Title: Epistemic vs ontic interpretations of the state of quantum systems in the presence of closed timelike curves

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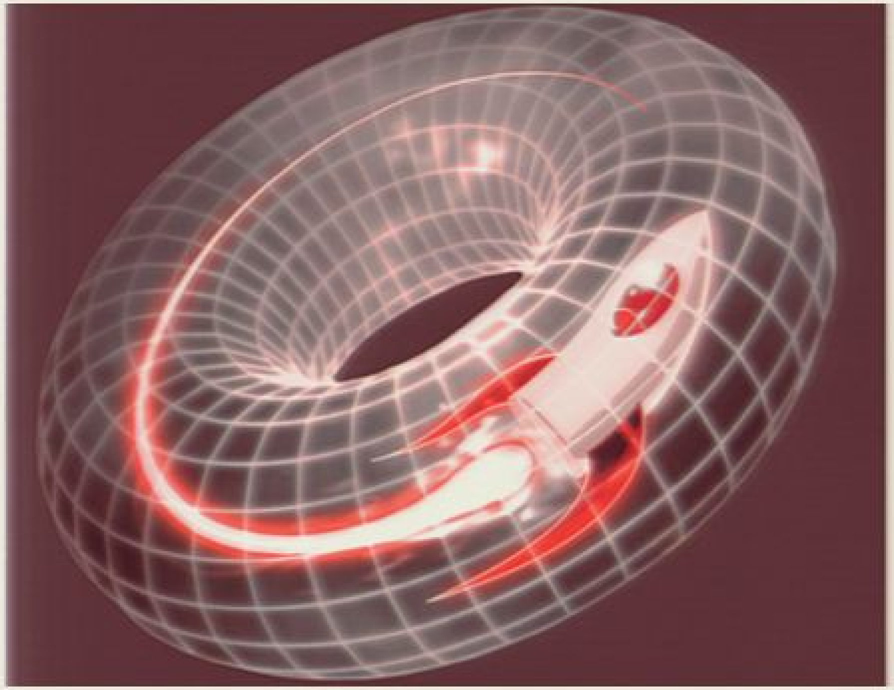
Abstract: TBA

Closed Timelike Curves

- 'Time Machines'
- Can lead to paradoxes
- Nature of the quantum state comes to the fore



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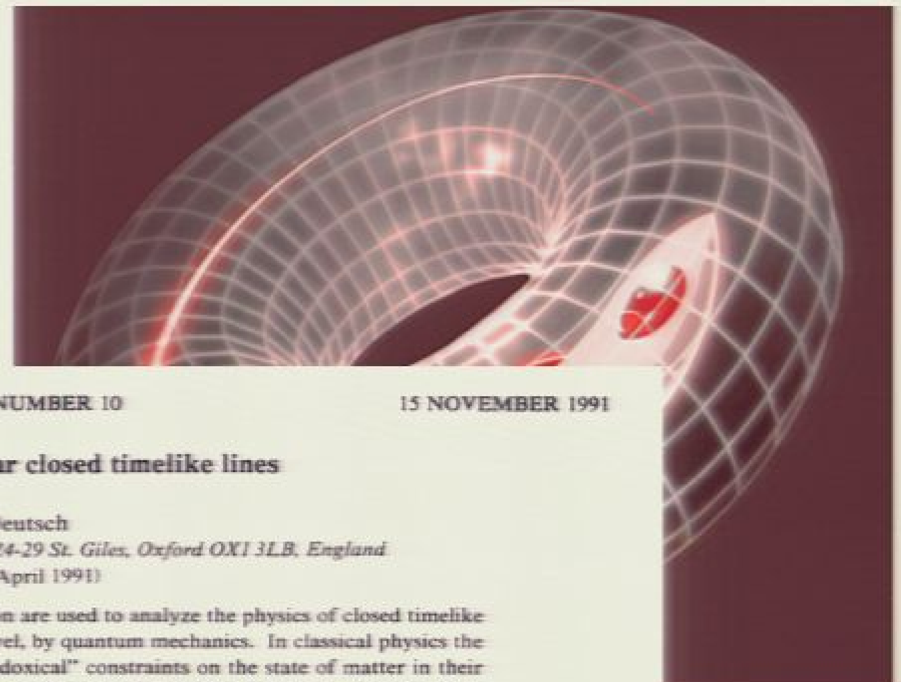

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Quantum mechanics near closed timelike lines

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Oxford University Mathematical Institute, 24-29 St. Giles, Oxford OX1 3LB, England
(Received 9 April 1991)

The methods of the quantum theory of computation are used to analyze the physics of closed timelike lines. This is dominated, even at the macroscopic level, by quantum mechanics. In classical physics the existence of such lines in a spacetime imposes "paradoxical" constraints on the state of matter in their past and also provides means for knowledge to be created in ways that conflict with the principles of the philosophy of science. In quantum mechanics the first of these pathologies does not occur. The second is mitigated, and may be avoidable without such spacetimes being ruled out. Several novel and distinctive (but nonparadoxical) quantum-mechanical effects occur on and near closed timelike lines, including violations of the correspondence principle and of unitarity. It becomes possible to "clone" quantum systems and to measure the state of a quantum system. A new experimental test of the Everett interpretation against all others becomes possible. Consideration of these and other effects sheds light on the nature of quantum mechanics.

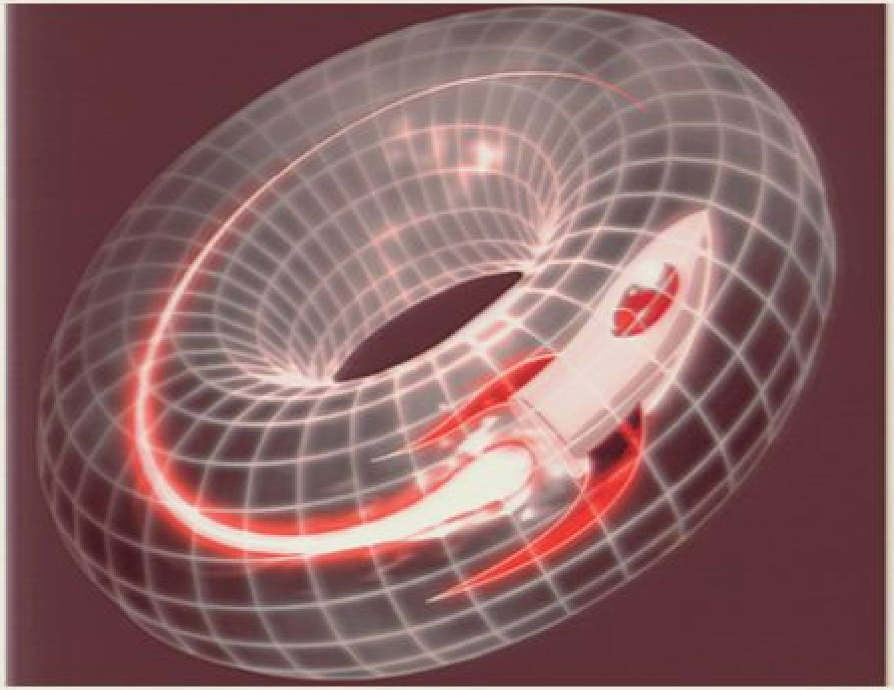
APPLYING THE QUANTUM THEORY OF COMPUTATION

This paper is about the physical effects of closed time-

ing two considerations should counteract that impression. First, the class of such models is essentially the class of *quantum computational networks* [7], which is computationally universal in the sense that such networks can simulate the behavior of any finite quantum

Outline

- Deutsch's analysis using a many-worlds interpretation
- Revisiting CTCs with an epistemic perspective
- Lessons from a toy theory



