a Superposition State



Entangled state!

- The photon and potato have lost their individuality

Potato in a Superposition State

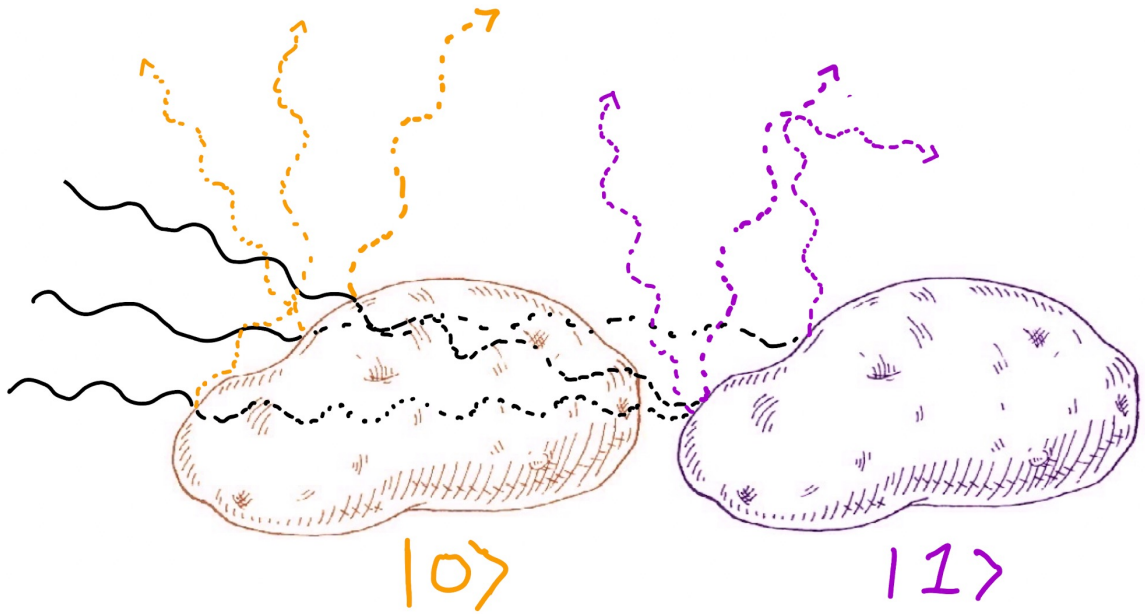


Entangled state!

- The photon and potato have lost their individuality
- The photon state is dependent on the potato state and vice versa

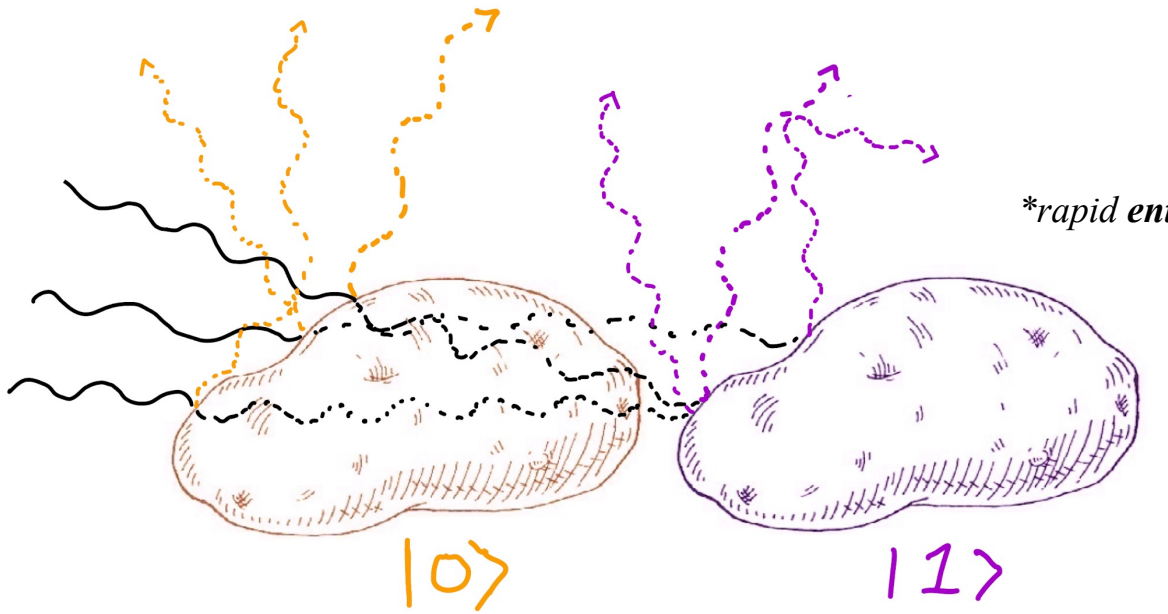
Decoherence to a Pointer State

Superposition state:



Decoherence to a Pointer State

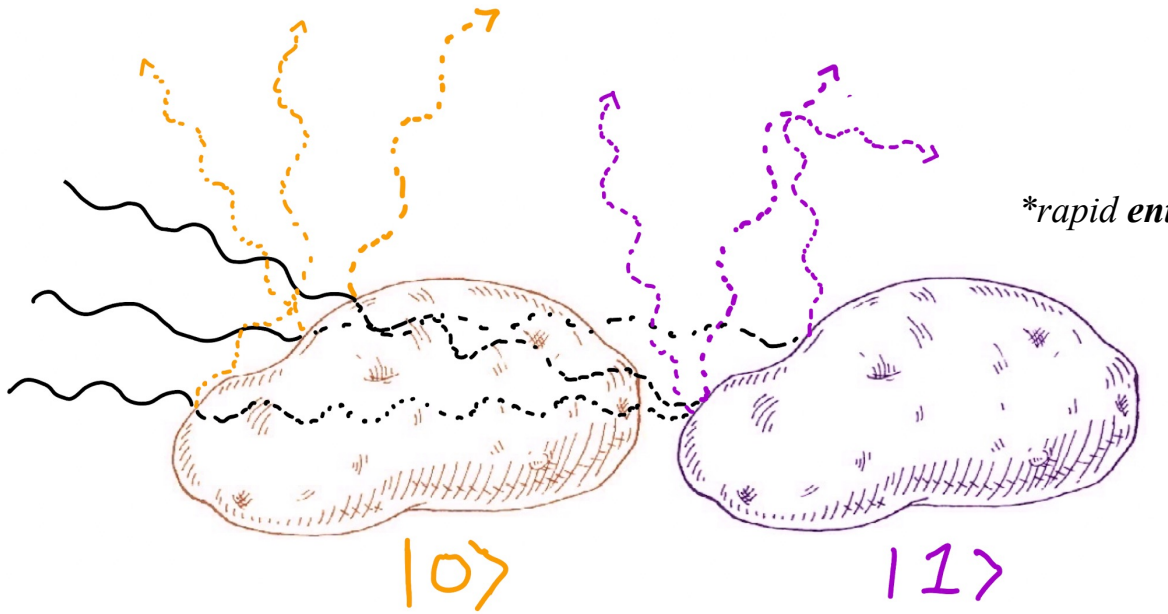
Superposition state:



rapid **entanglement growth**

Decoherence to a Pointer State

Superposition state:

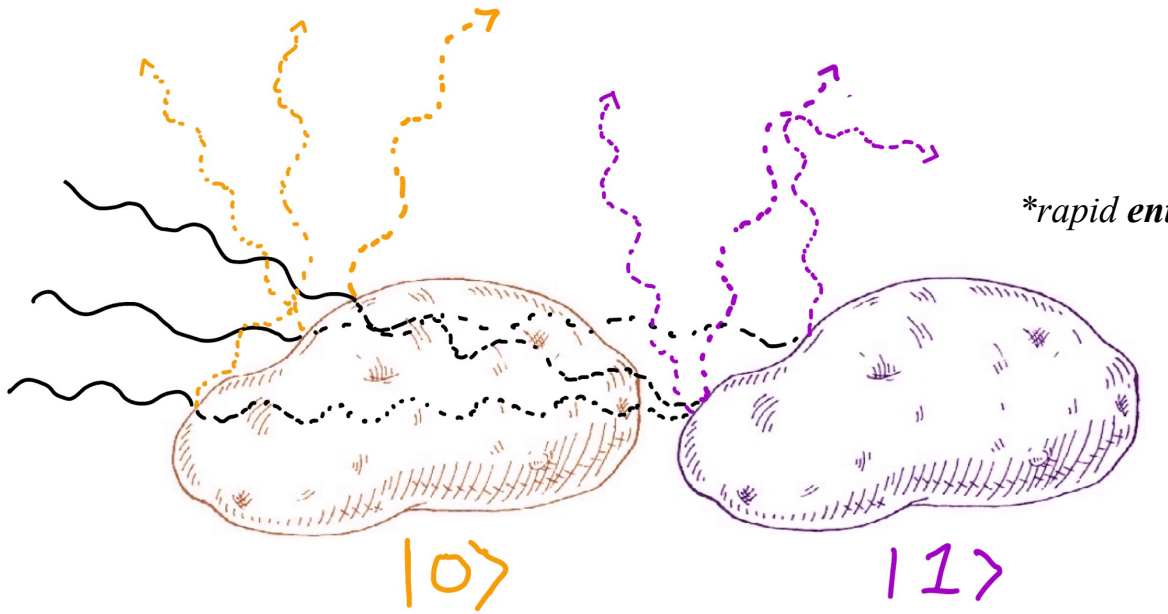


rapid **entanglement growth**

Decoherence

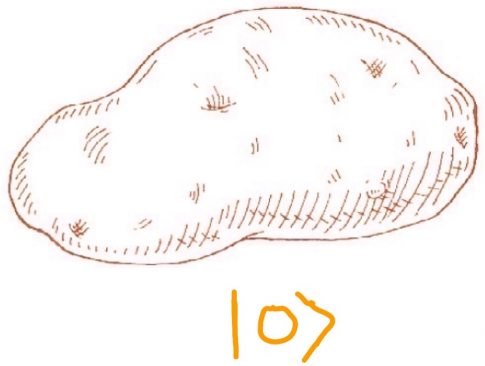
Decoherence to a Pointer State

Superposition state:



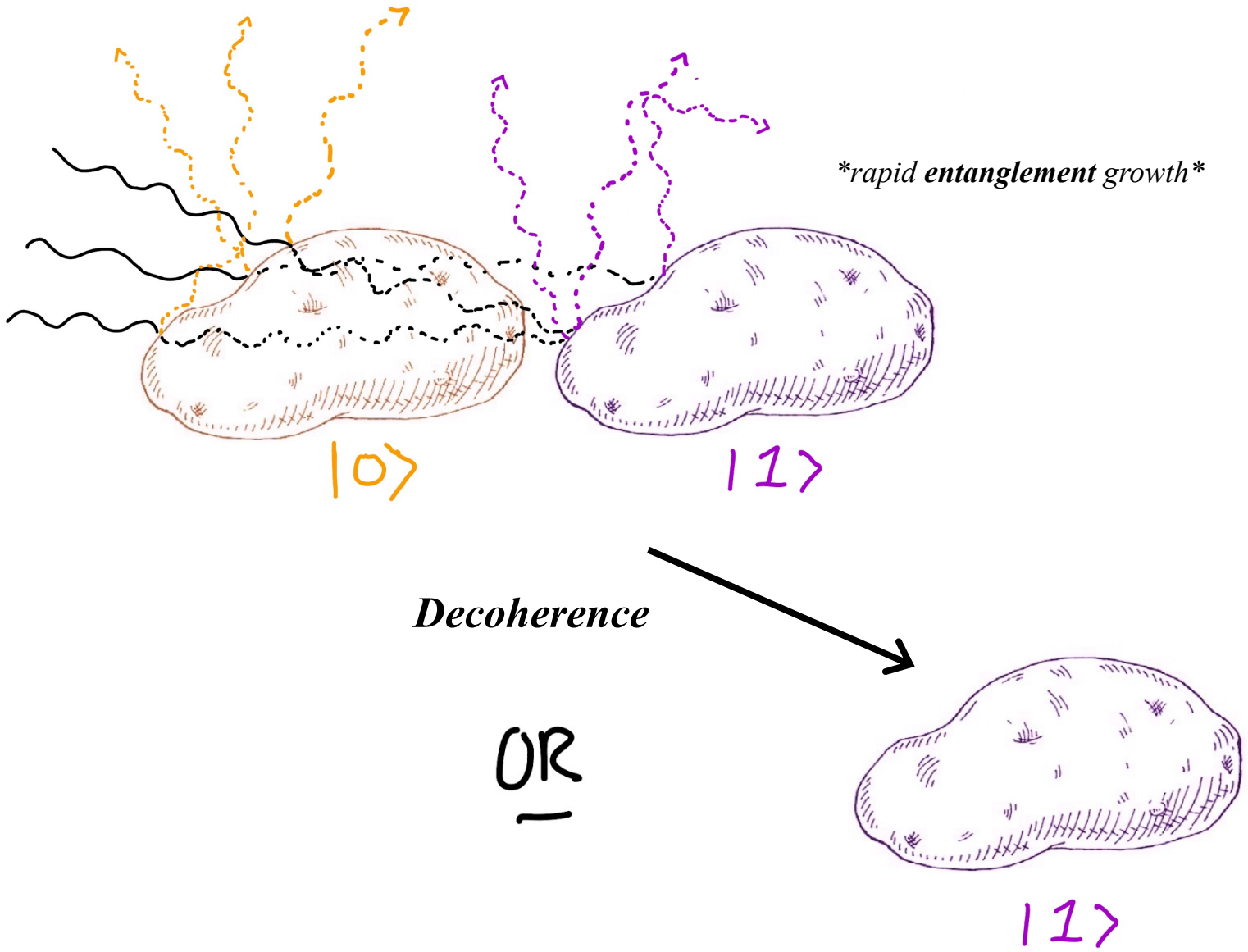
*rapid **entanglement** growth*

Decoherence



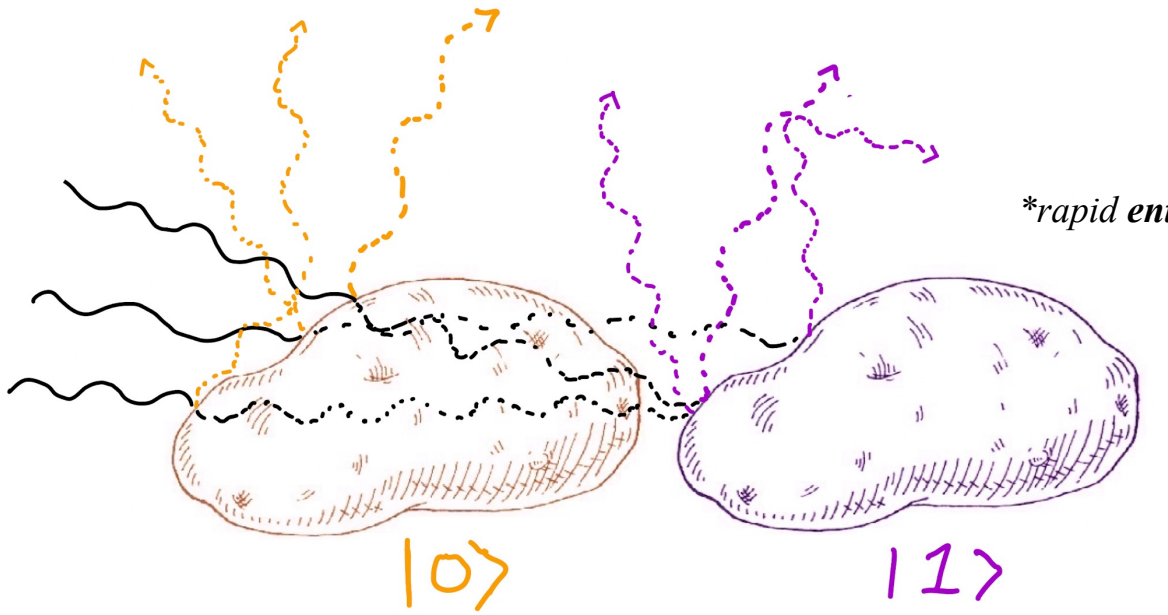
Decoherence to a Pointer State

Superposition state:



Decoherence to a Pointer State

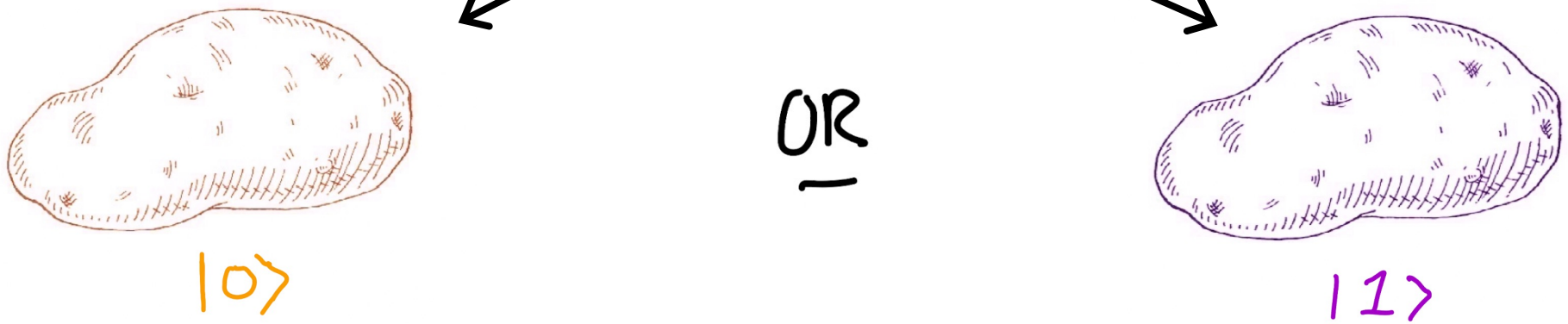
Superposition state:



rapid **entanglement growth**

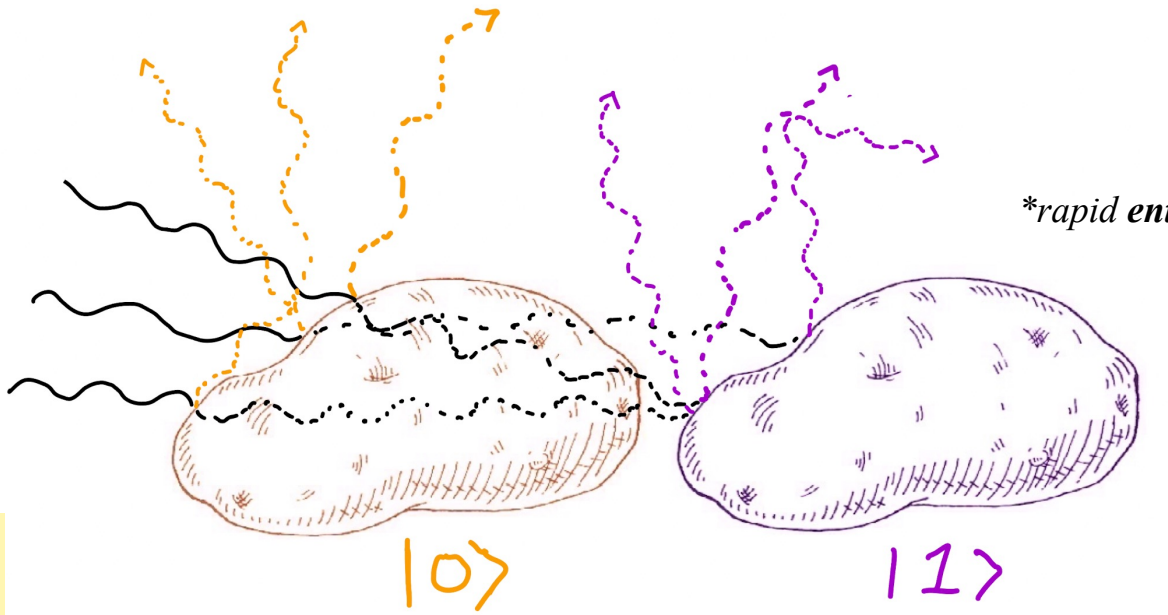
Decoherence

Pointer states:



Decoherence to a Pointer State

Superposition state:

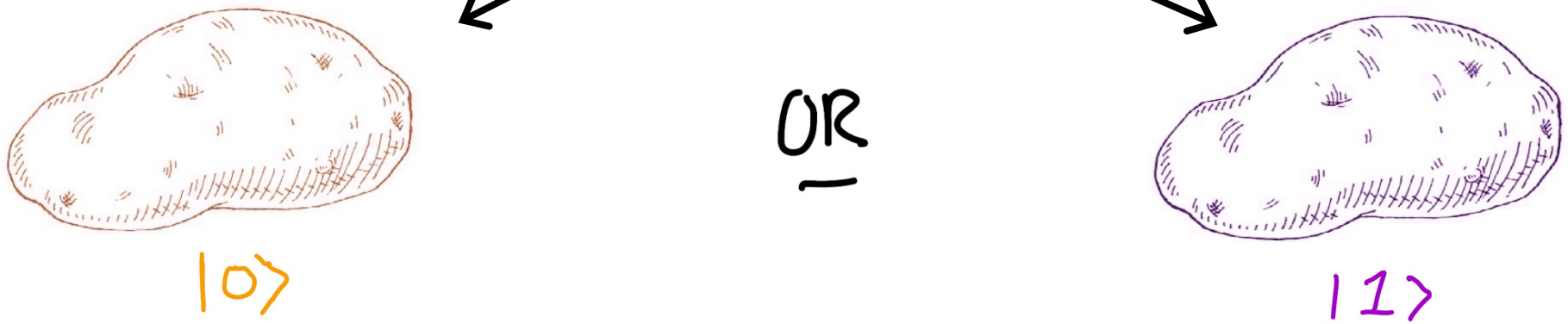


rapid **entanglement growth**

Decoherence is why potatoes don't enter superpositions!