A framework for systems travelling in CTCs

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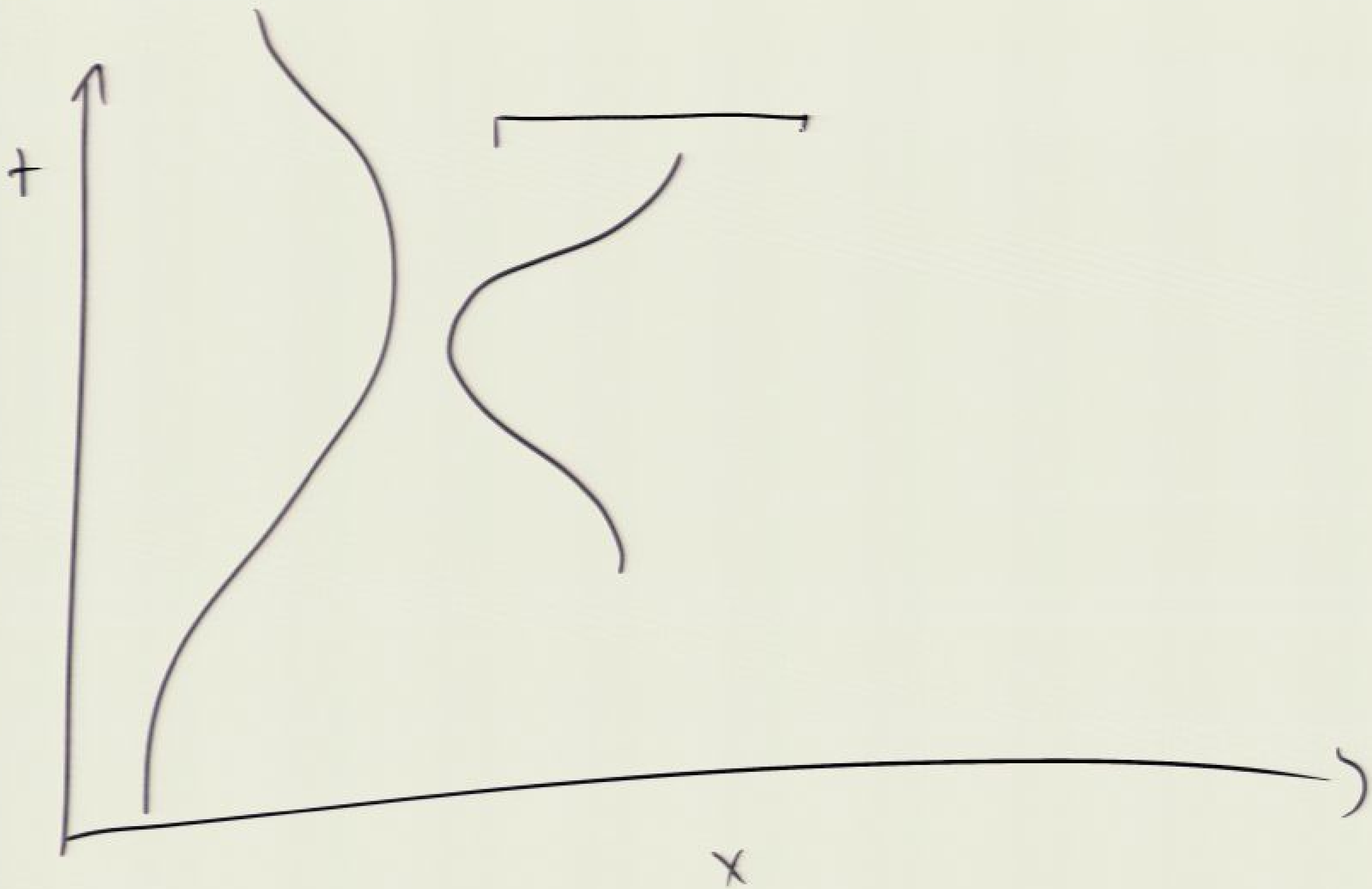

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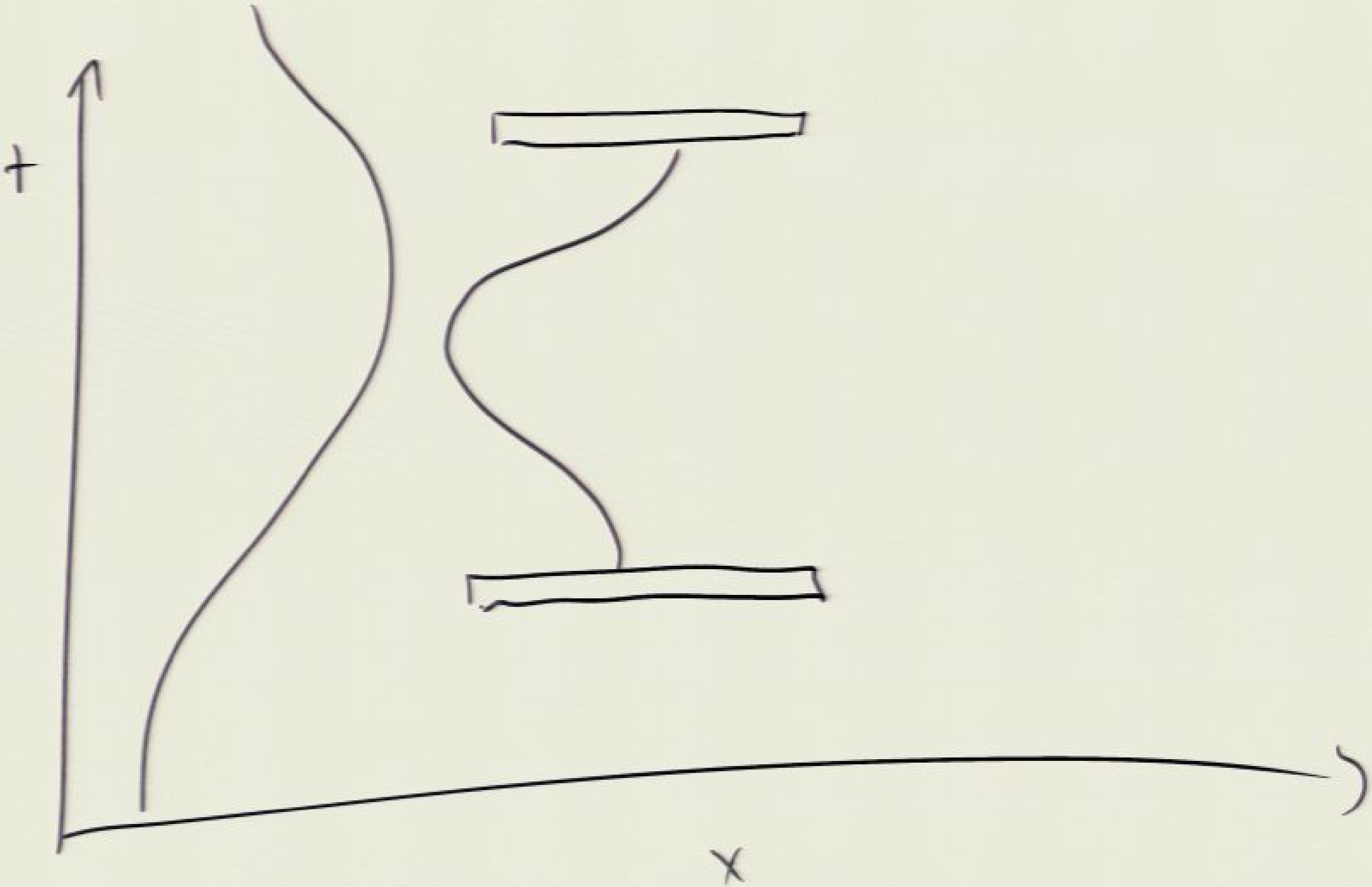

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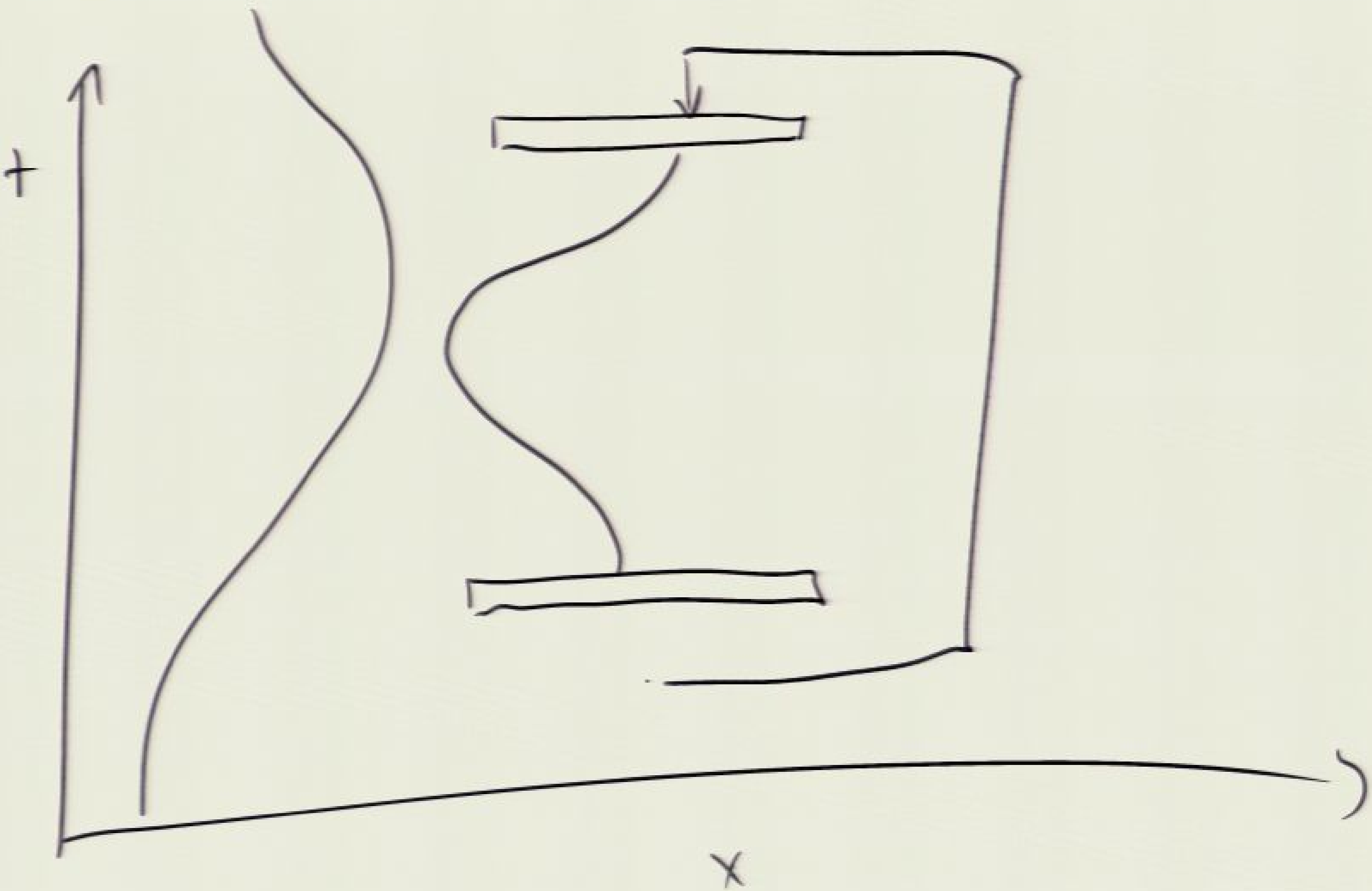