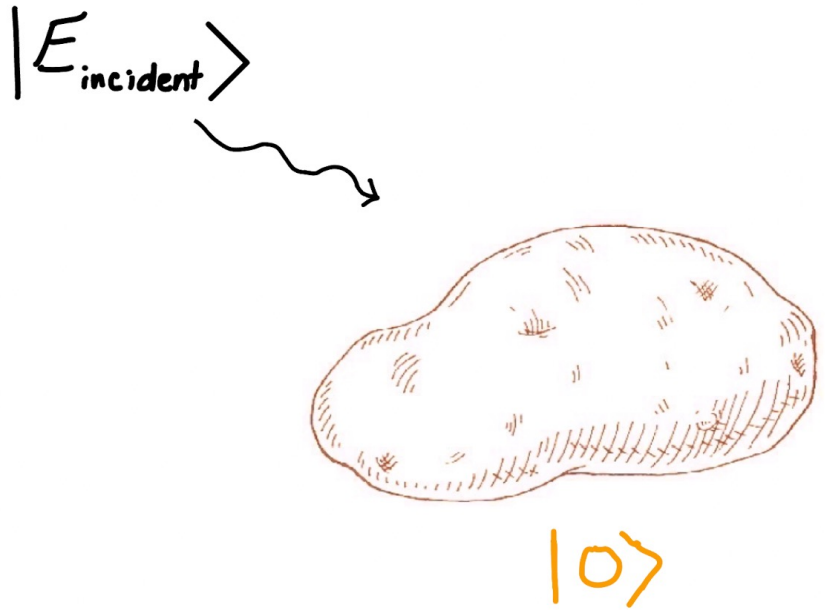
Decoherence

Pointer states:

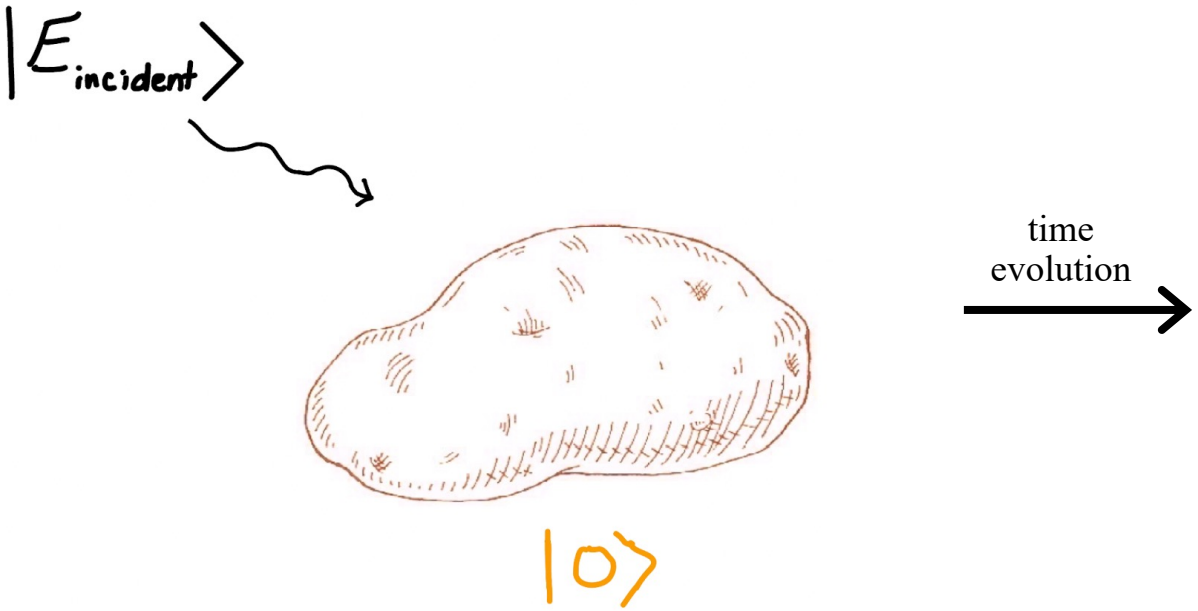


Potato Initialized in a Pointer State

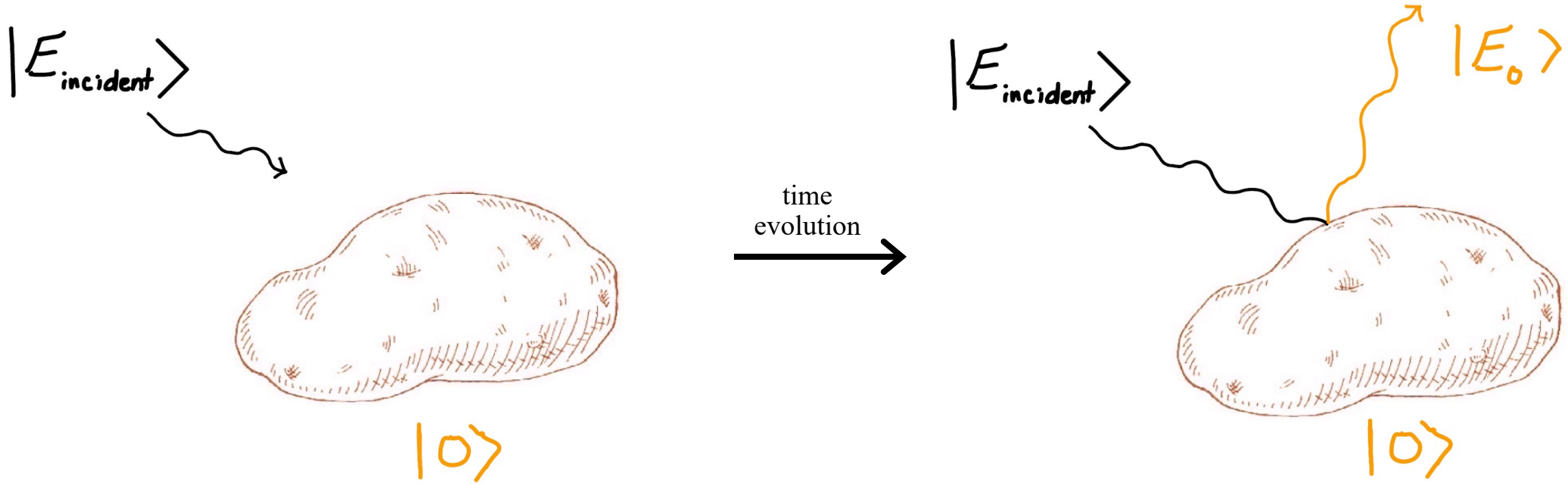
Potato Initialized in a Pointer State



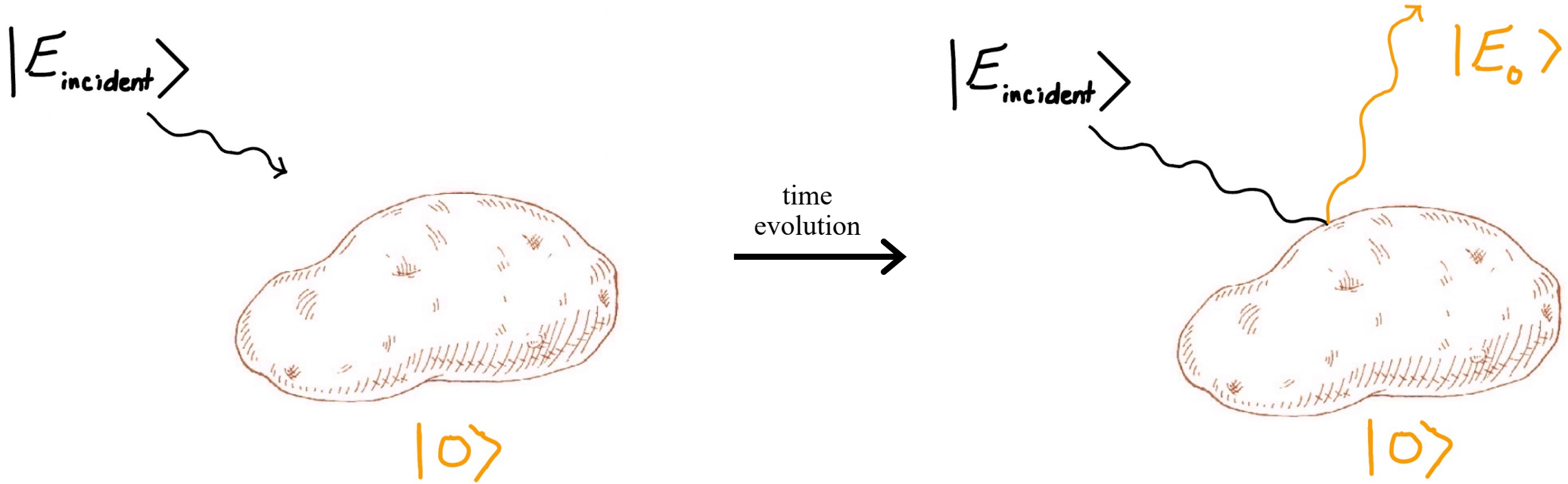
Potato Initialized in a Pointer State



Potato Initialized in a Pointer State



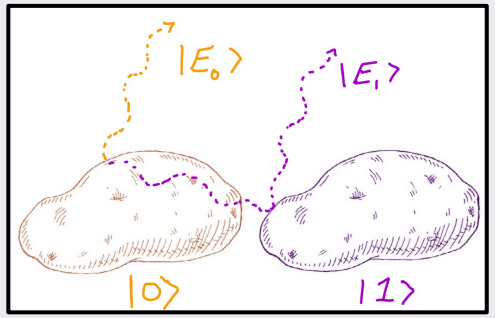
Potato Initialized in a Pointer State



Unentangled state!

Focus of Thesis:

The division of a composite quantum system into subsystems.

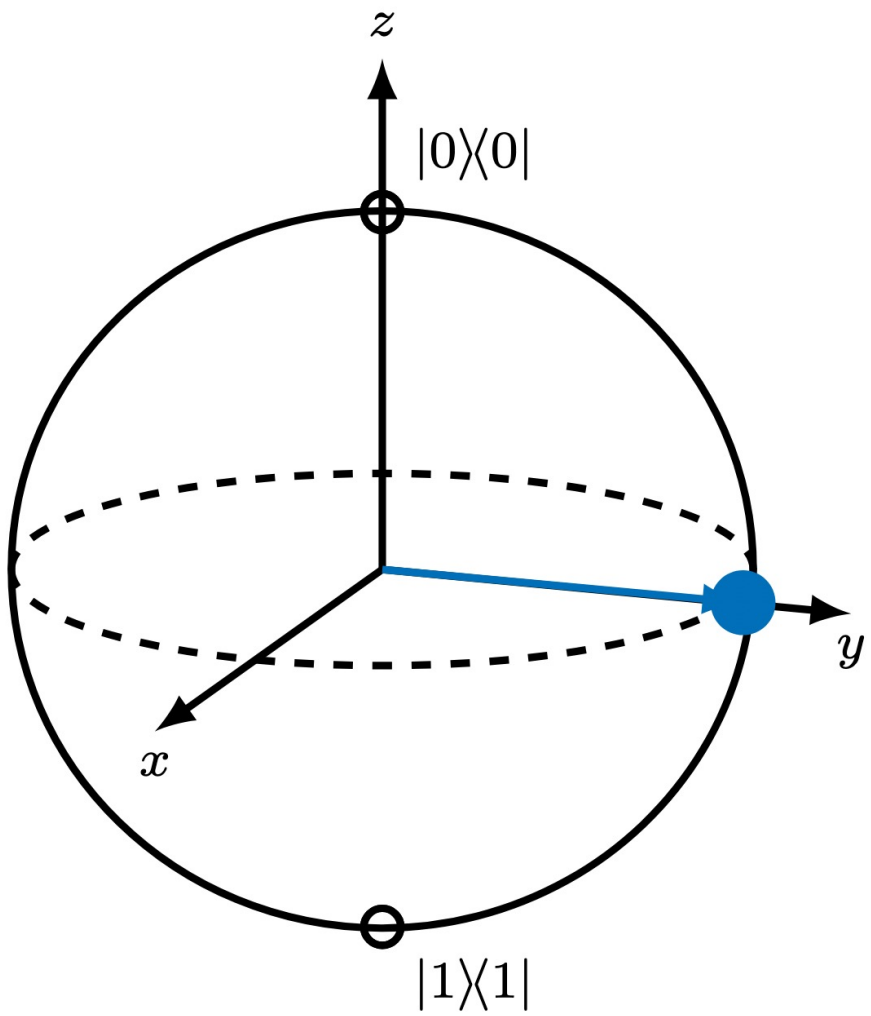


Sometimes our subsystems are not as clear as "potato" and "photon"

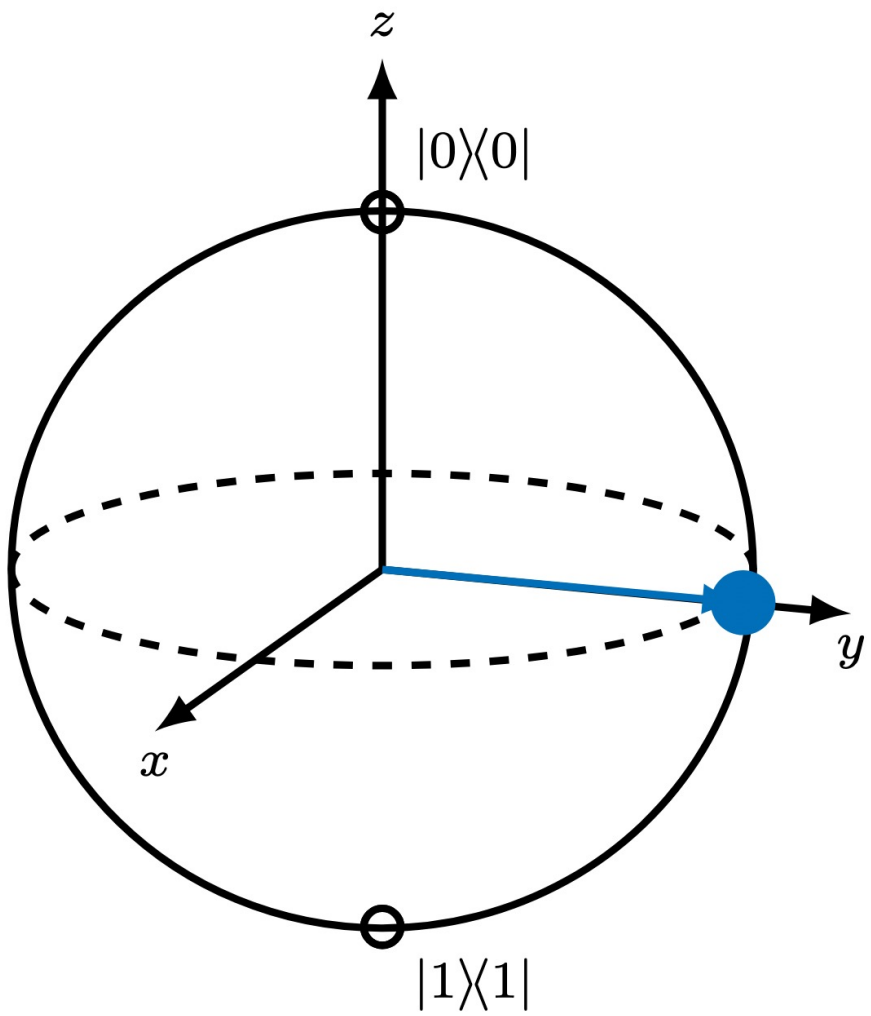
Question:

How do we determine these subsystems given an abstract quantum system?

The Bloch Ball: A Visualization Tool



The Bloch Ball: A Visualization Tool

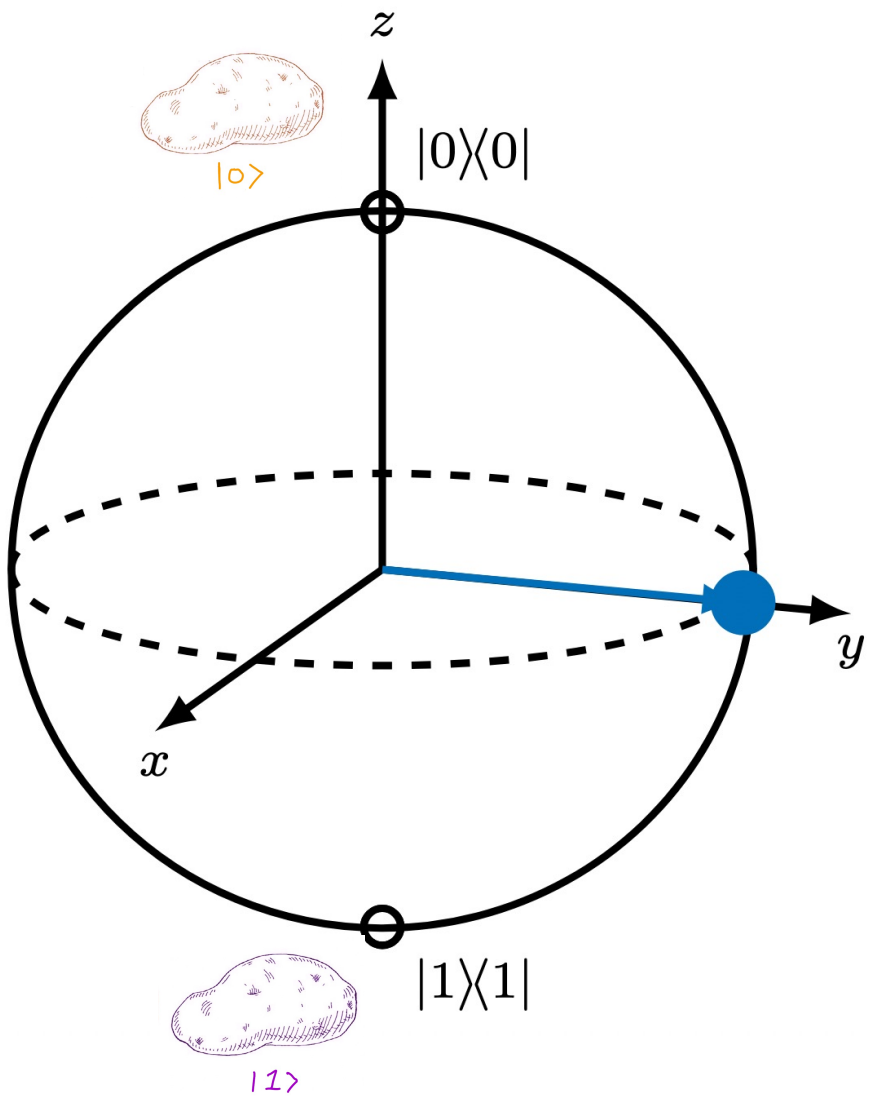


Bloch Ball with blue state represents our “system” (e.g., potato)

The Bloch Ball: A Visualization Tool

KEY:

Poles = basis states

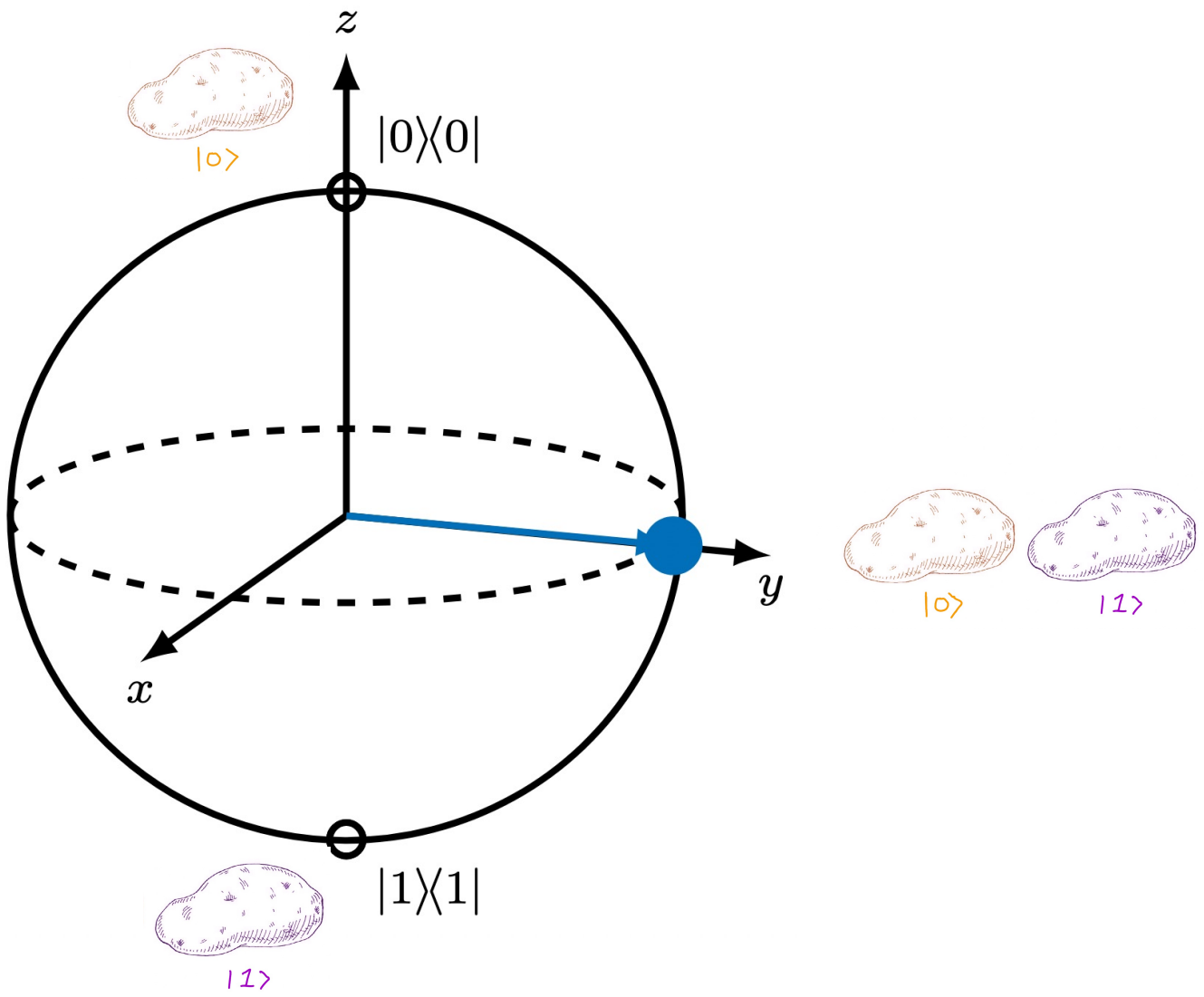


The Bloch Ball: A Visualization Tool

KEY:

Poles = basis states

Surface = unentangled state



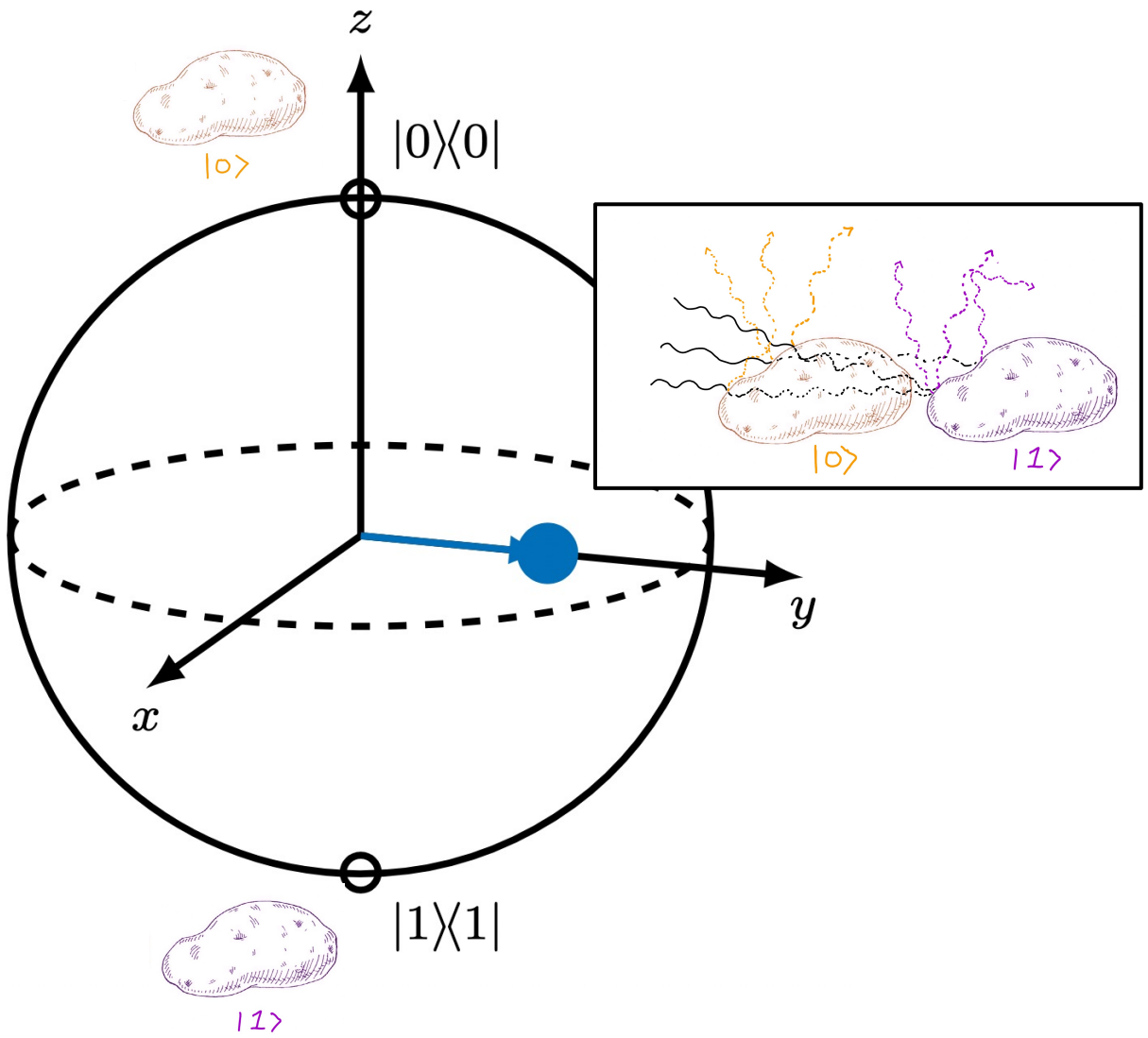
The Bloch Ball: A Visualization Tool

KEY:

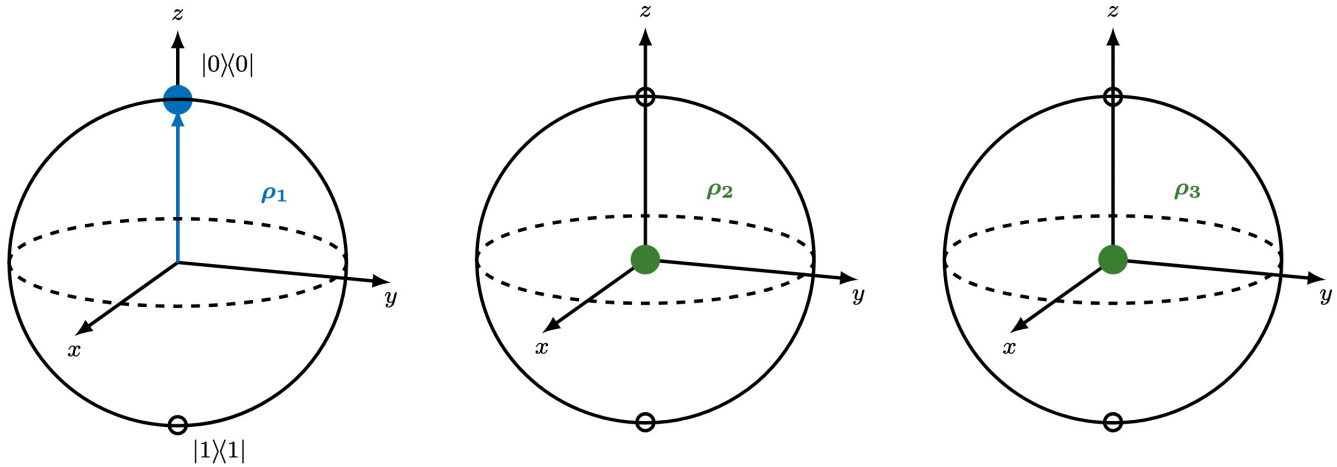
Poles = basis states

Surface = unentangled state

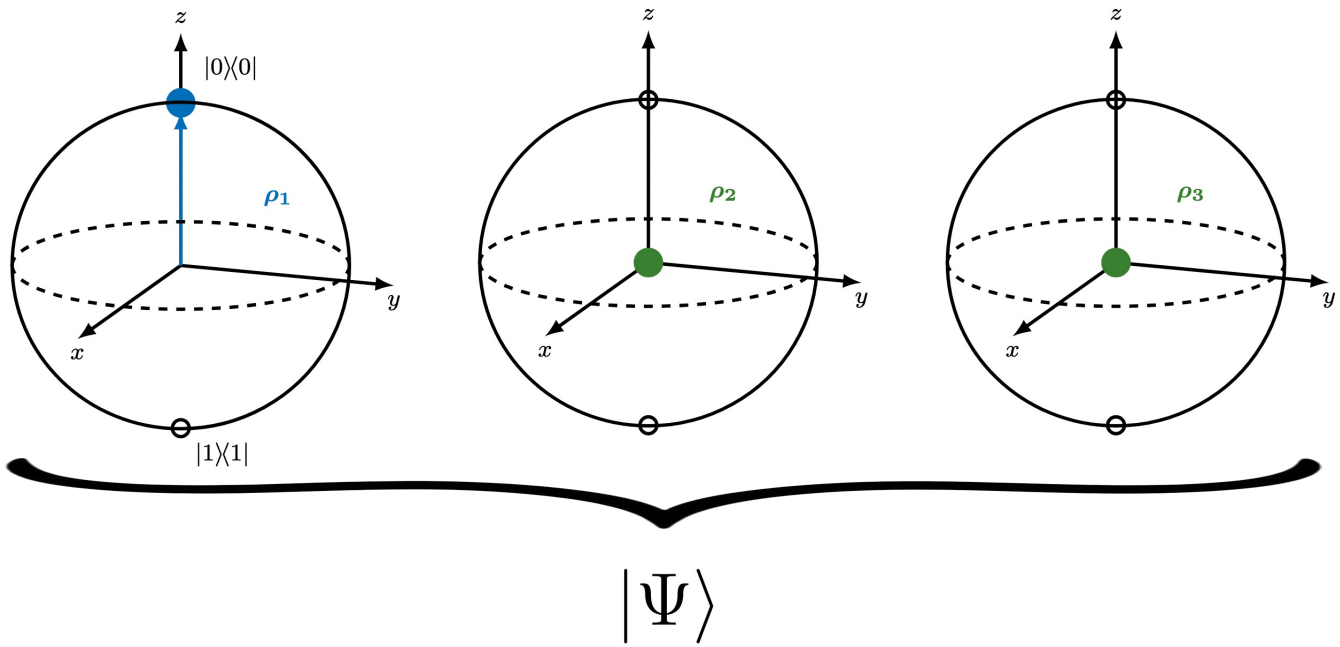
Interior = entangled state



Tensor Product Structures

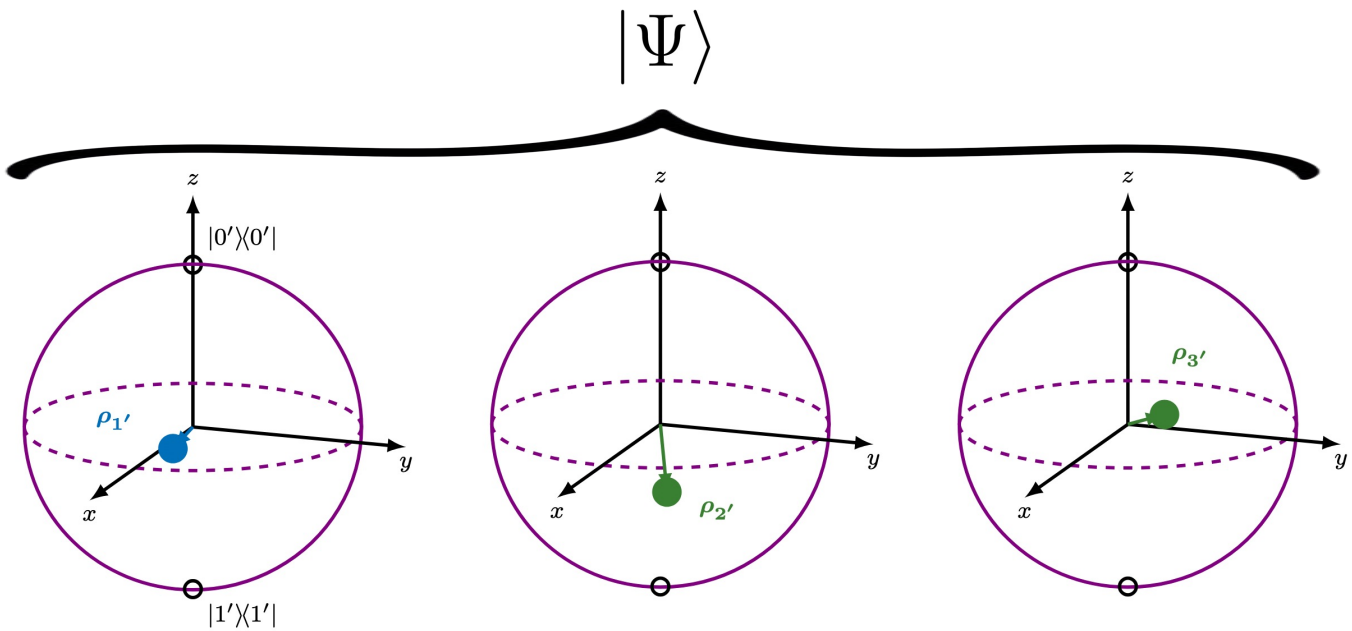


Tensor Product Structures

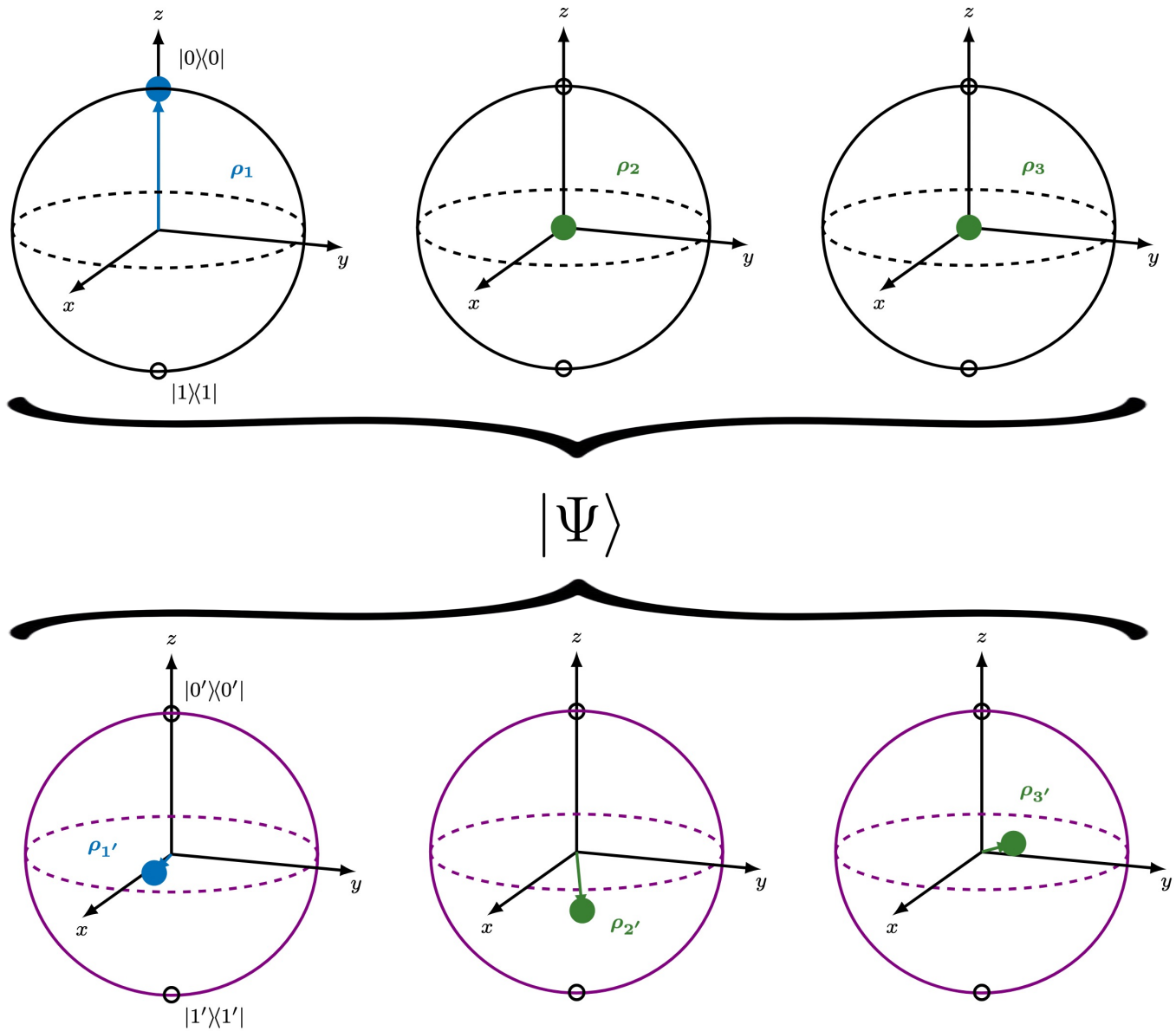


$$|\Psi\rangle$$

Tensor Product Structures

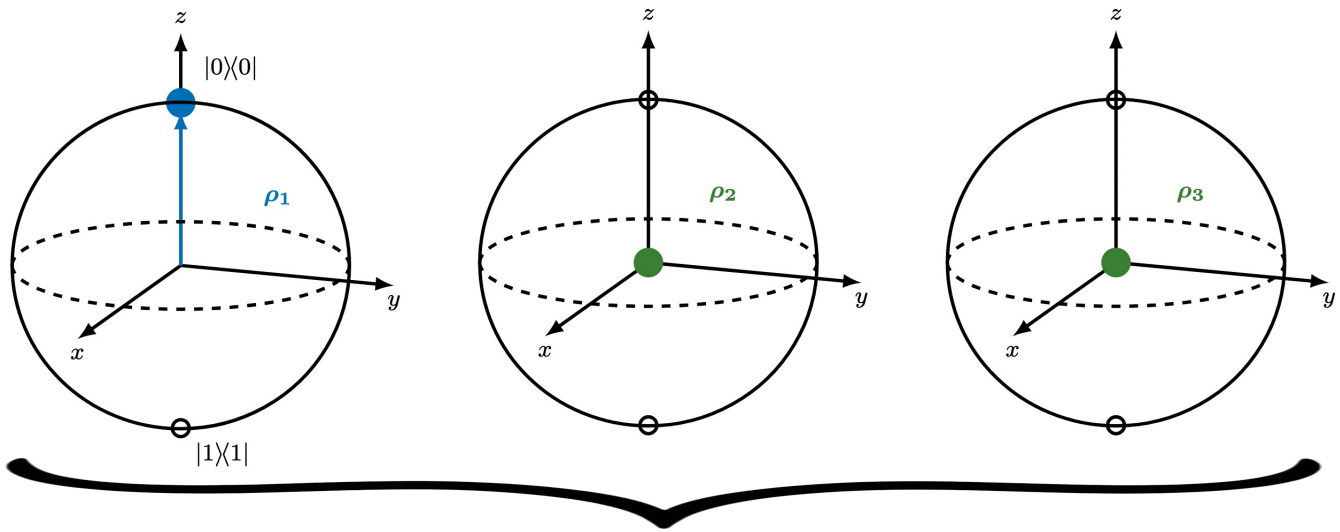


Tensor Product Structures



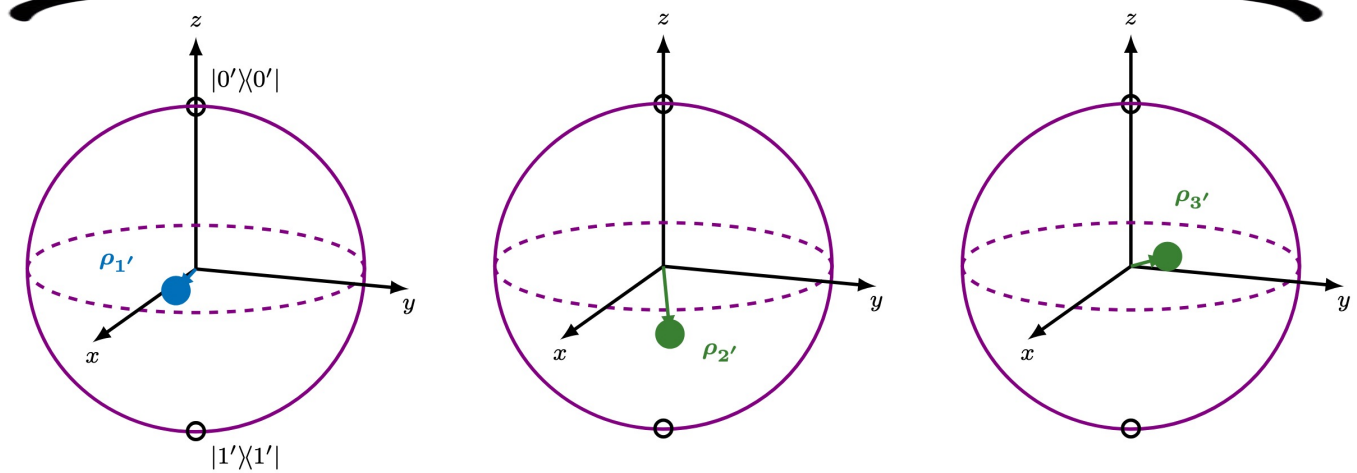
Tensor Product Structures

Tensor Product Structure 1 (Qubits 1, 2, 3):



$$|\Psi\rangle$$

Tensor Product Structure 2 (Qubits 1′ , 2′, 3′):