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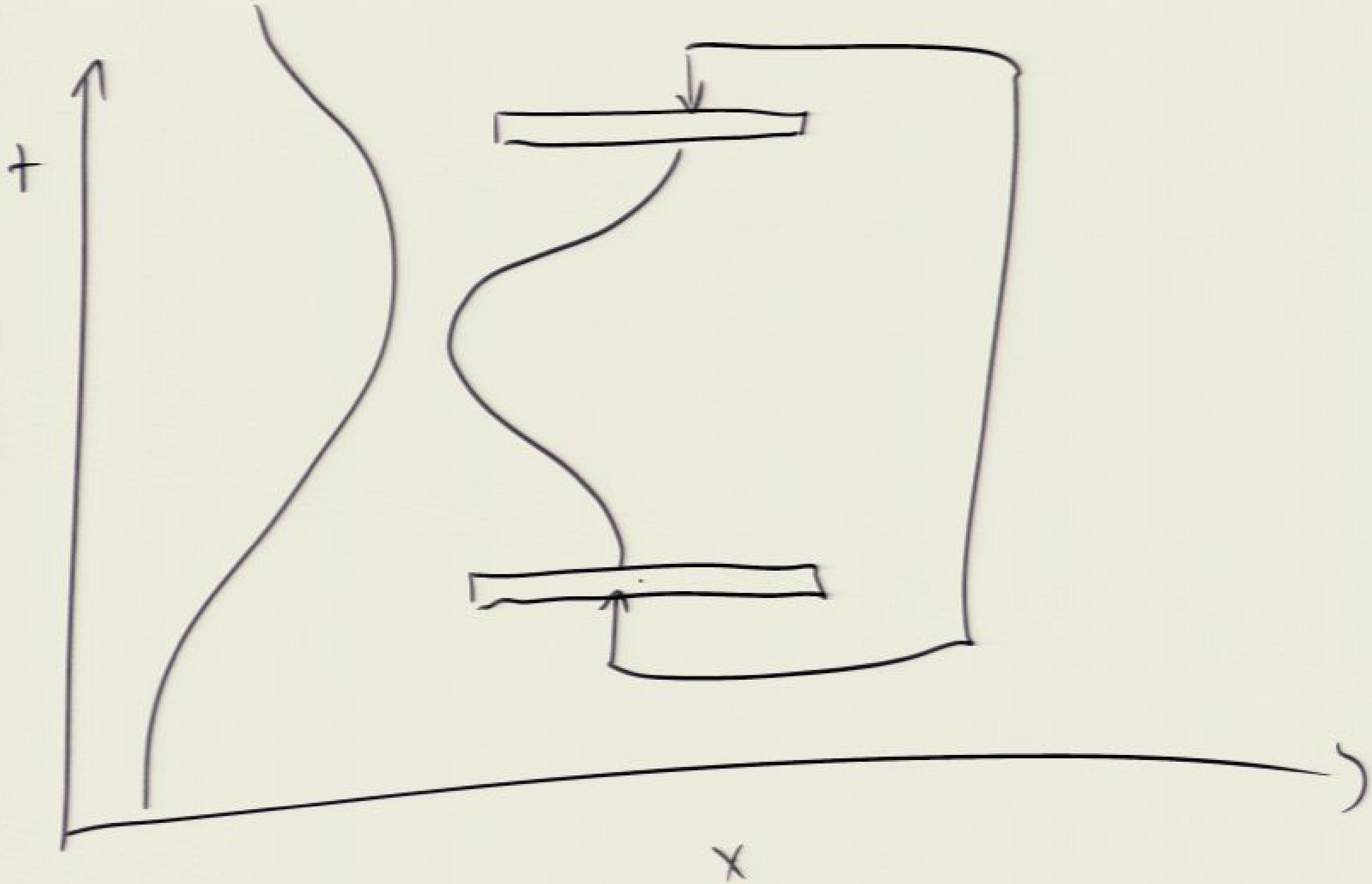
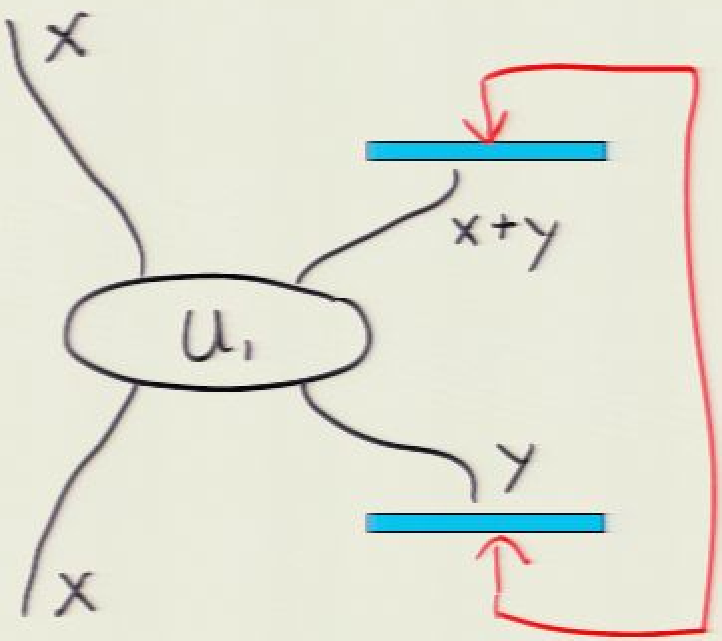


Paradoxes with classical systems

Classical Paradox 1



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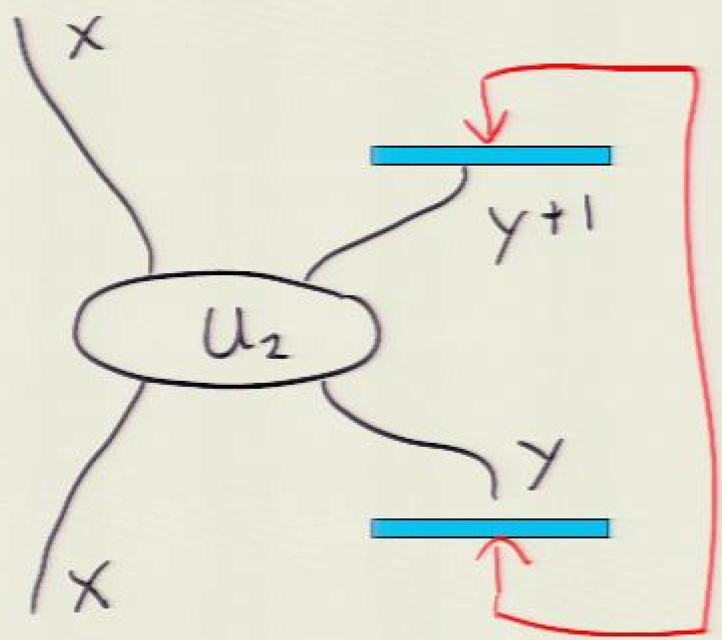

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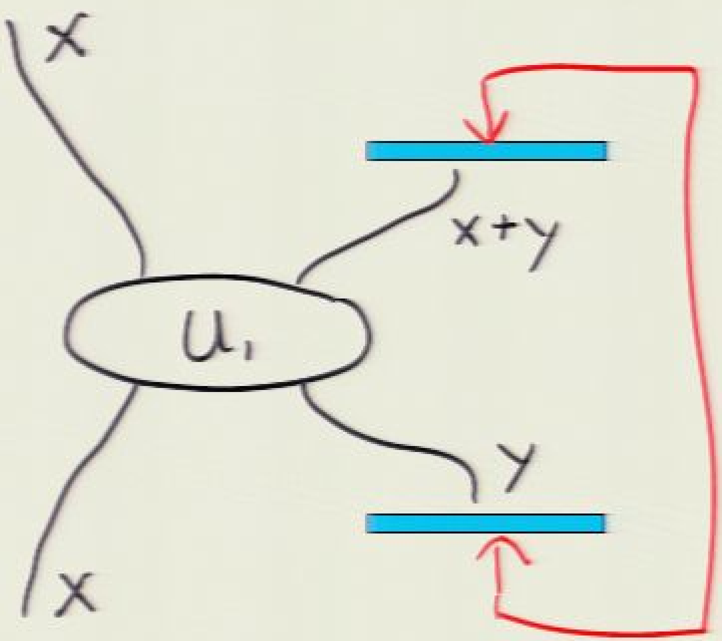