Tensor Product Structures

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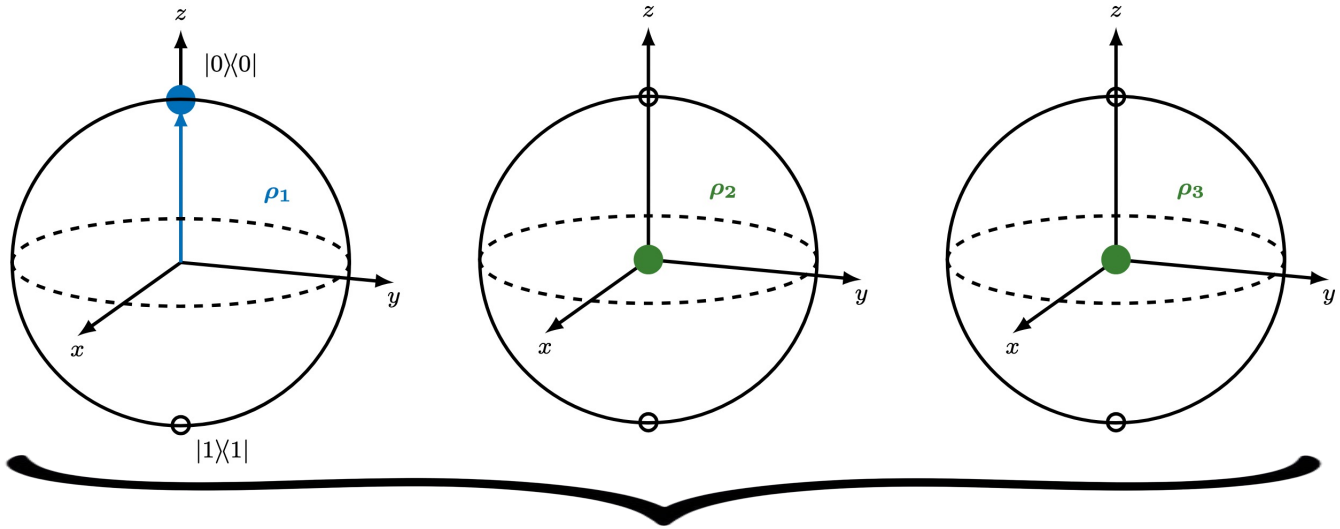
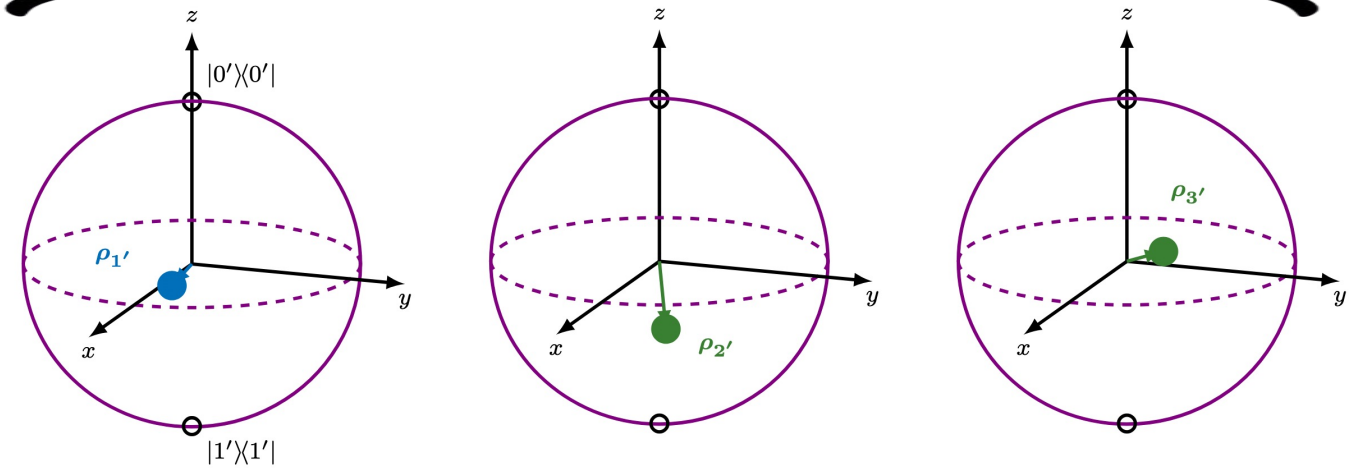


Entanglement is a Relative Concept!

$$|\Psi\rangle$$

Tensor Product Structure 2 (Qubits 1′ , 2′, 3′):



Tensor Product Structures

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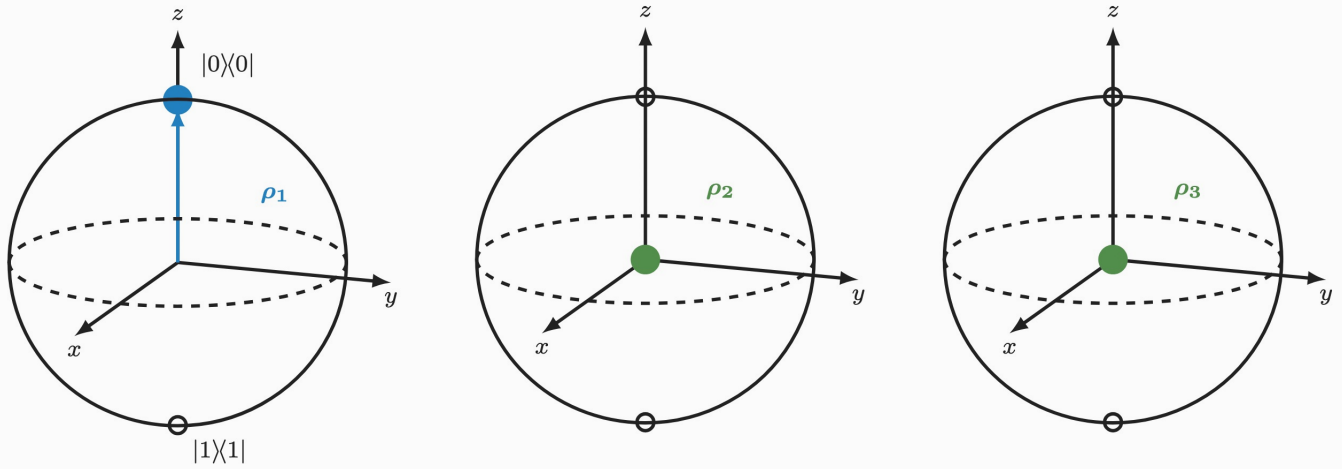

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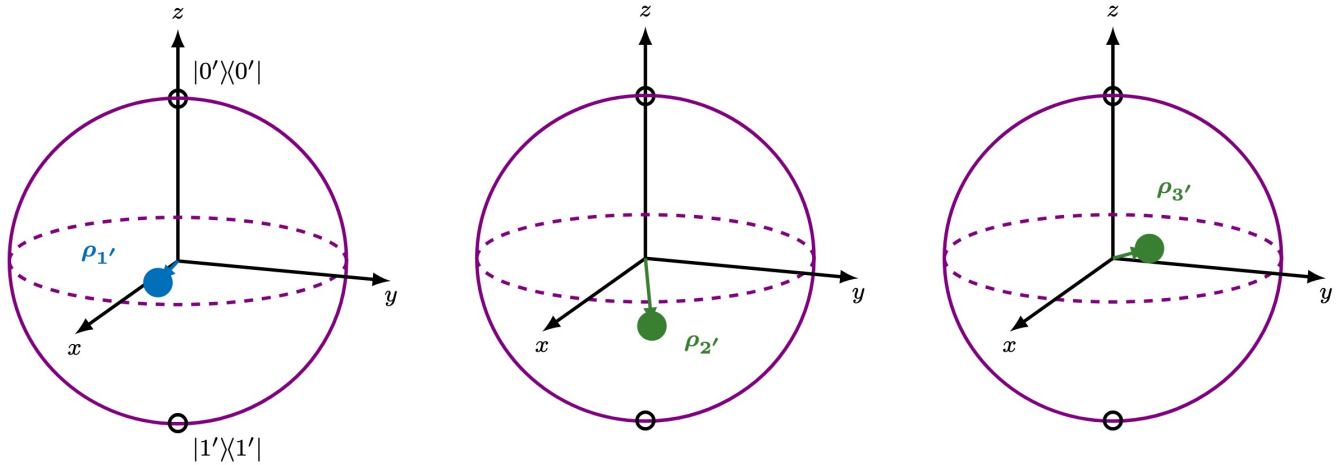
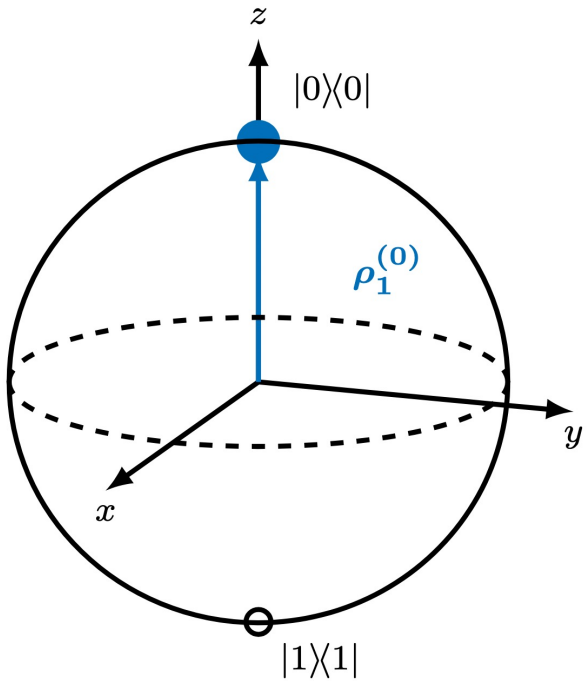
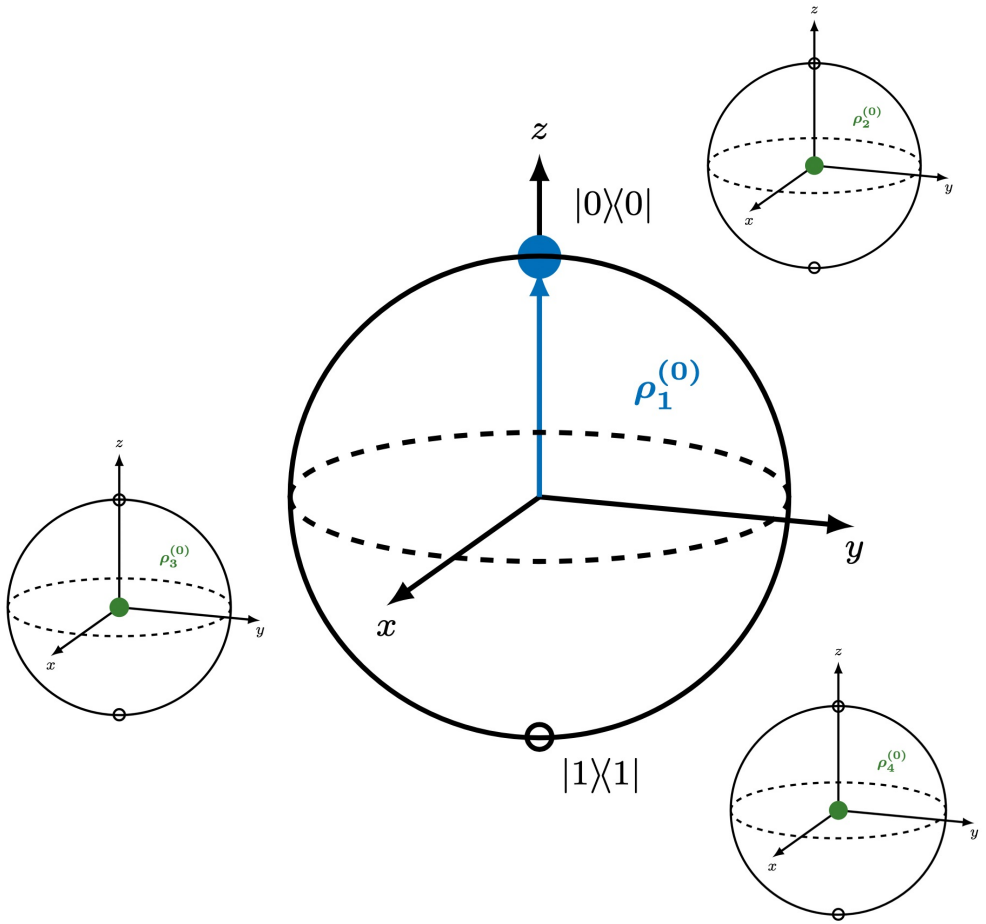
Tensor Product Structure 2 (Qubits 1′ , 2′, 3′):



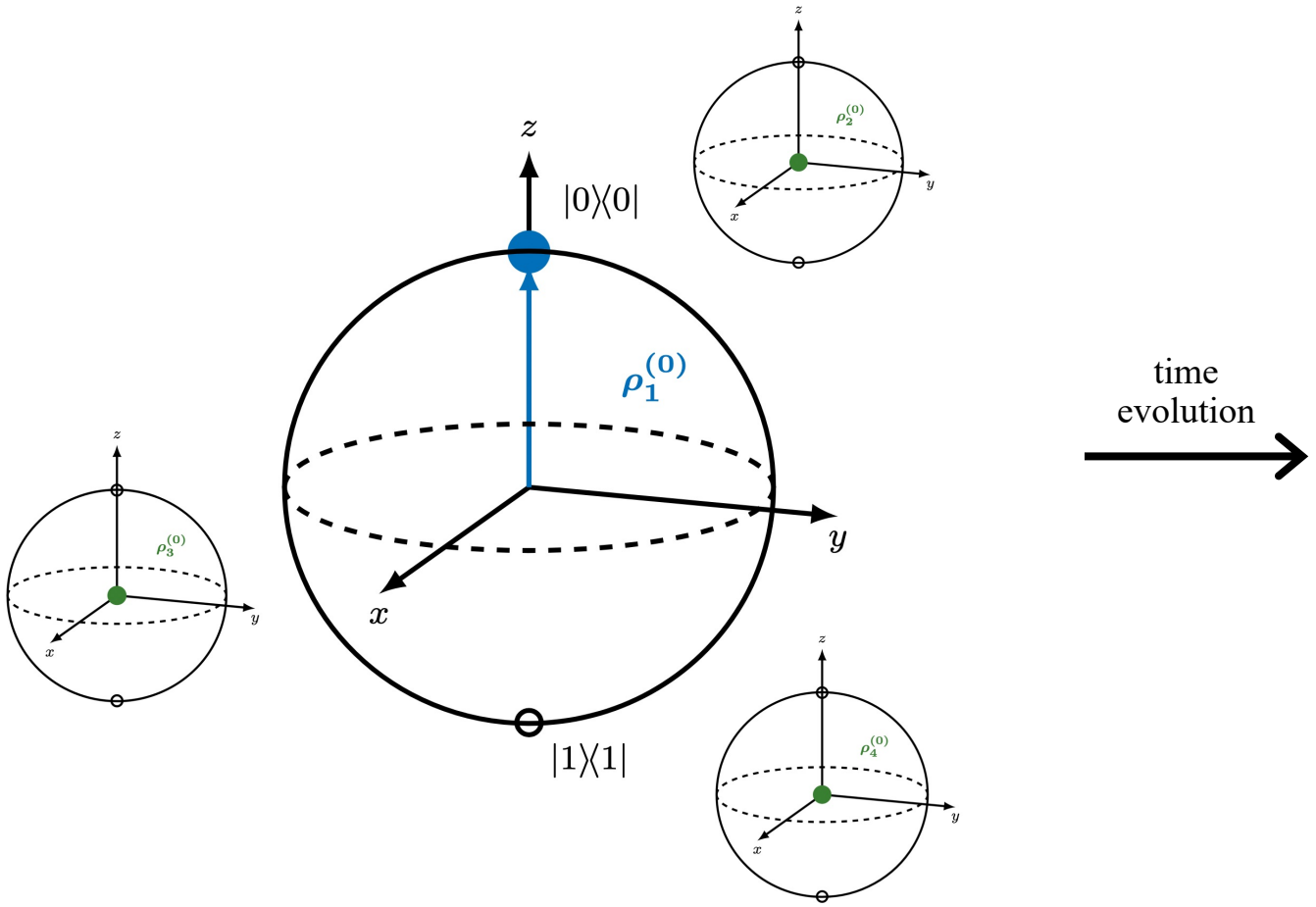
Quasi-classical Tensor Product Structure (qcTPS)



Quasi-classical Tensor Product Structure (qcTPS)



Quasi-classical Tensor Product Structure (qcTPS)