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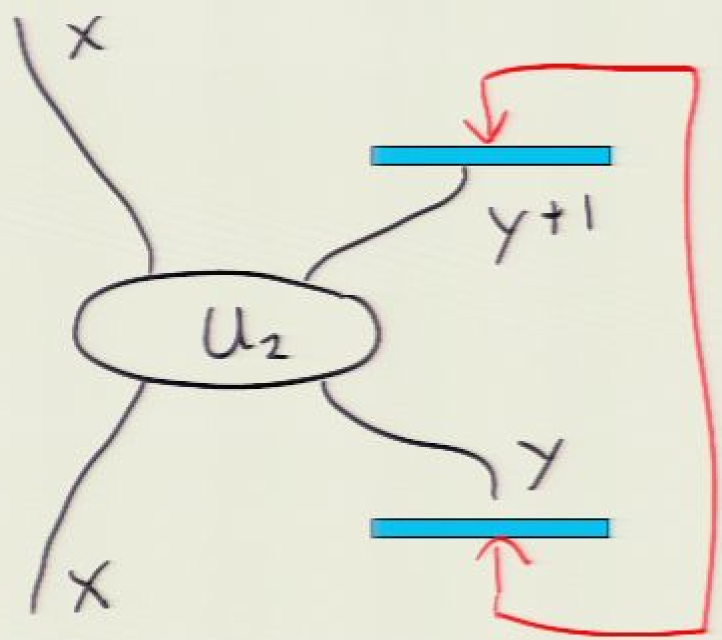

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- constraint on initial conditions
- y is underdetermined

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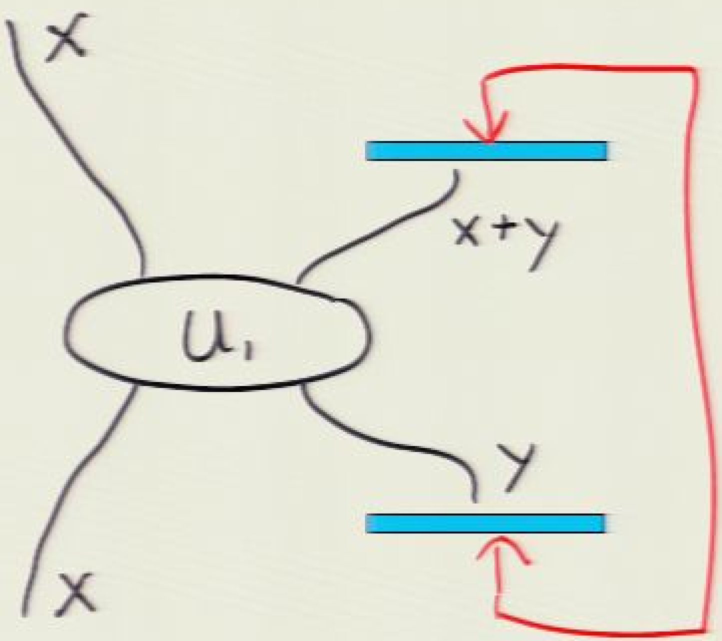

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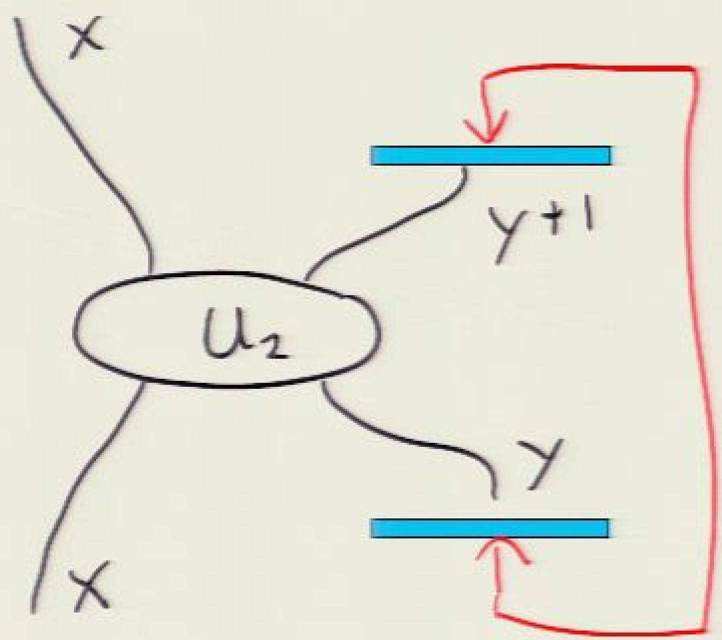


- no (single-valued) solution for any initial conditions

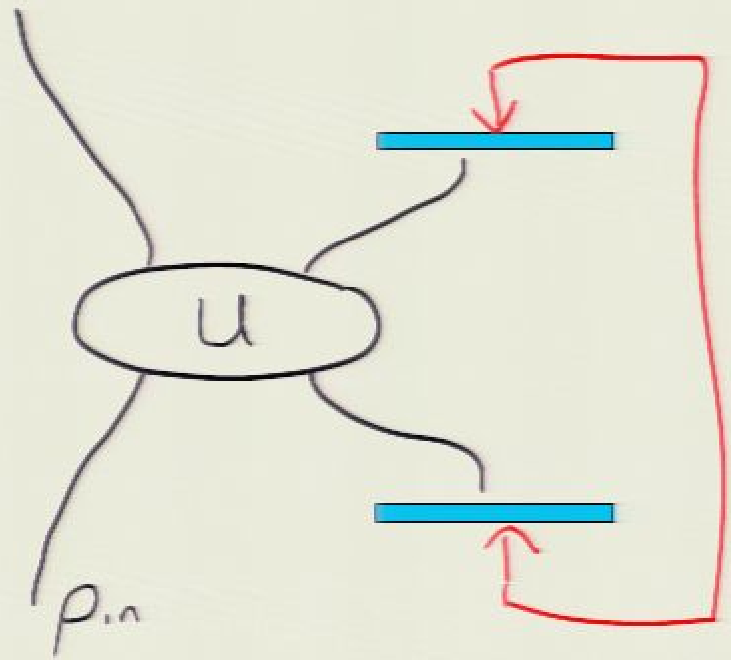
More about classical paradoxes

- **Consistency paradox:**
  existence of initial conditions that do not lead to a globally-consistent single-valued solution
  e.g., grandfather paradox

- **Information paradox:**
  e.g., proof of mathematical theorem without a prover
  theory of computation with CTCs is very different

Quantum systems in CTCs a la Deutsch

- Initial state ρ
- Let σ be the state of the CTC particles prior to interaction



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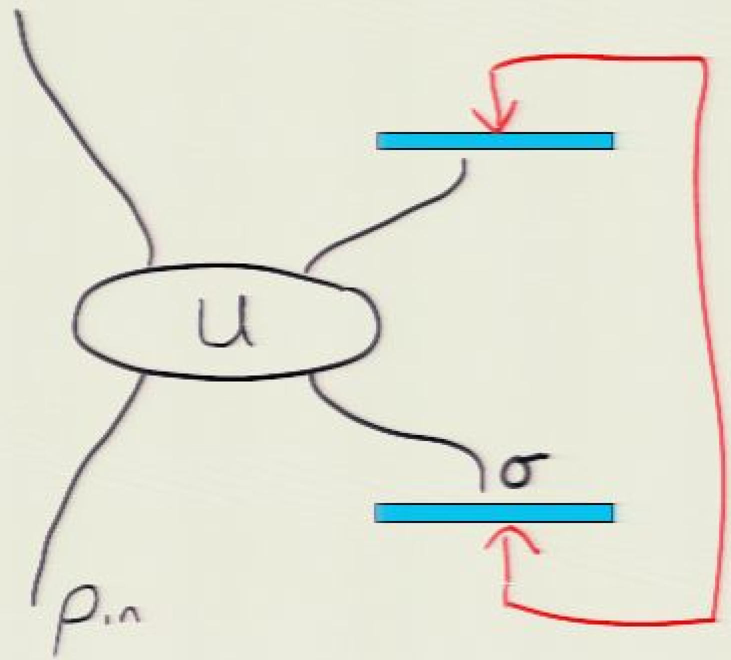

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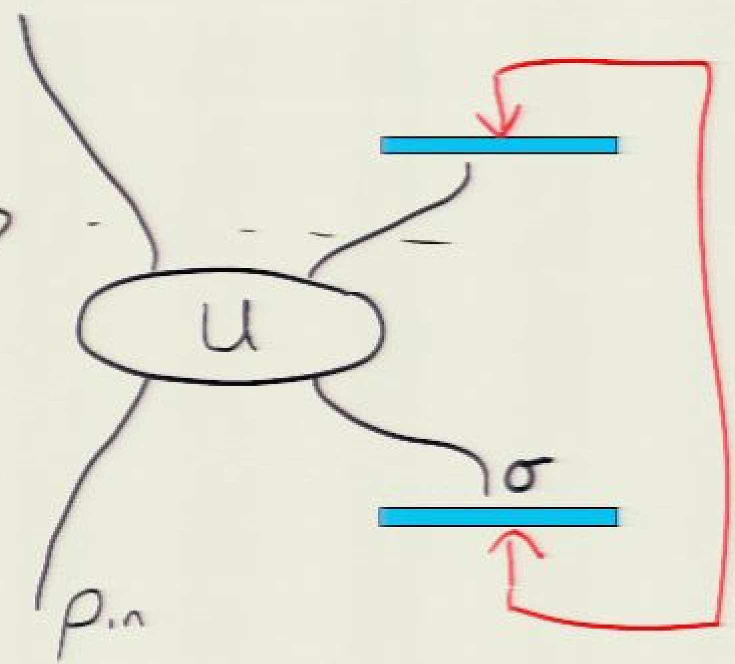

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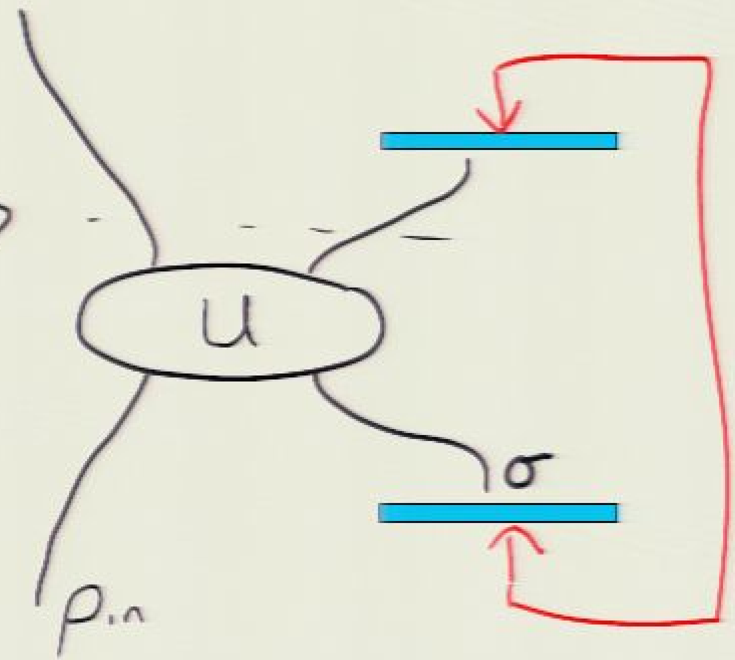

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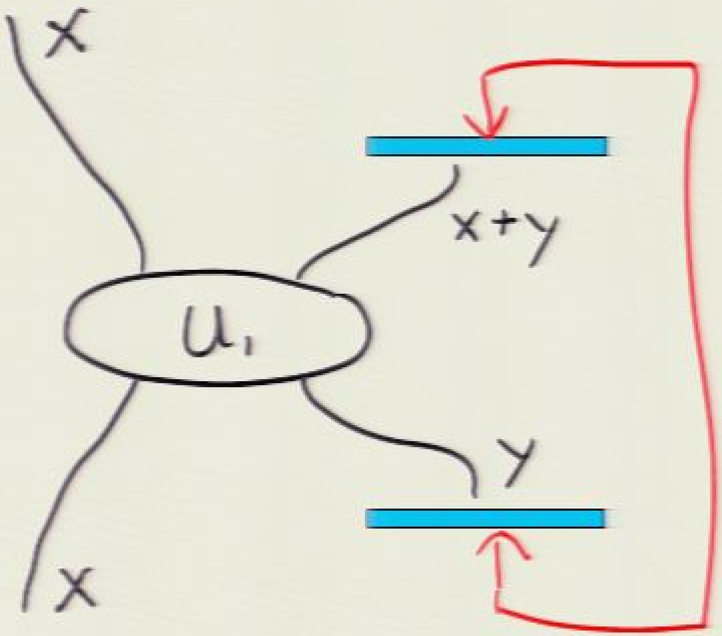

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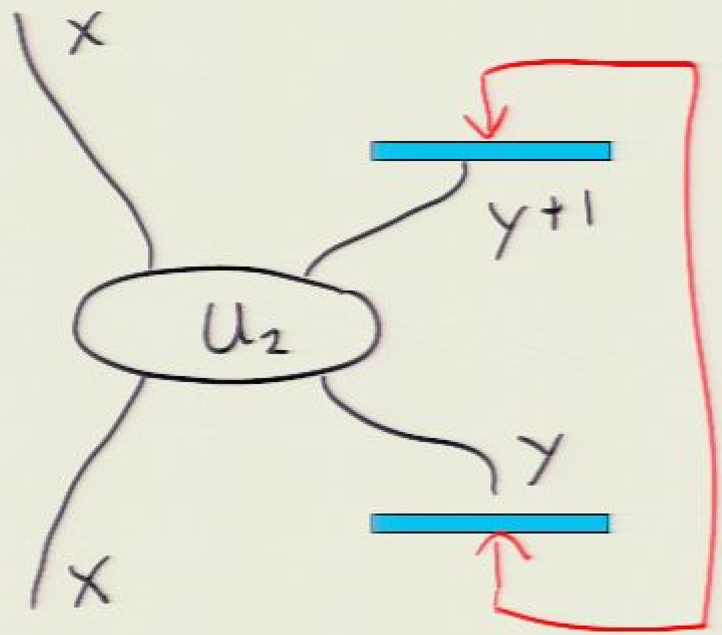

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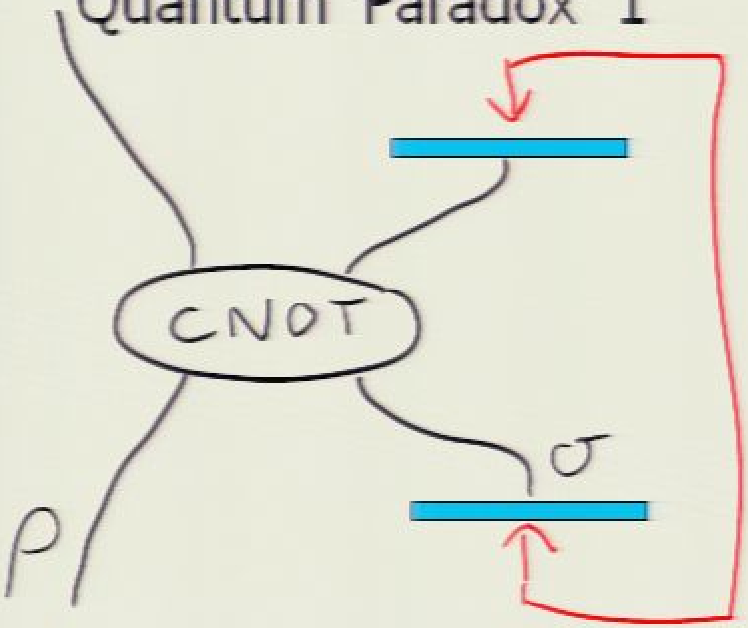

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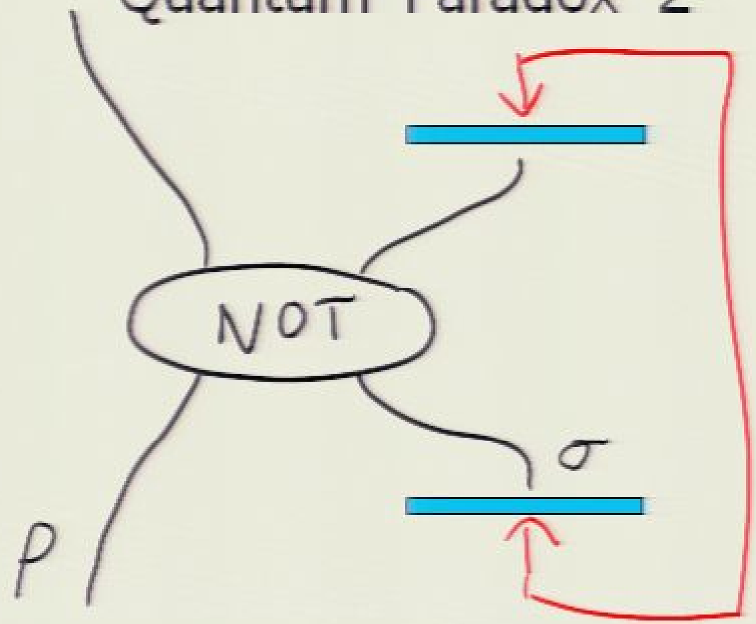

$$\sigma = \frac{1}{2}(I + \lambda X)$$

- solution for any ρ
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Quantum Mechanics and CTCs

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Interpreting the kinematic consistency

- Kinematic consistency condition:

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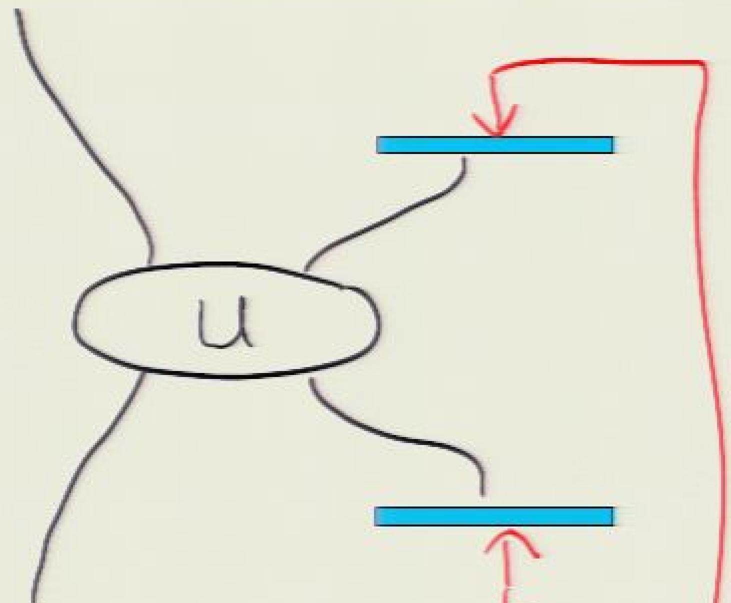

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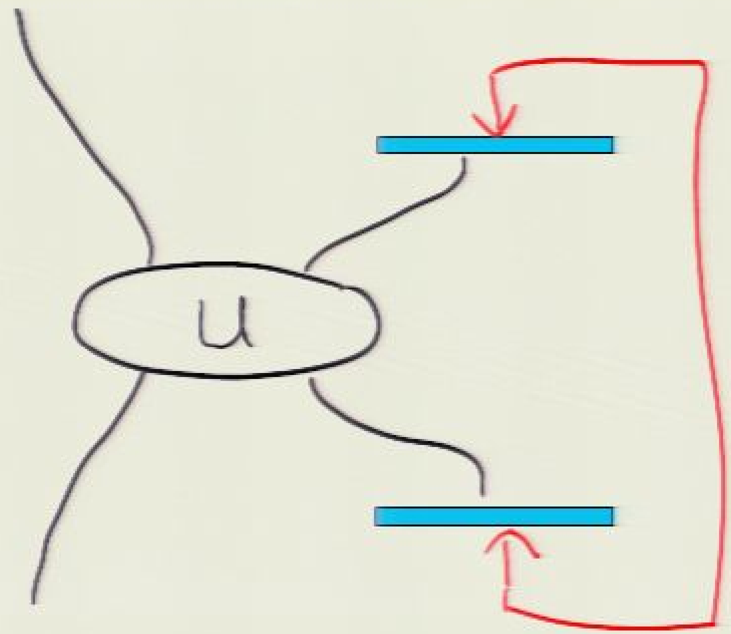

Conflicting predictions of rival "interpretations" of quantum theory

Now recall the consistency condition for the evolution round a closed timelike line. In the quantum case I have taken it to be that the density operator of each chronology-violating bit must return to its original value at a given event, as expressed by (15). That is the correct condition under the unmodified quantum formalism, *but it is either wrong or insufficient under every other version of quantum theory,* just as under classical physics.

An Epistemic Perspective

- Quantum state represents an observer's knowledge

- Revisiting Deutsch's consistency conditions:
  Ontological properties must be made consistent

- What consistency conditions must be applied to an epistemic state?
  - Subjective probabilities – How can one place bets in a world with time machines?
  - Probabilities of ontological properties (hidden variables)

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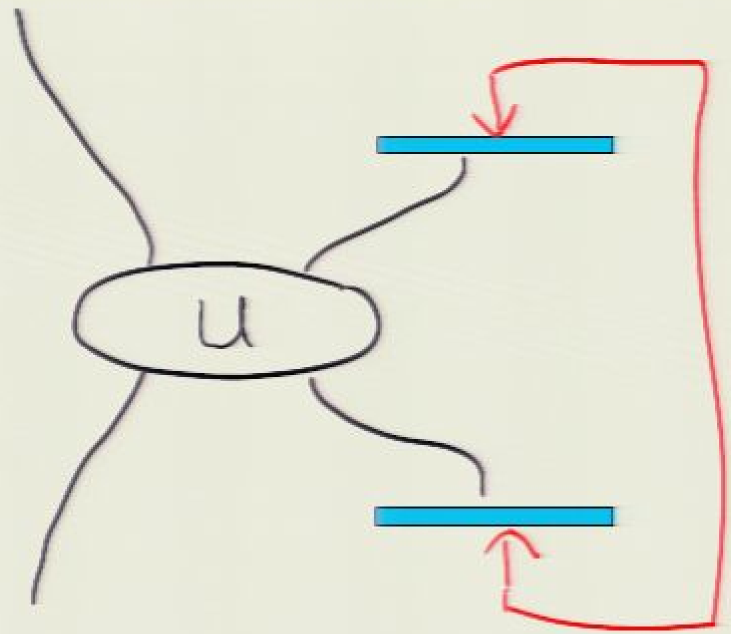

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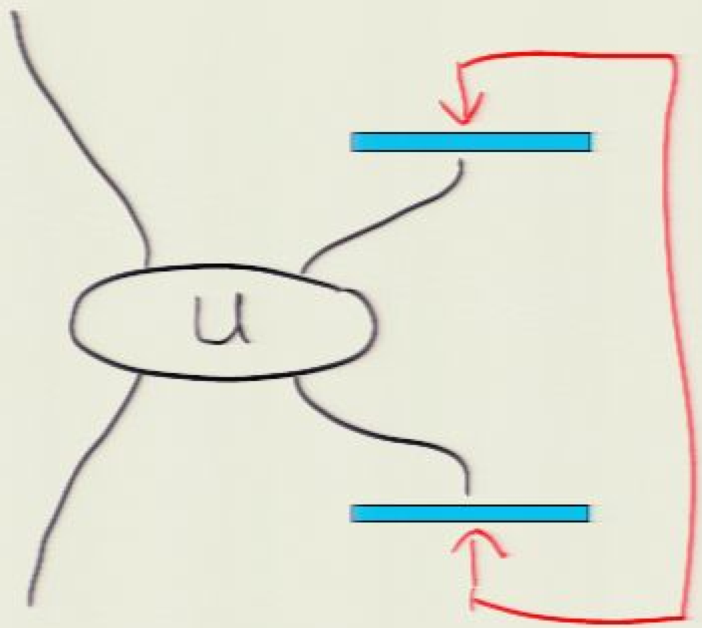

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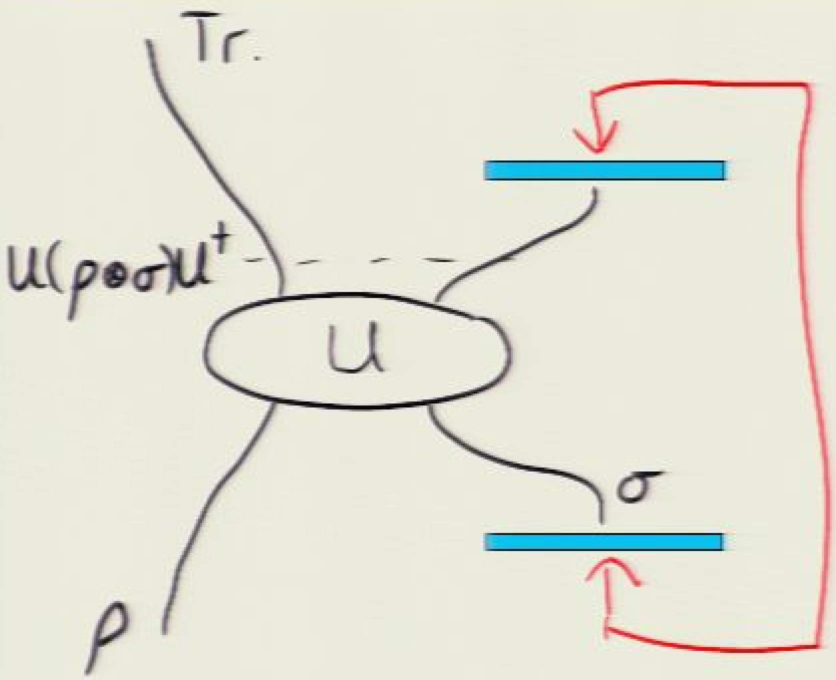