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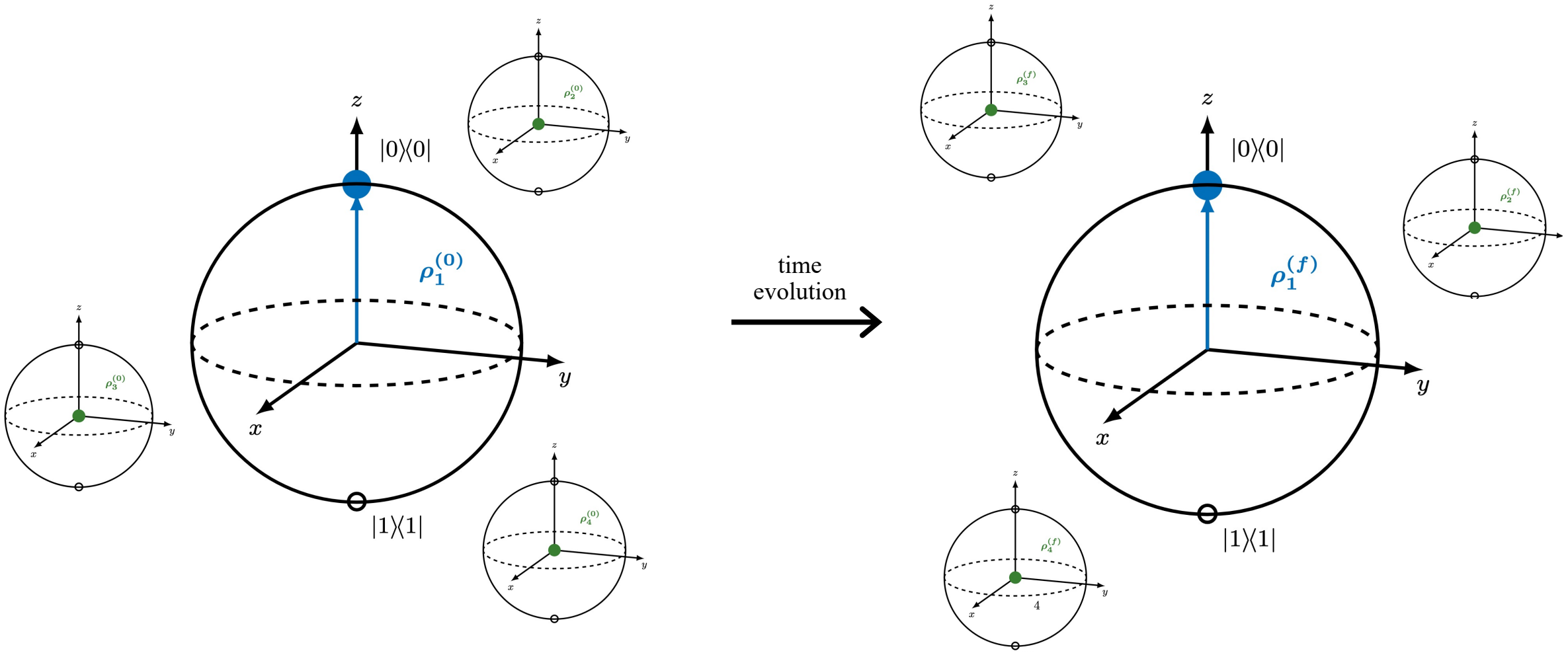

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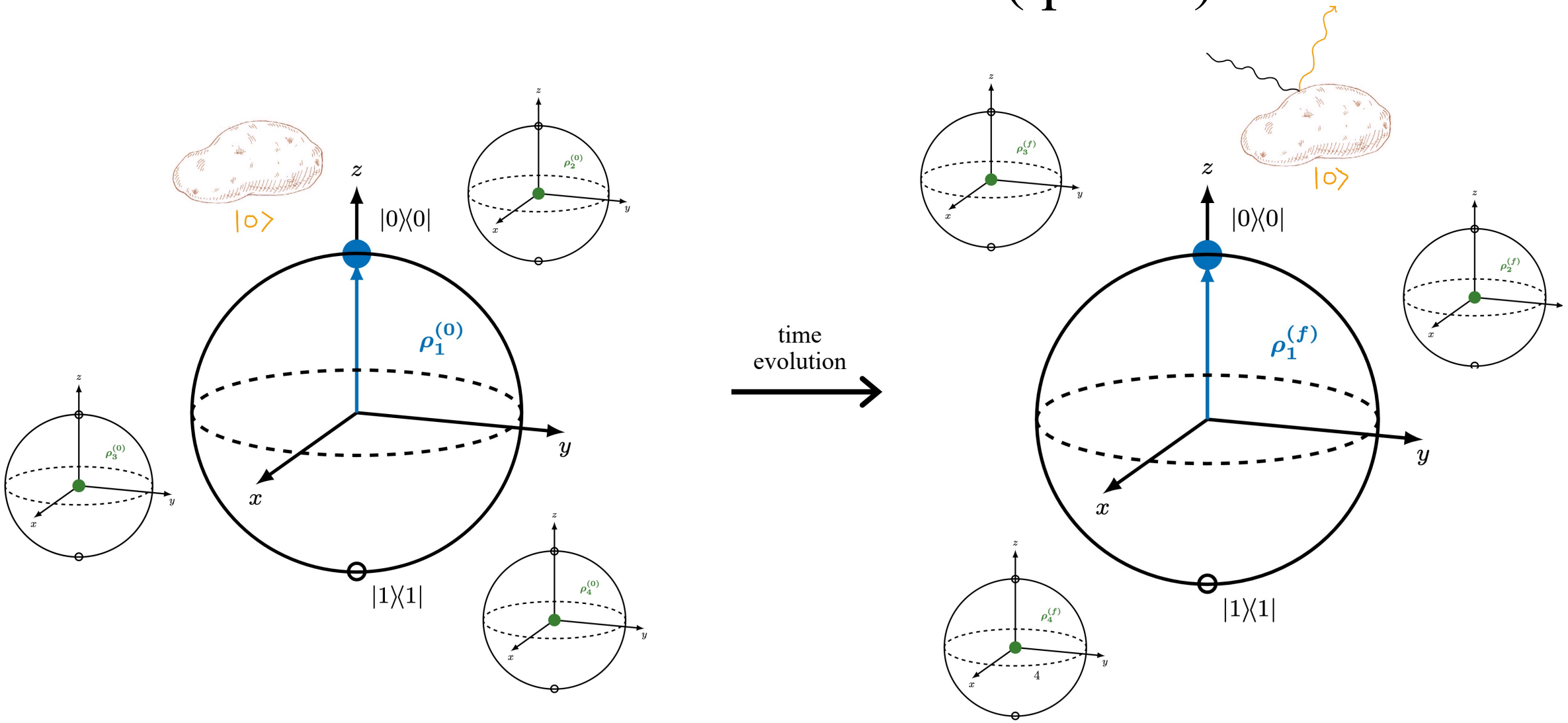

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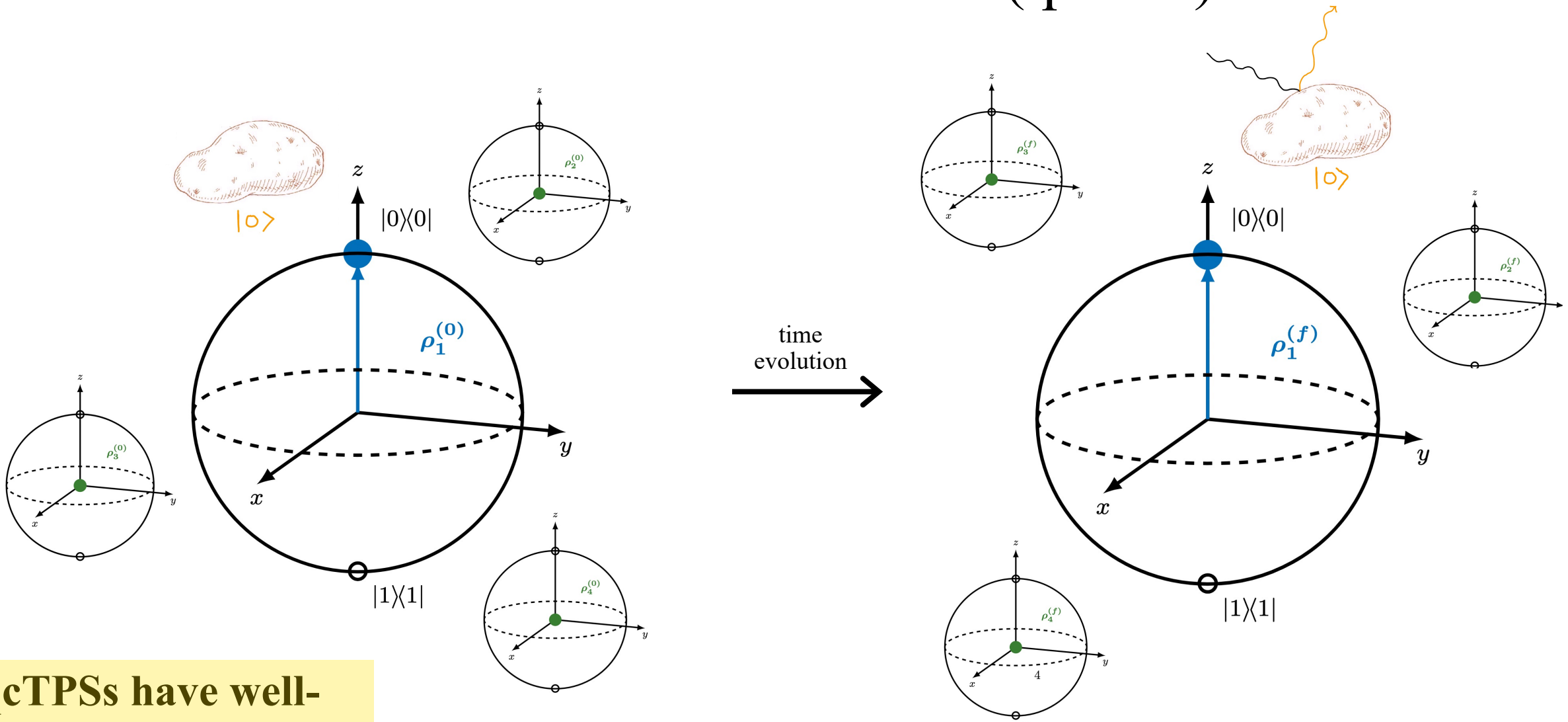
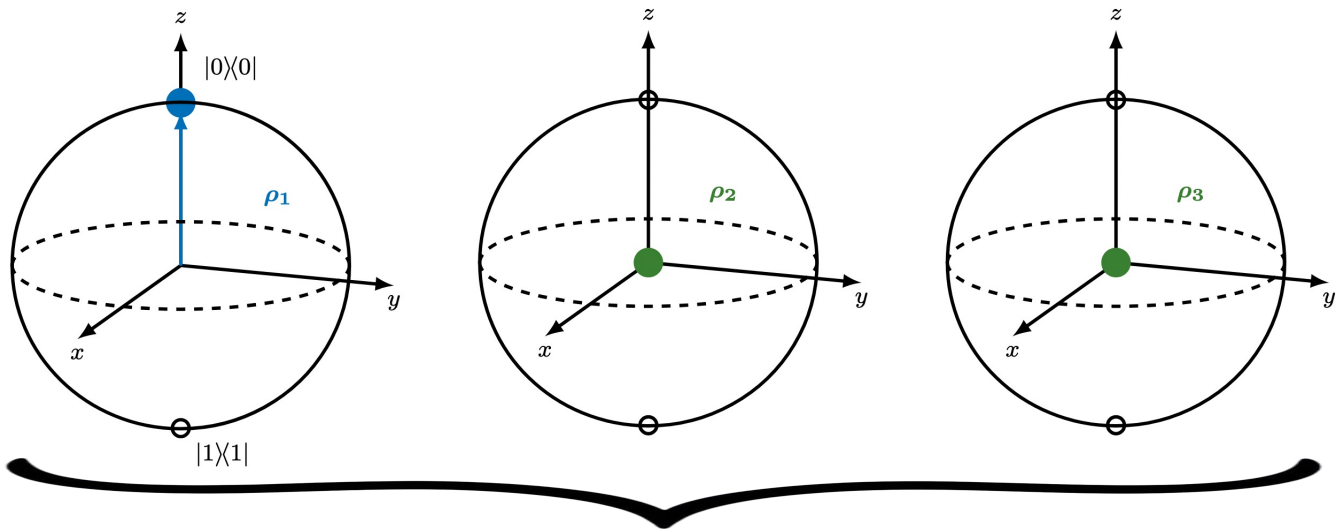


qcTPSs have well-defined pointer states!

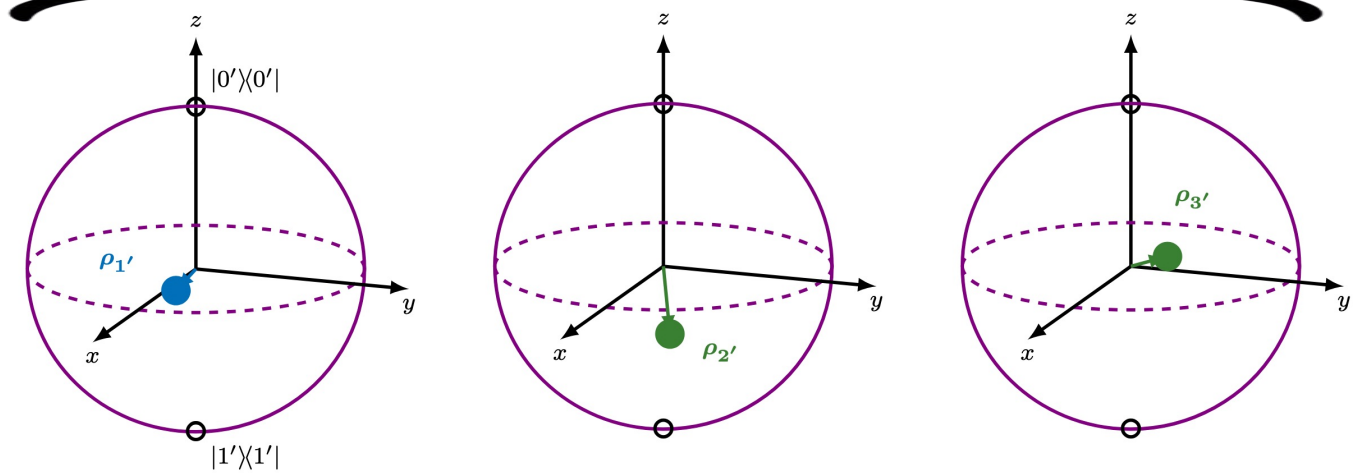
Tensor Product Structures

Tensor Product Structure 1 (Qubits 1, 2, 3):



$|\Psi\rangle$

Tensor Product Structure 2 (Qubits 1′ , 2′, 3′):



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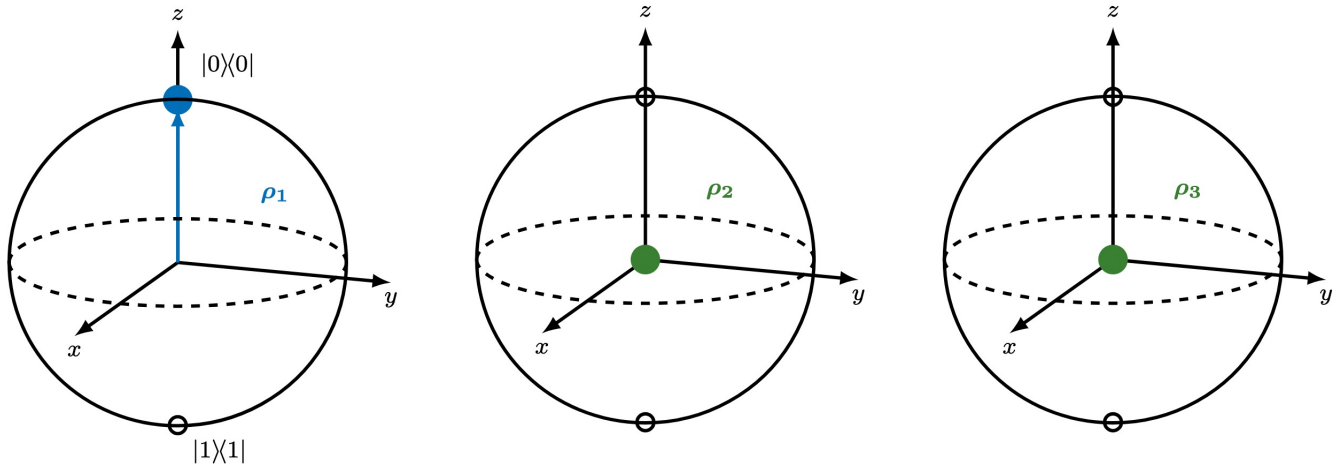
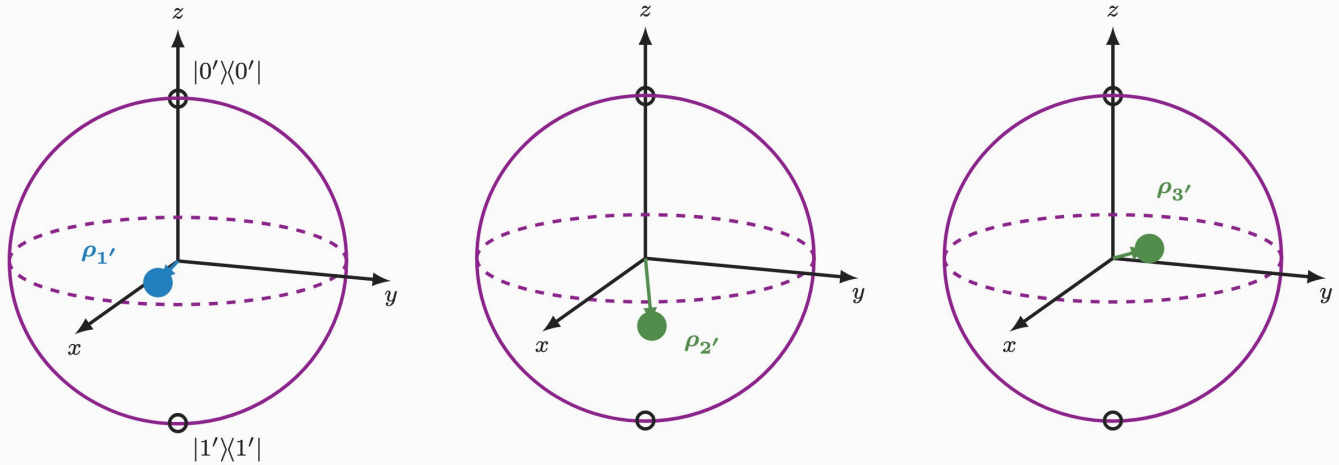
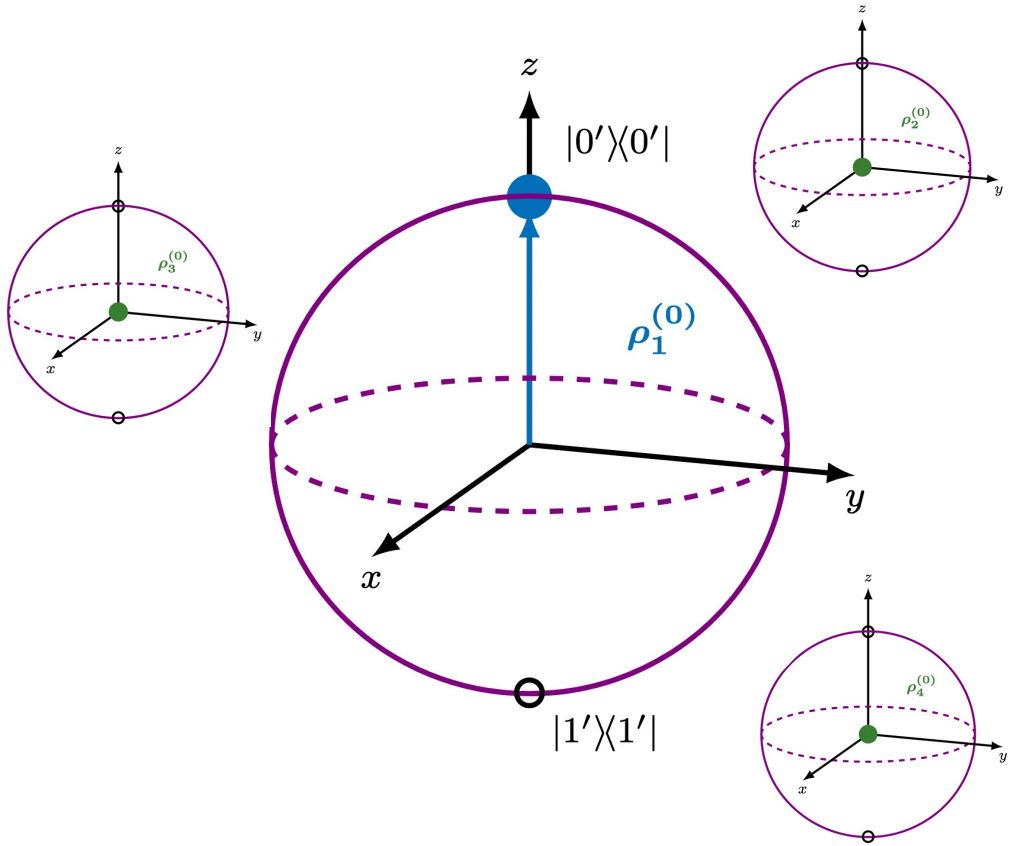


$|\Psi\rangle$

Tensor Product Structure 2 (Qubits 1′ , 2′, 3′):



Generic Tensor Product Structure



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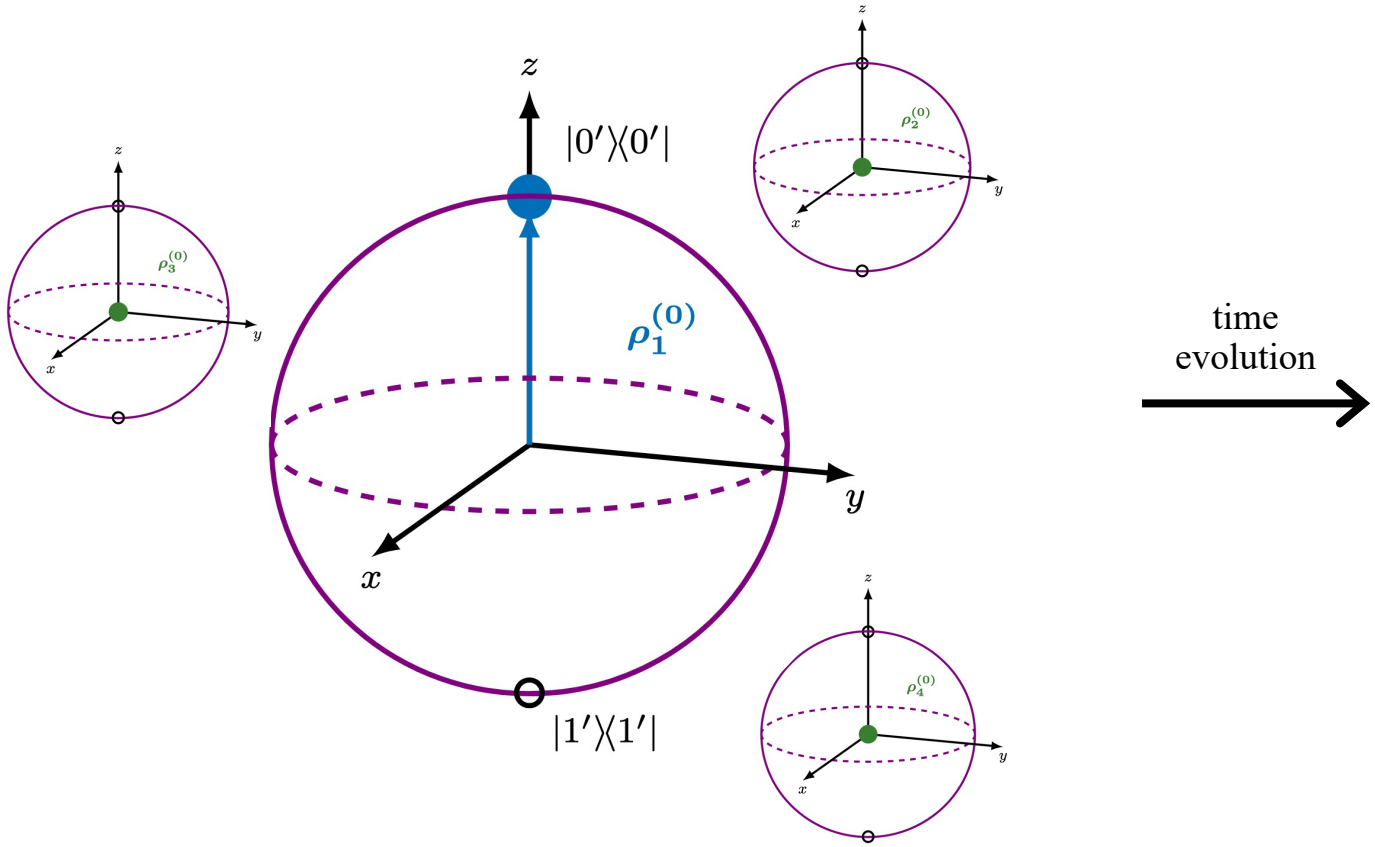

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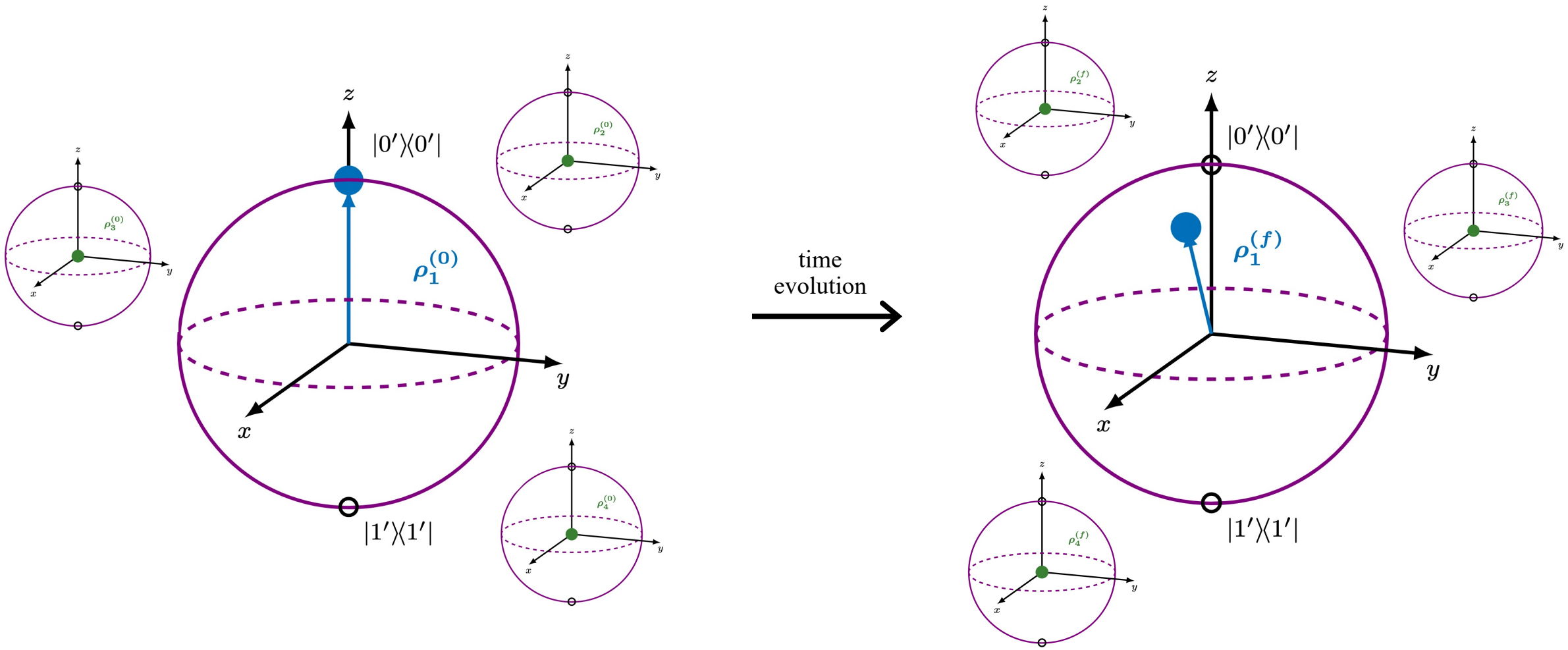

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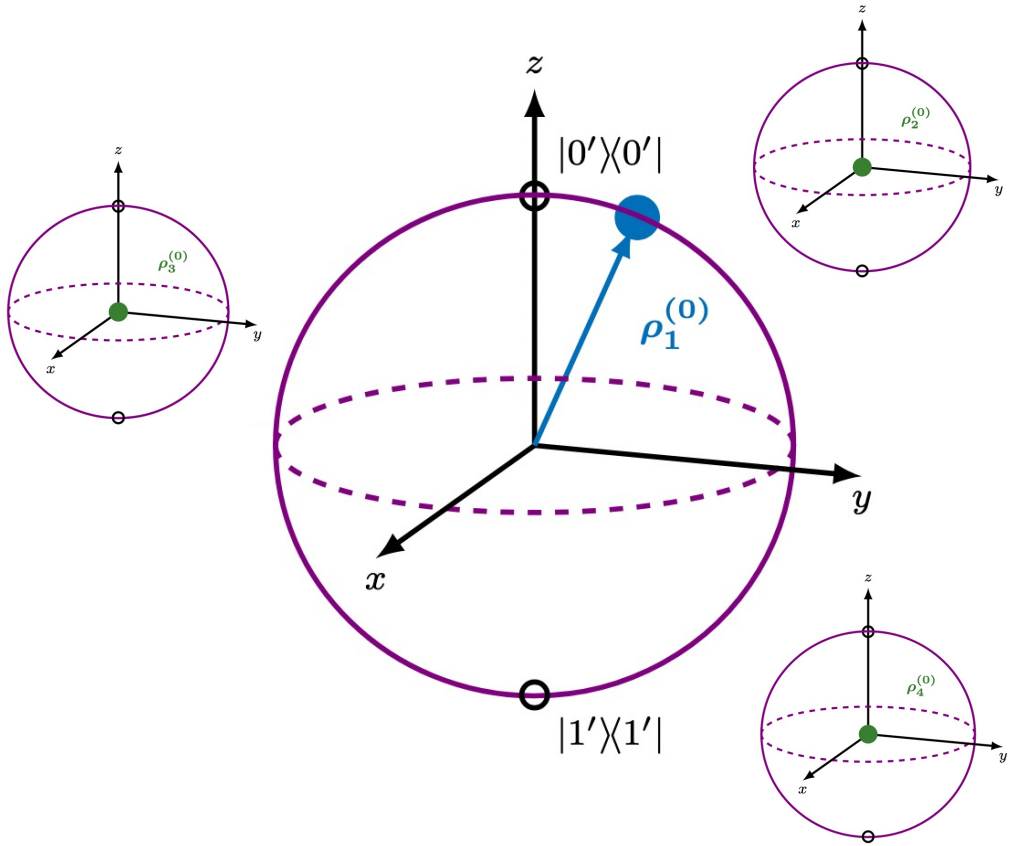

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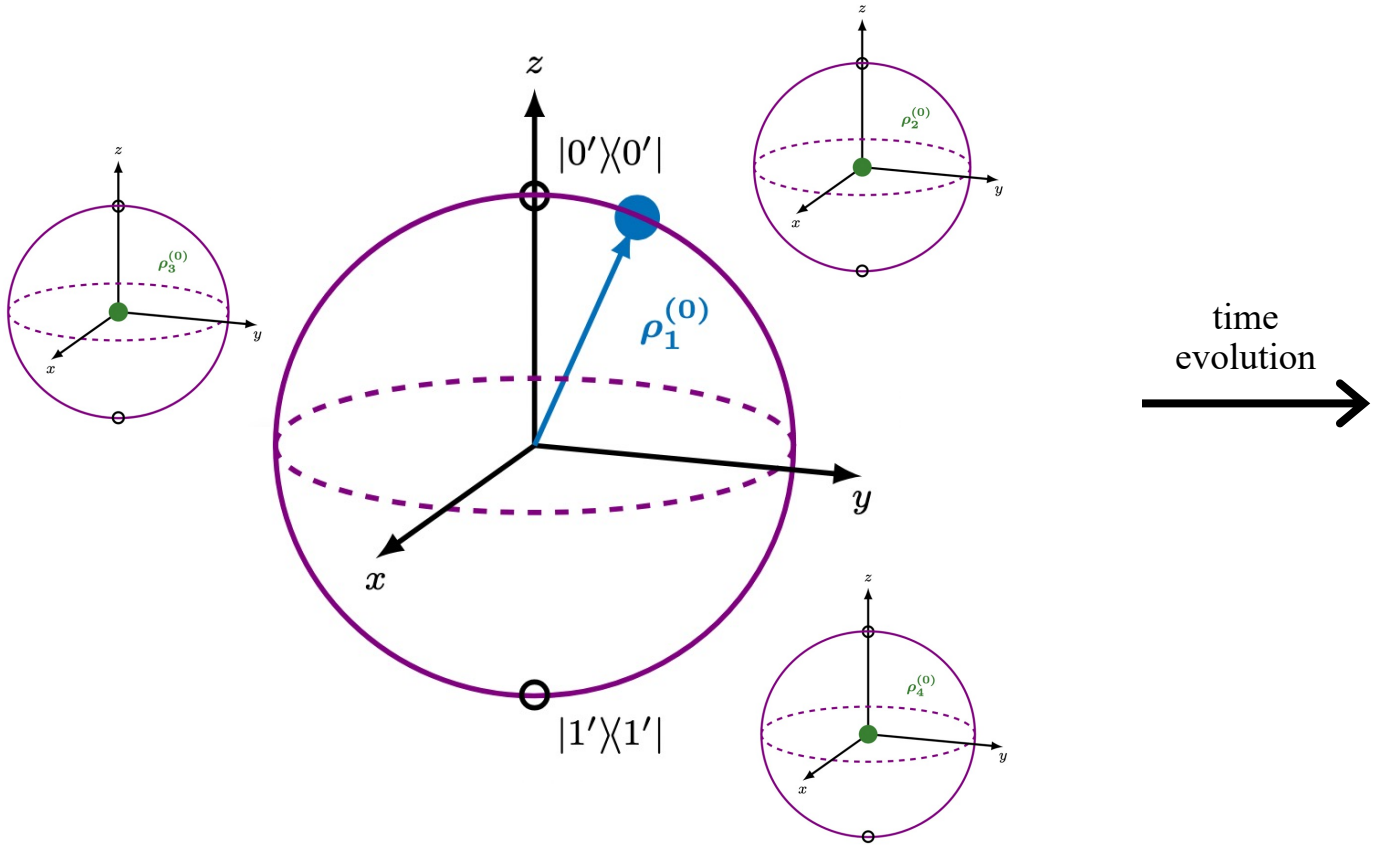
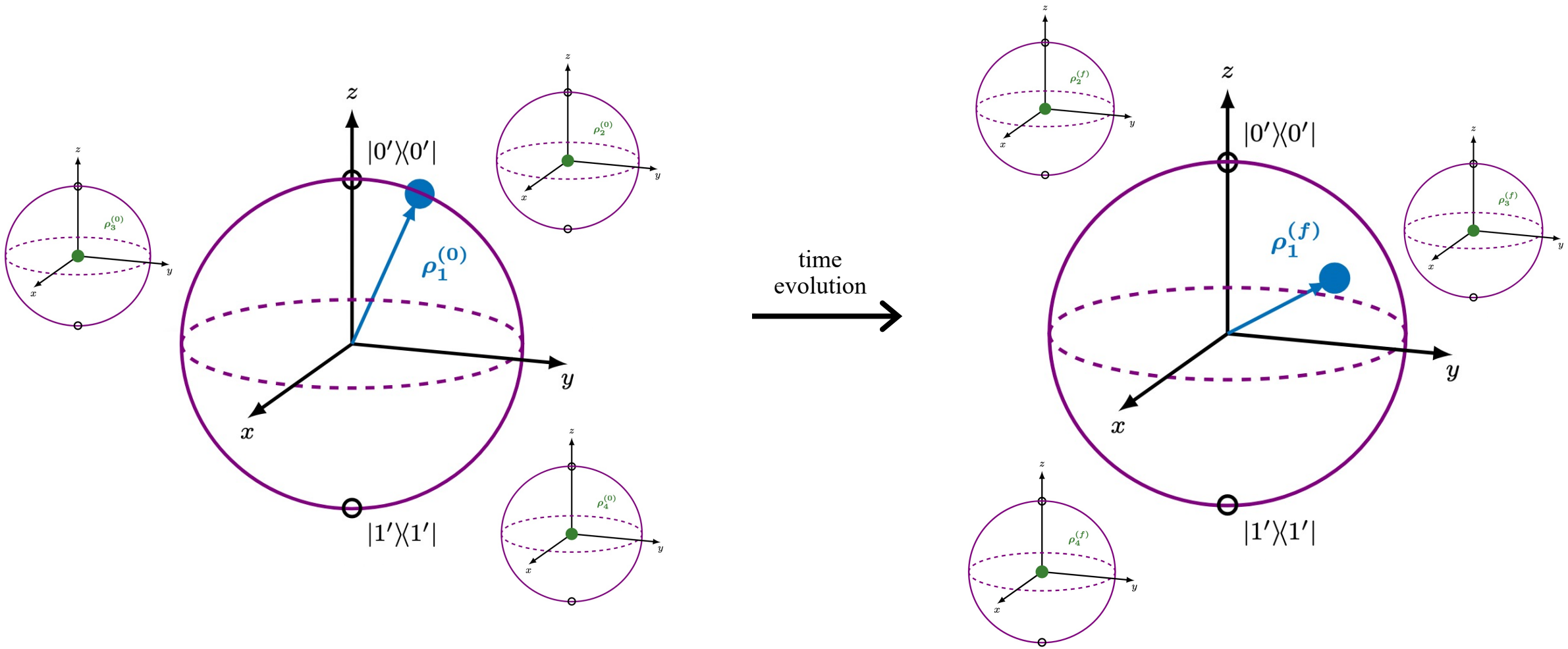
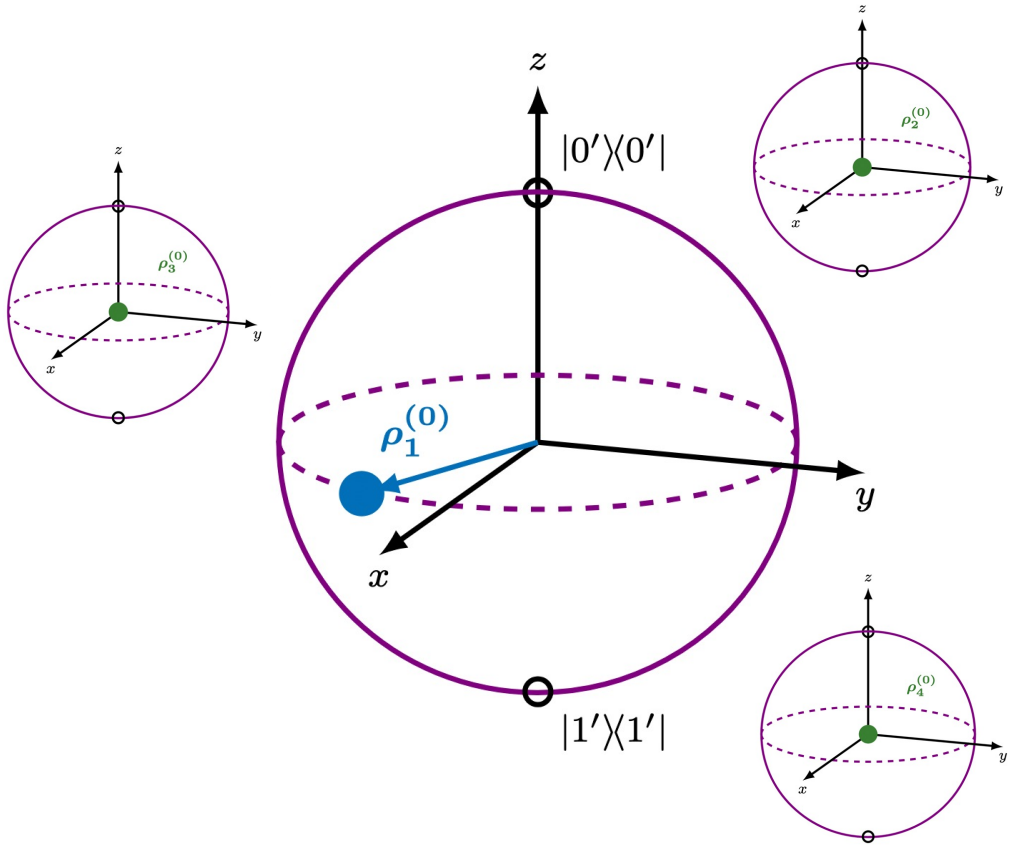