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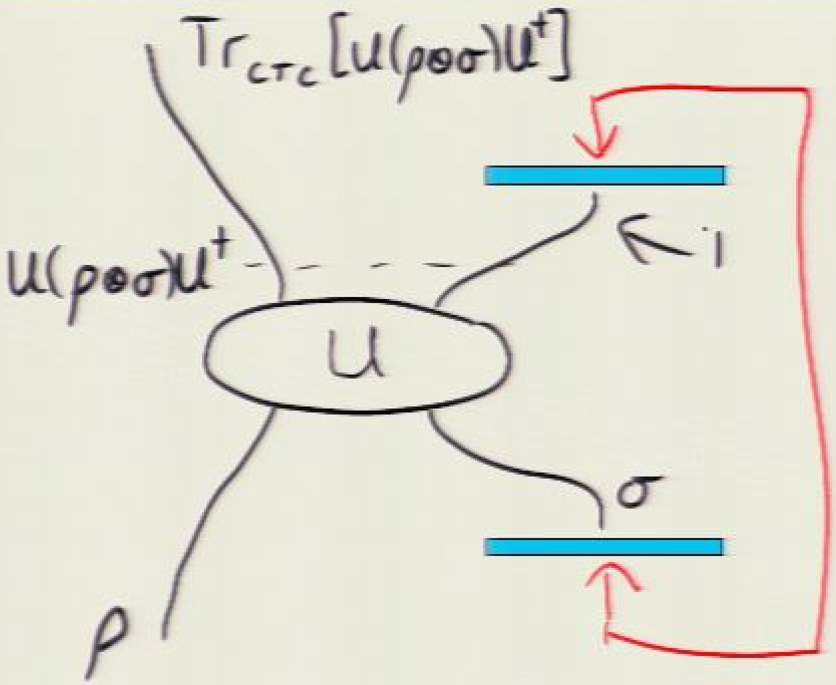

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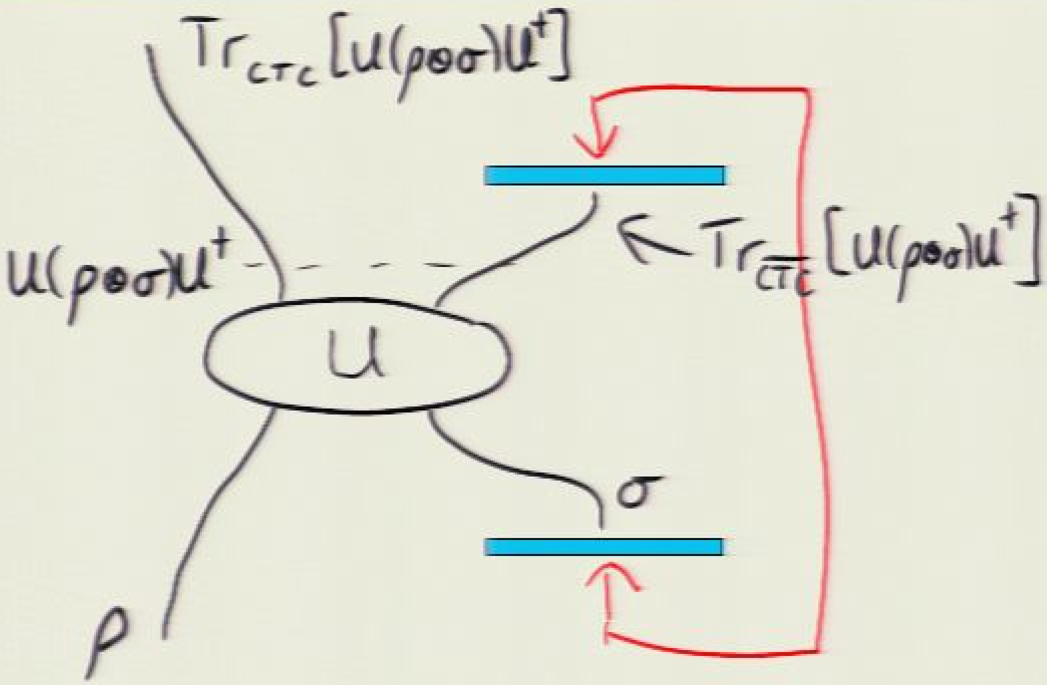

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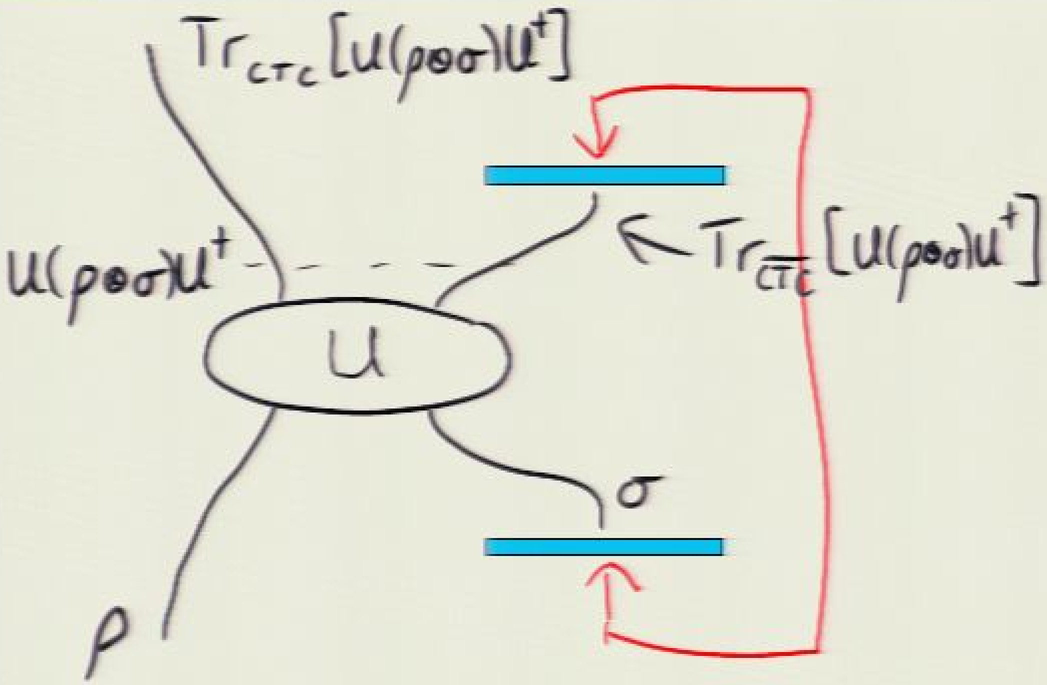

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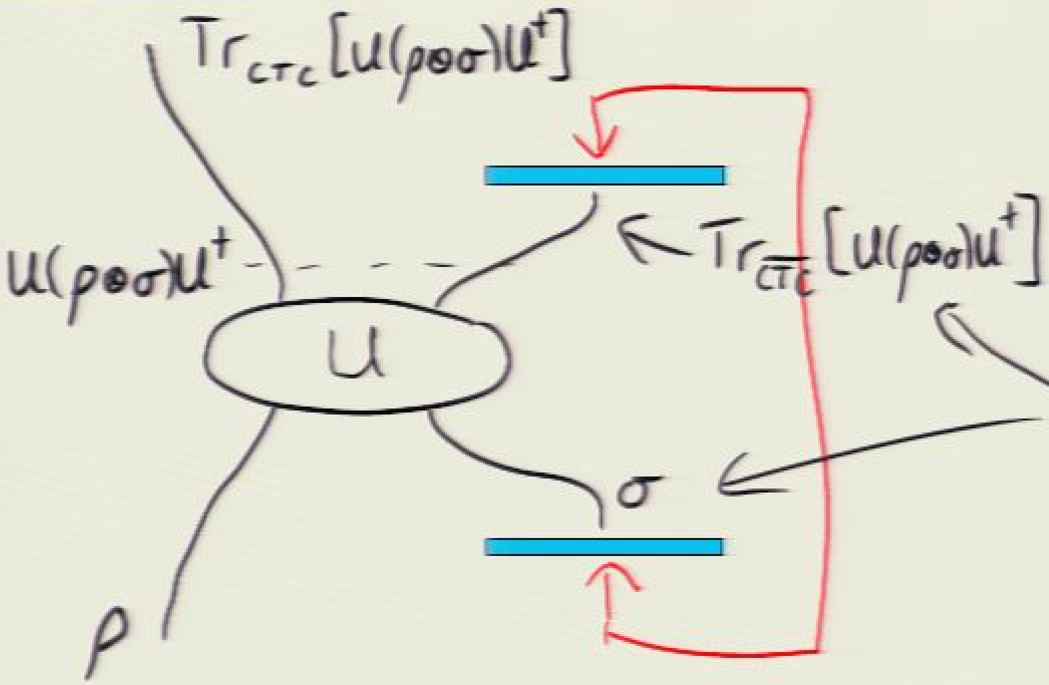
Epistemic consistency conditions



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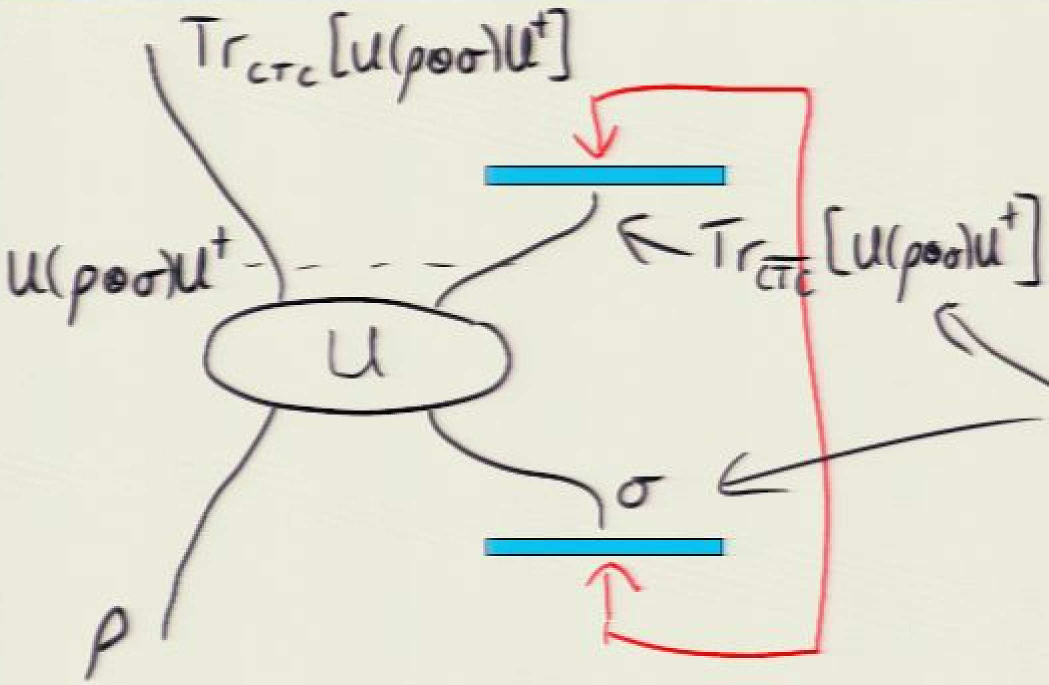

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- Question:

  How do ontological consistency conditions constrain σ ?

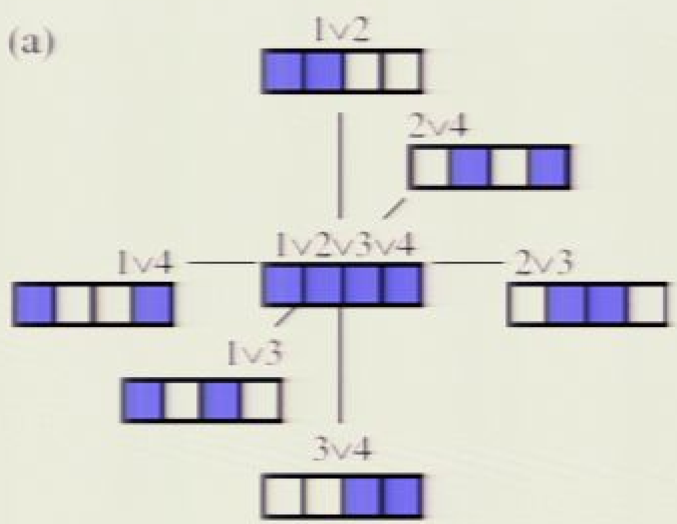
  How do ontological paradoxes present themselves?
- Difficult to answer without an ontological model...

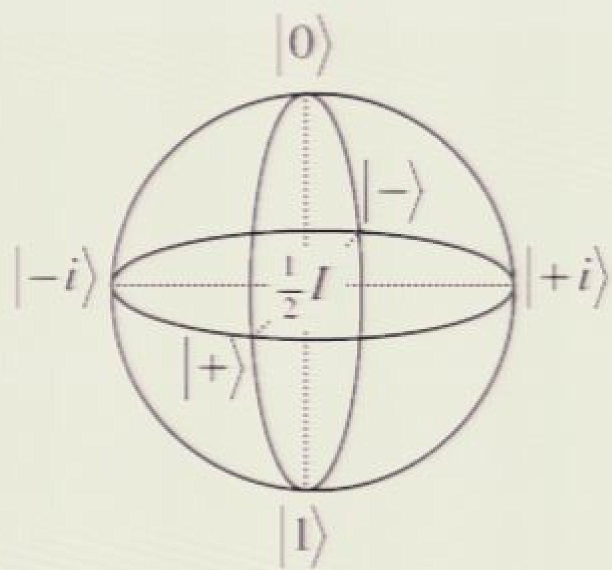
Outline of remainder of talk

- Investigate CTCs within Spekkens' toy theory
  - clear distinction within toy theory between ontic and epistemic states
- Demand consistency of ontic states
- Consider appropriate constraints on epistemic states
- Check for paradoxical behaviour

Spekkens' toy theory

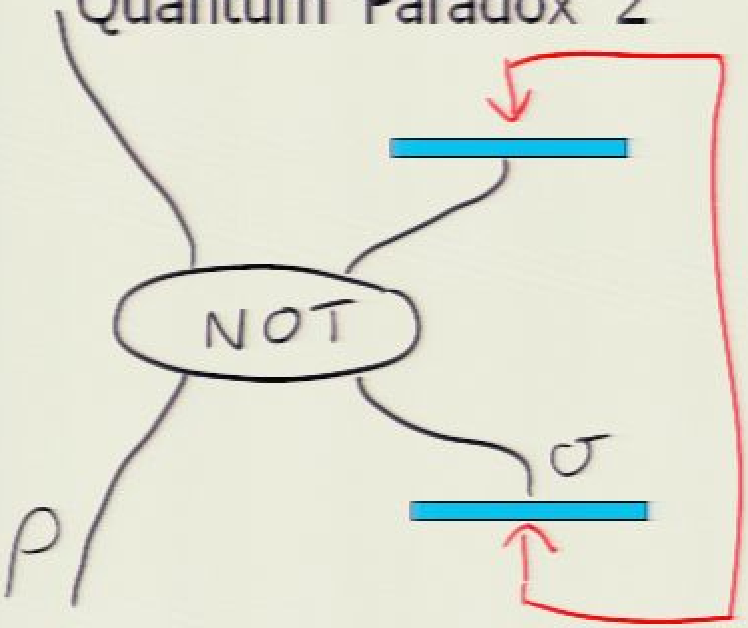
- Knowledge balance principle: For a state of maximal knowledge, the amount of knowledge you possess equals the amount of knowledge you lack
- Elementary systems: ontic state defined by two yes/no questions maximal-knowledge epistemic state gives one such answer





Paradoxes with classical systems

Quantum 'Paradox' 2



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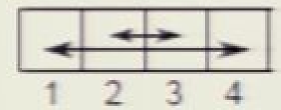
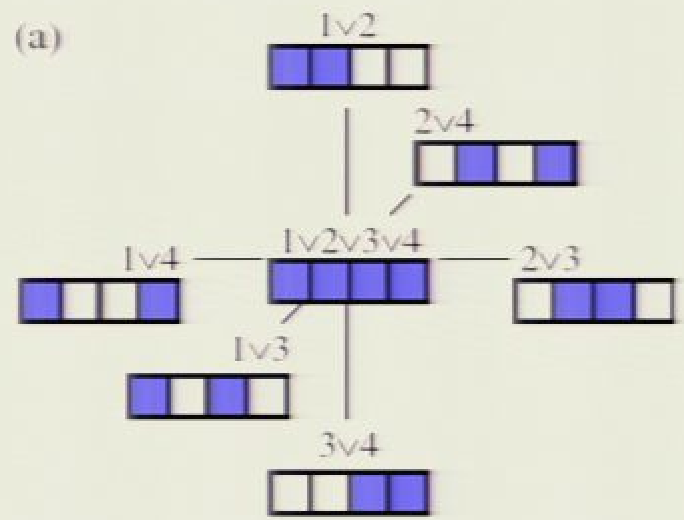
'Toy' NOT: (14)(23)





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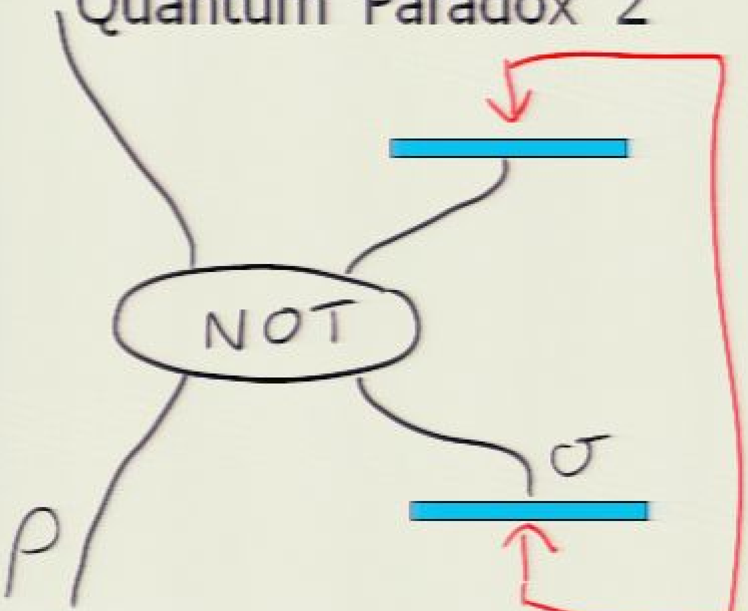

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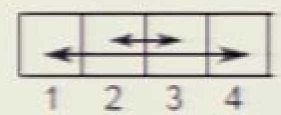