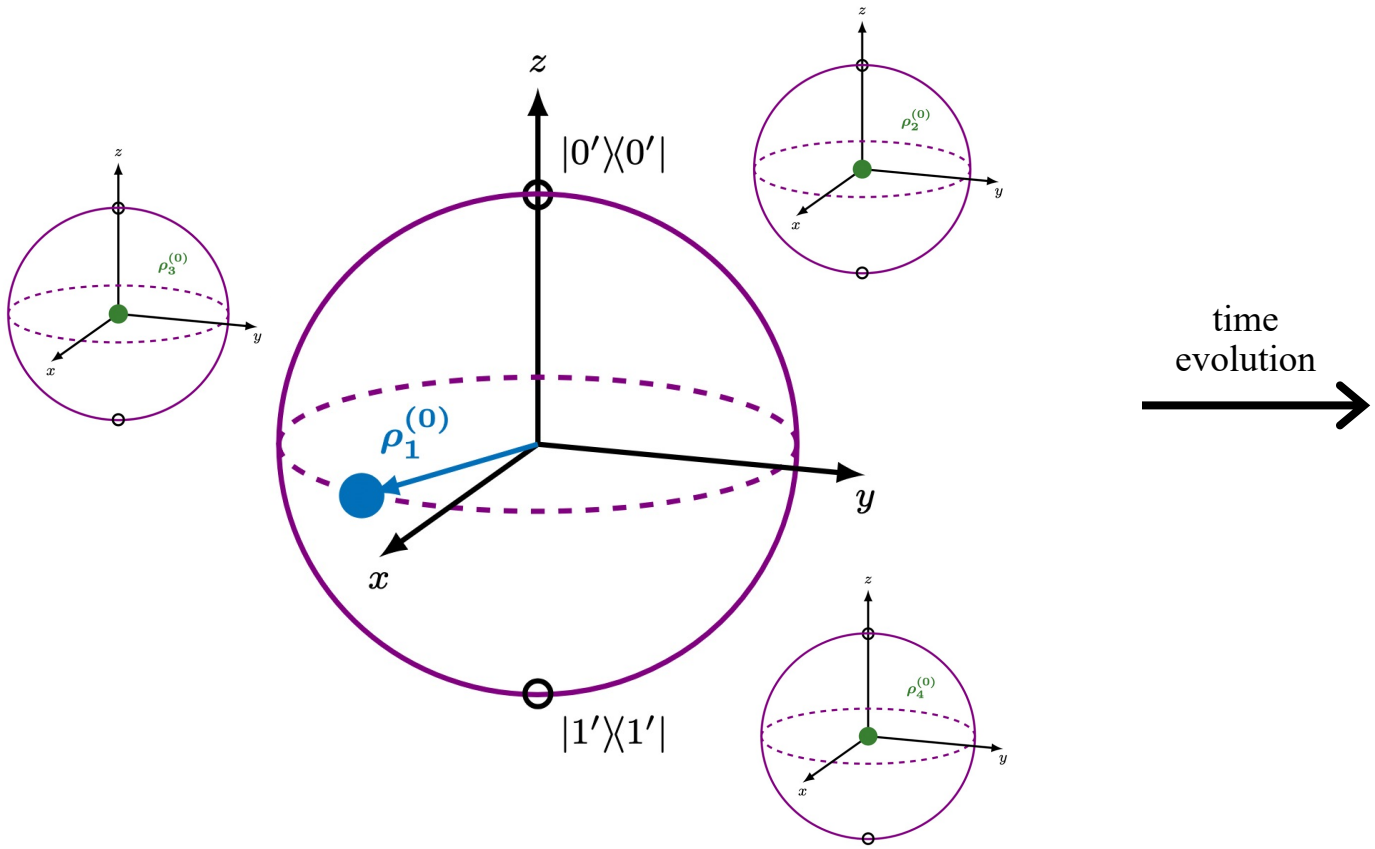
Generic Tensor Product Structure



Generic Tensor Product Structure

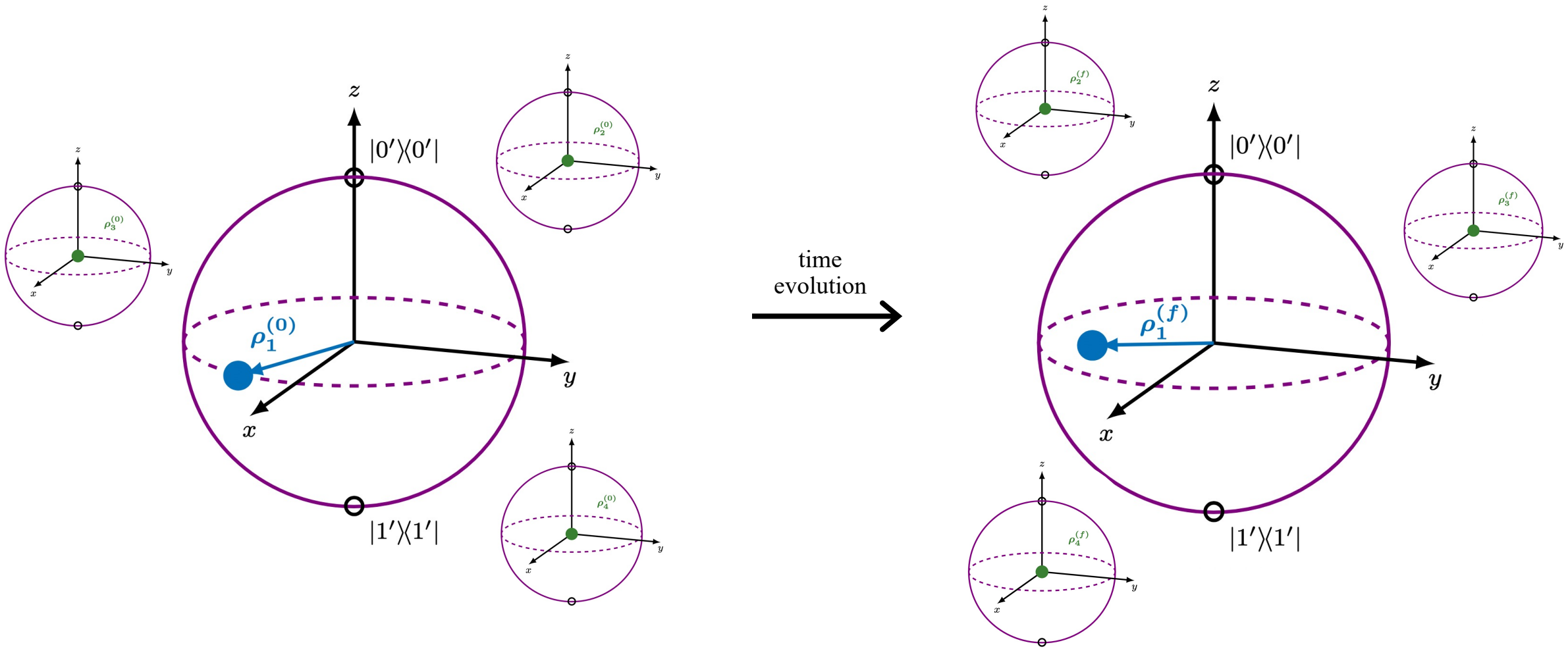


Generic Tensor Product Structure

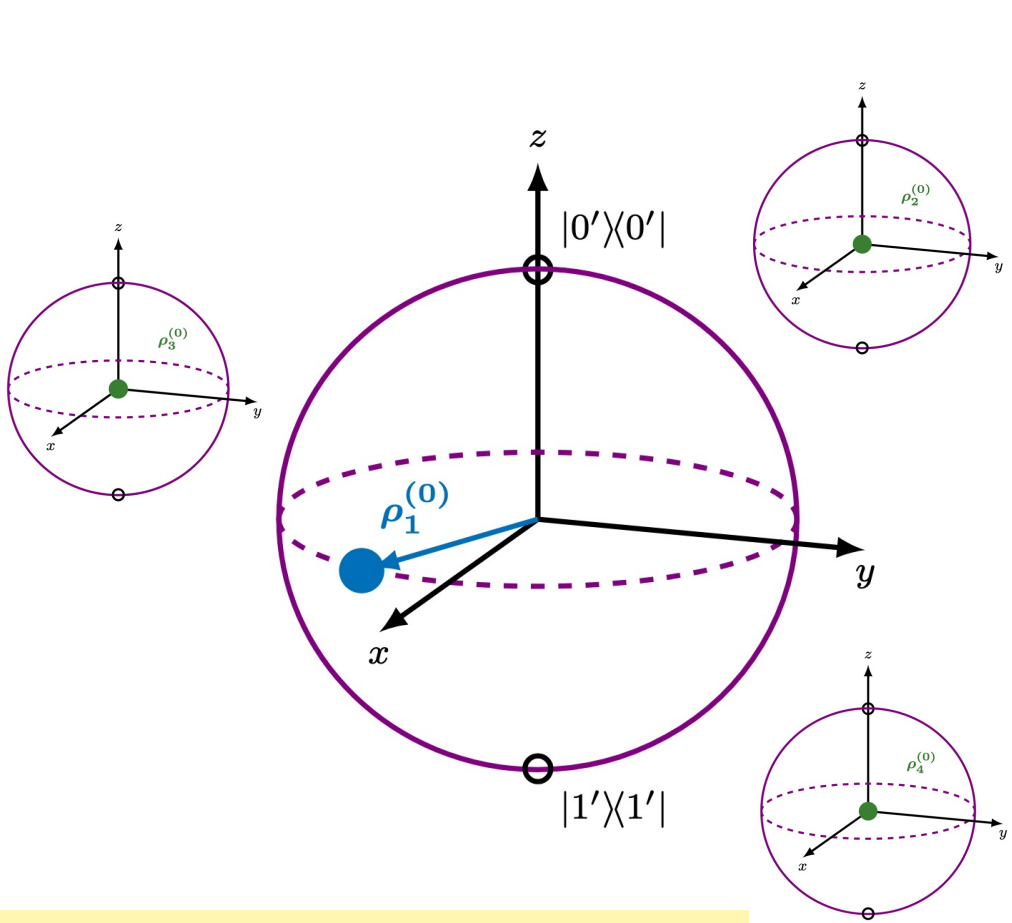


time evolution

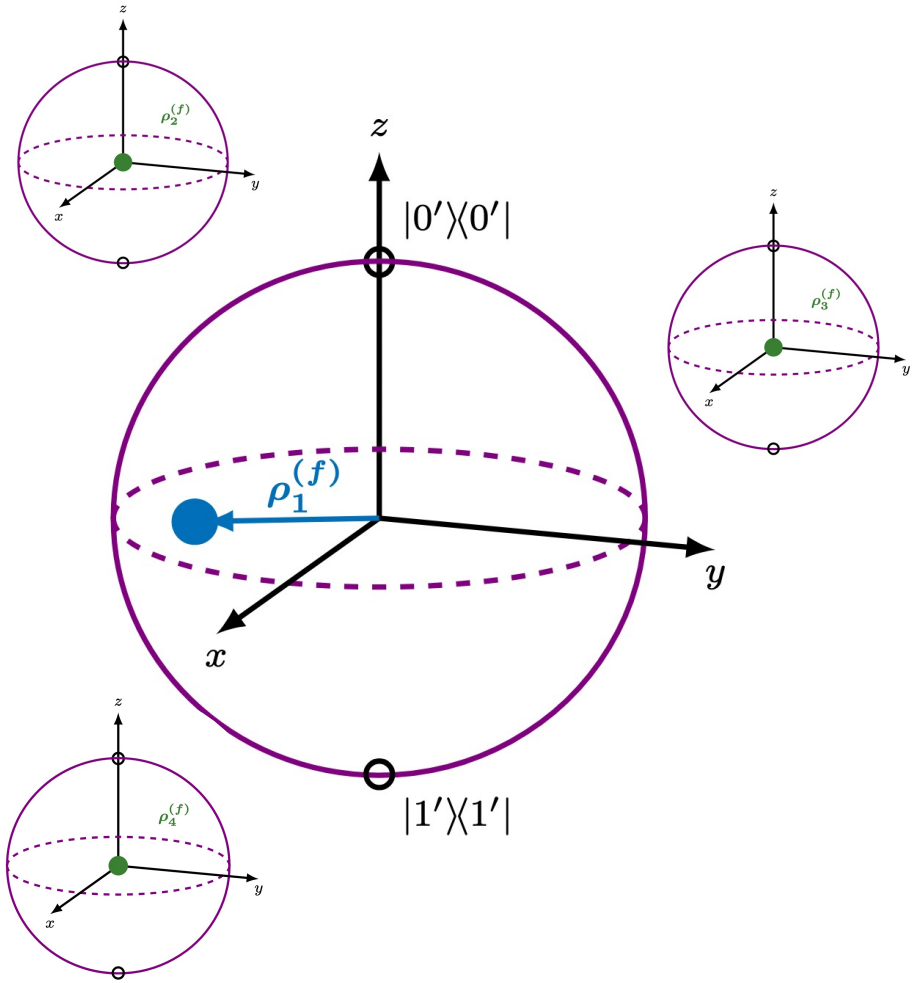
Generic Tensor Product Structure



Generic Tensor Product Structure



time evolution



In general, a TPS has no well-defined pointer state

How to Determine the Preferred Division into Subsystems?

- Require that a valid TPS can exhibit quasi-classical dynamics (has a well-defined pointer state)
- Metrics:
  - Predictability
  - Robustness
- Carroll and Singh [1]: Both metrics are required

[1] S. M. Carroll and A. Singh, “Quantum Mereology: Factorizing Hilbert Space into Subsystems with Quasi-Classical Dynamics,”

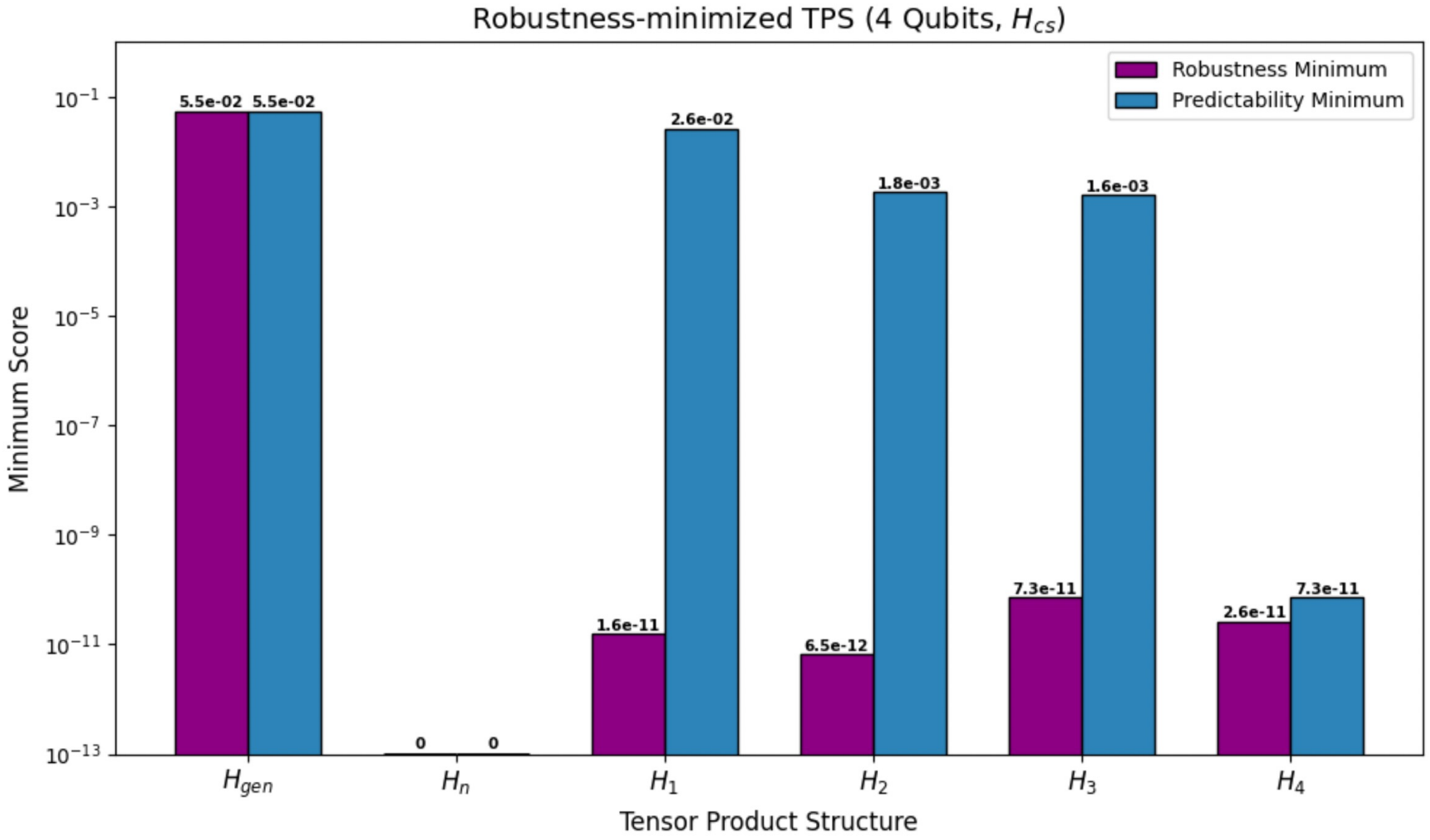
Primary Guiding Question of Thesis:

What is the relationship between the metrics of "predictability" and "robustness"?

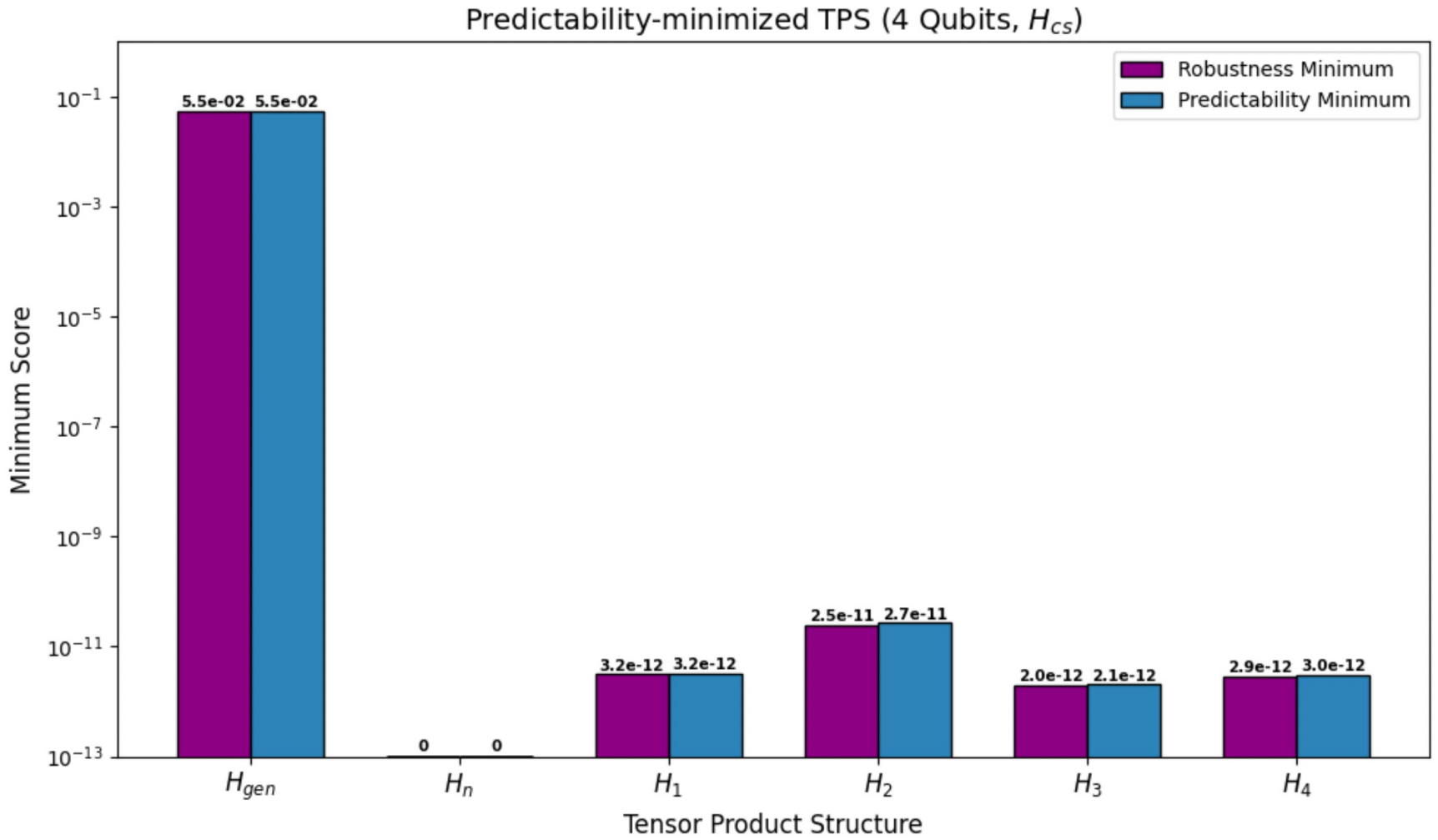
Method:

Use a machine learning algorithm to search the space of all possible TPSs to find qcTPSs according to each metric.

Results: Predictability Implies Robustness



Results: Predictability Implies Robustness



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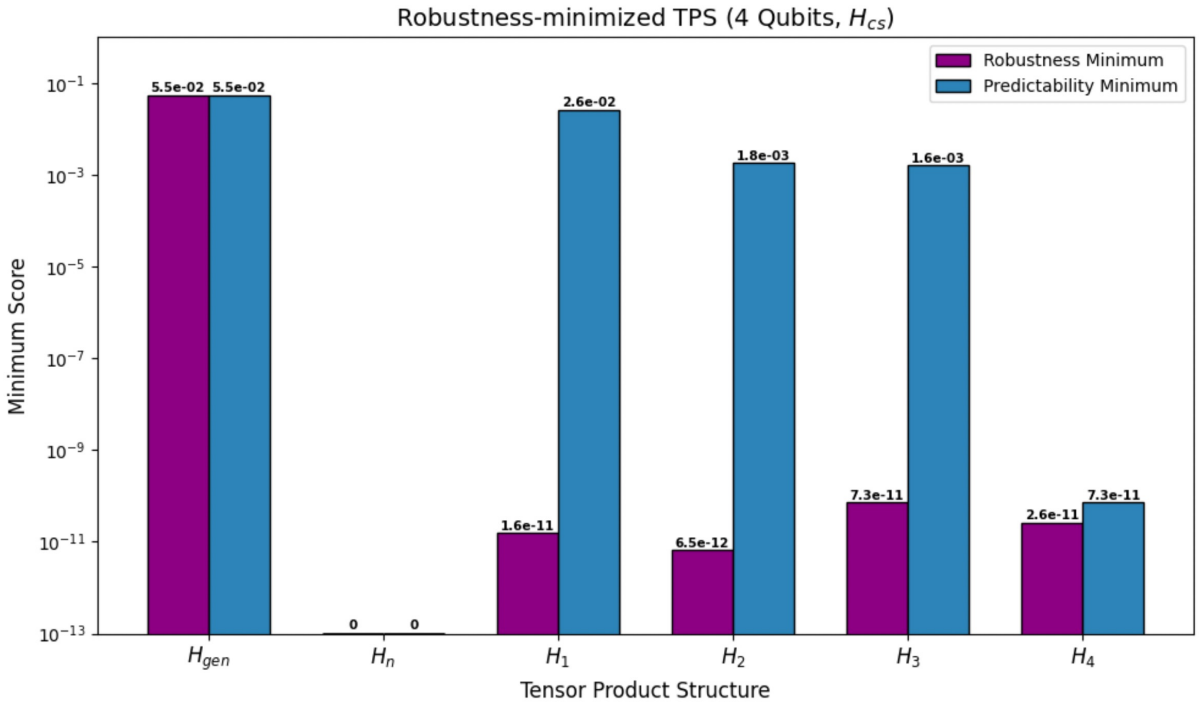

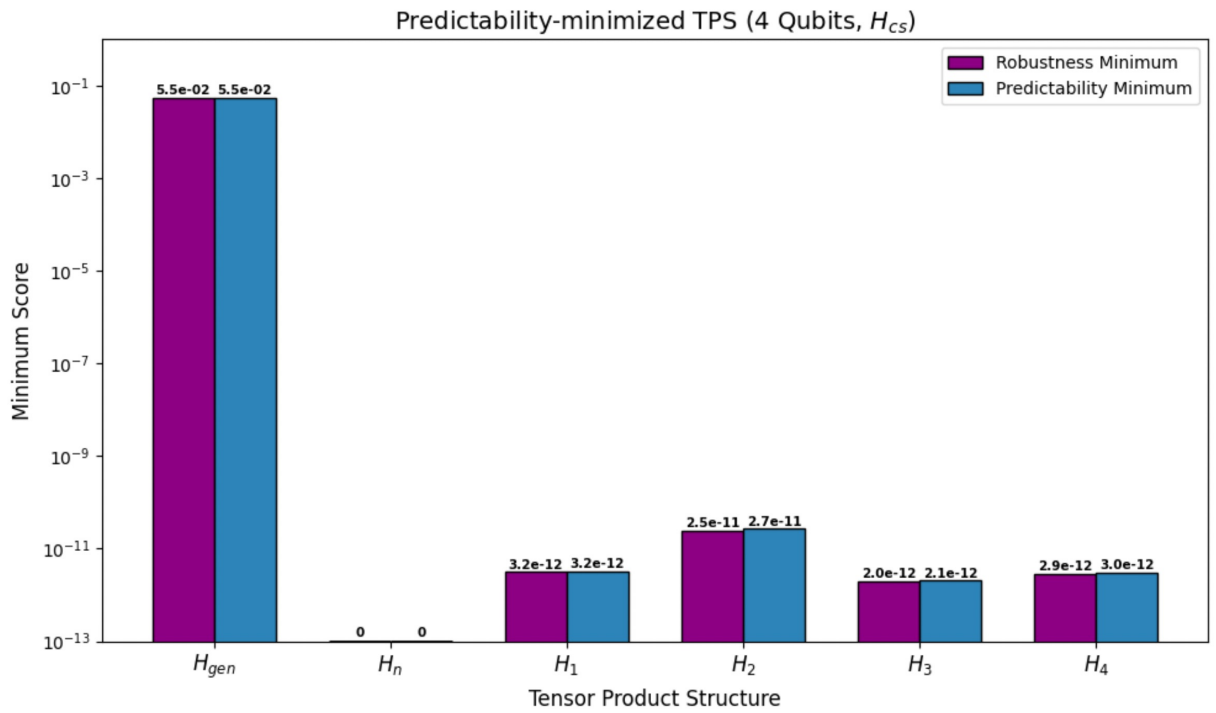

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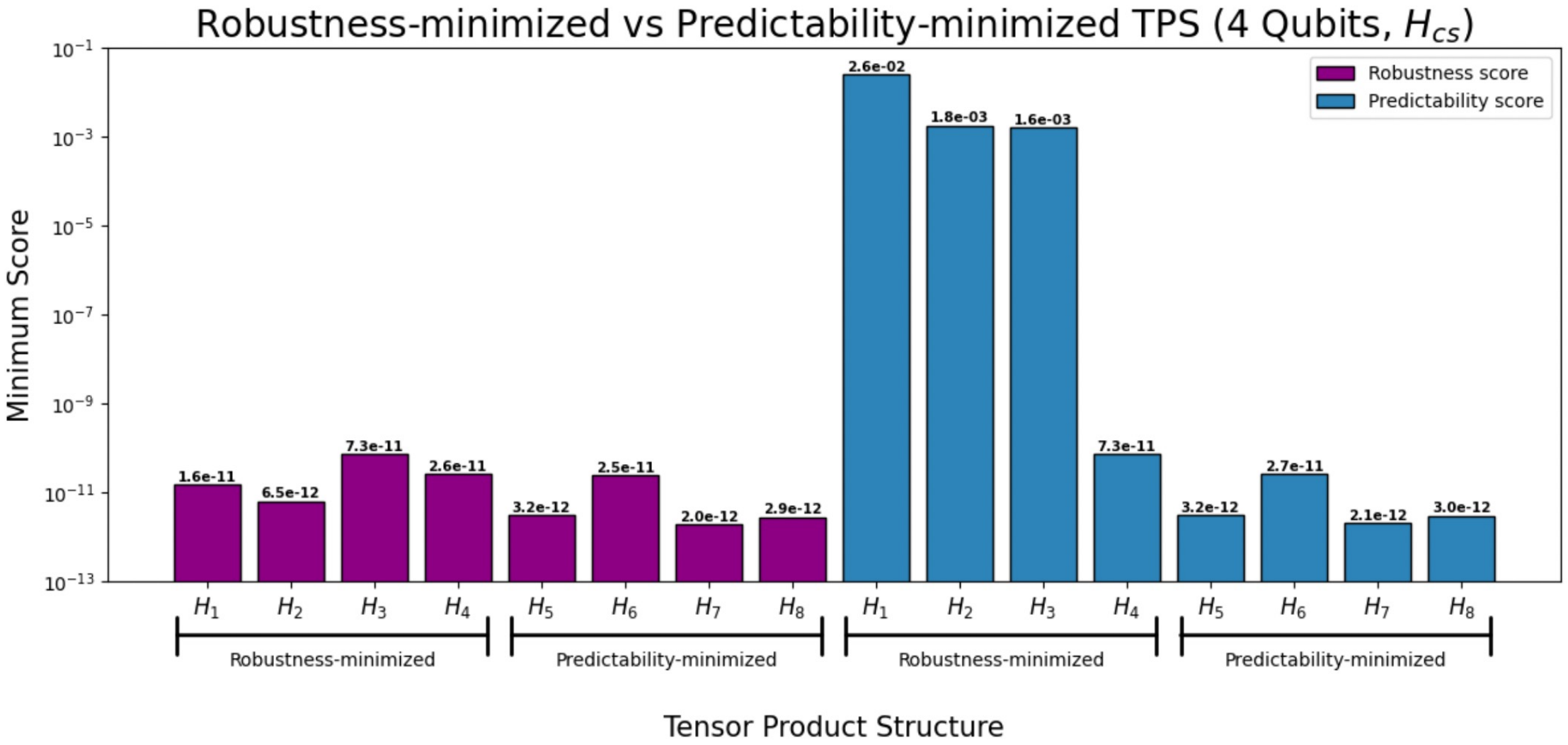

Conclusions

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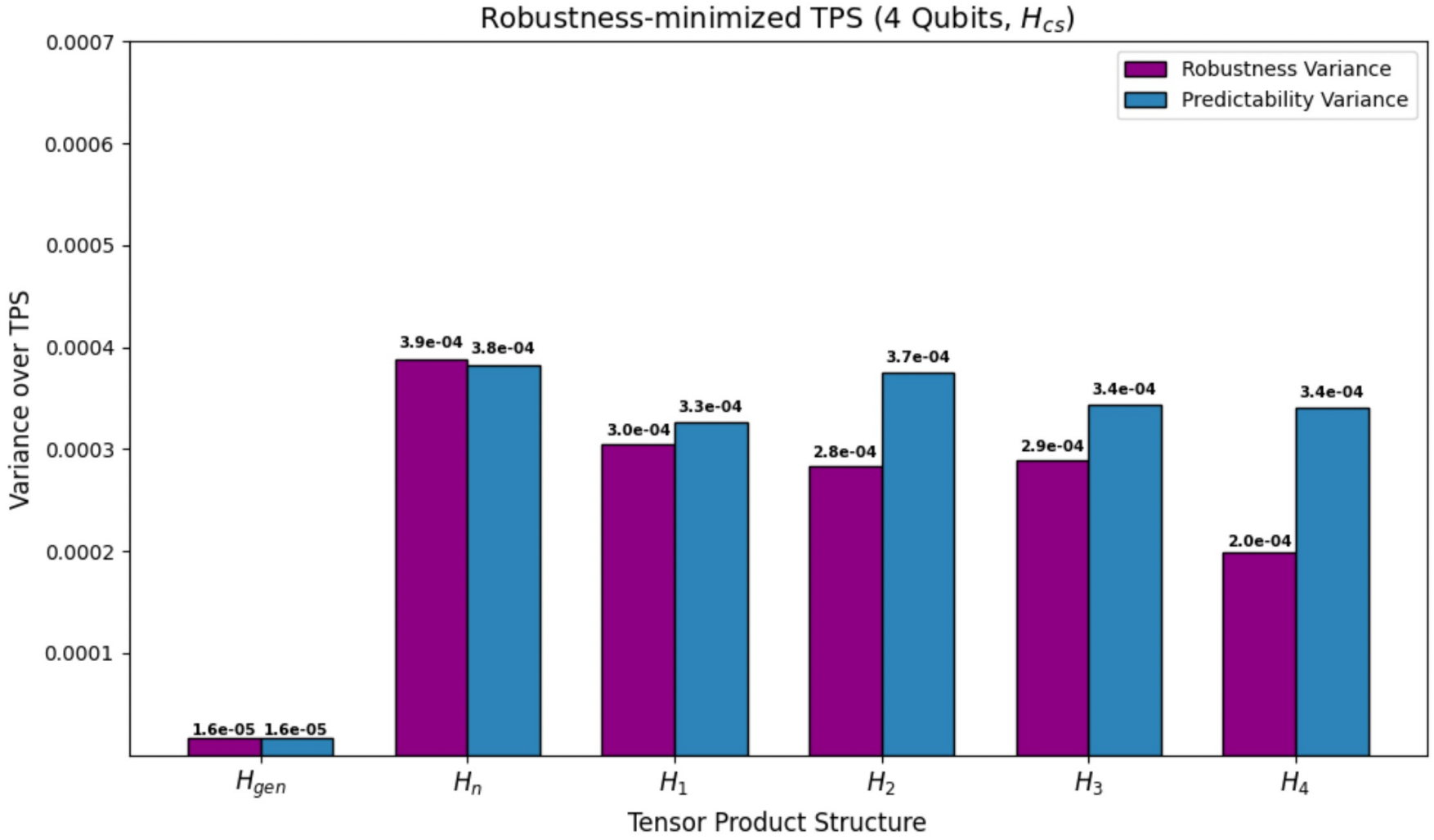
Conclusions

1. Predictability implies robustness. In particular, a TPS with a minimal predictability score must also have a minimal robustness score.
2. *Quasi-classical TPSs exhibit a significantly higher variance of scores across their initial states than a generic TPS.*

Gratitude

- Prof. Setter for all of the time he's spent talking with me about quantum and his incredible guidance
- Dwight, Prof. Moore, and the rest of the Pomona Physics Department for their unwavering support both throughout this thesis and my time at Pomona
  - Also Dwight for pushing me to attempt an explanation of my thesis without any equations
- All of the context in my life that has provided me with the privileged opportunity to study physics at Pomona College
- The indeterminacy of quantum mechanics for deeply connecting me to the universe

Results: Variance Greater for qcTPS



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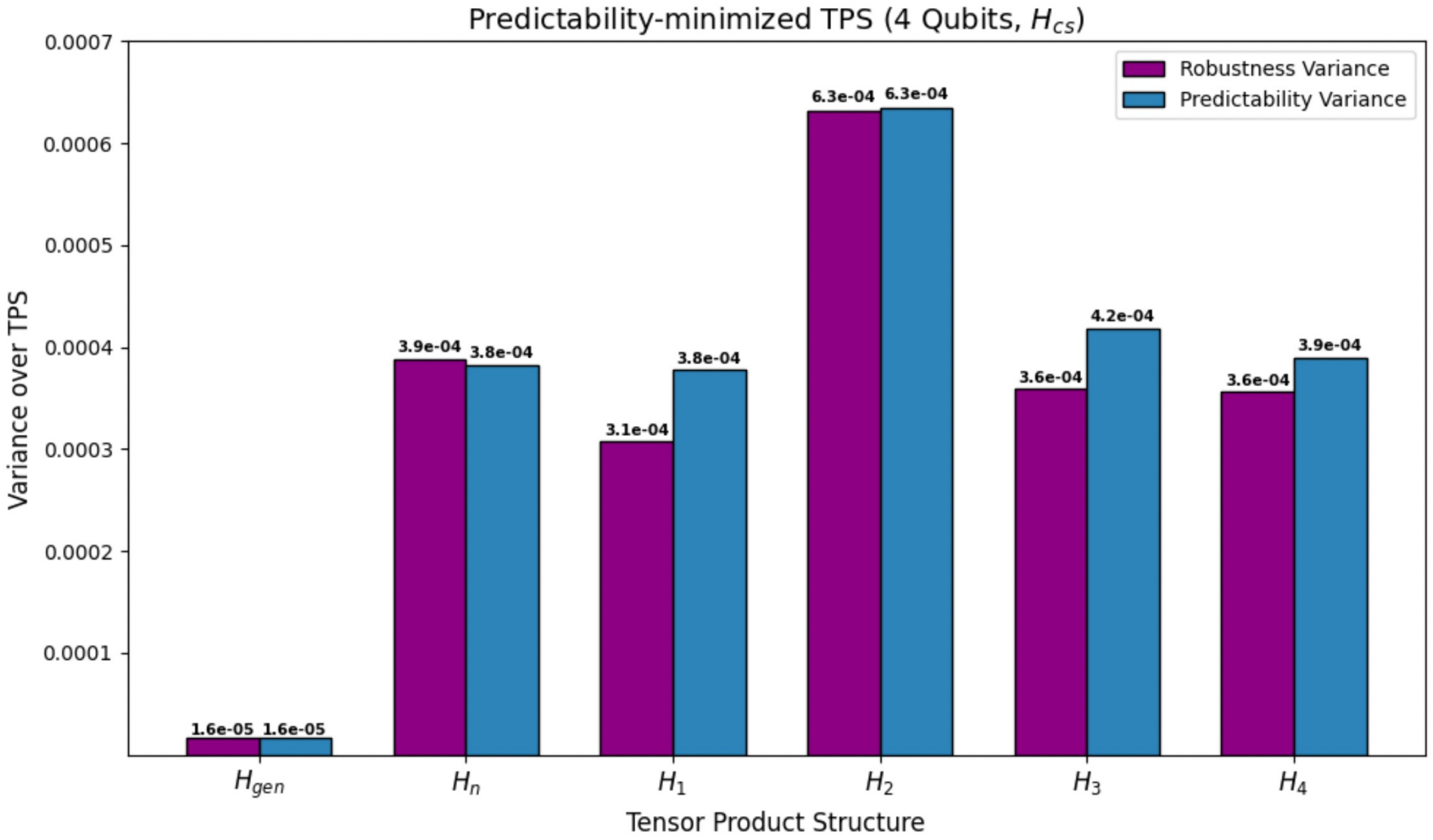
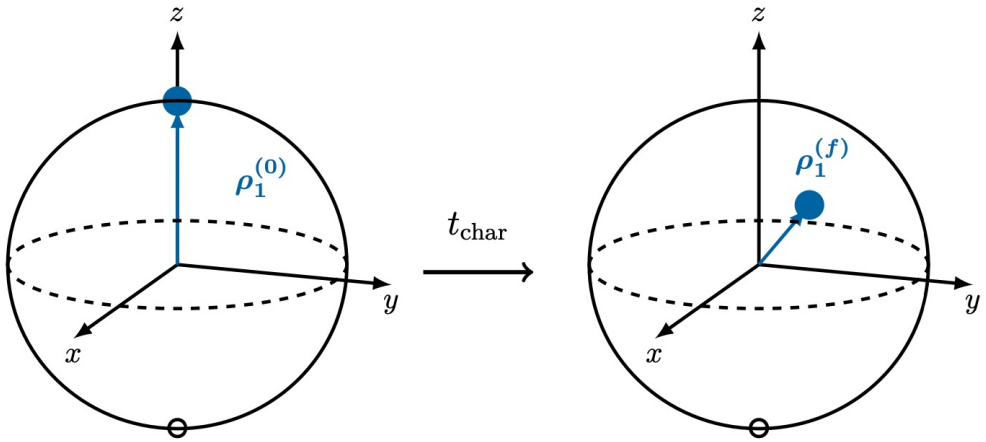


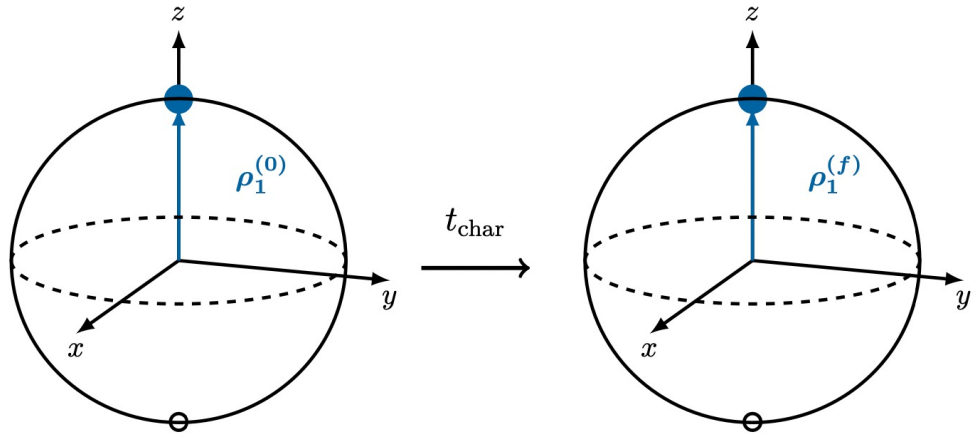
What Did I Actually Do?

Predictability and Robustness

Neither robust nor predictable:



Robust and predictable:



Robust, not predictable: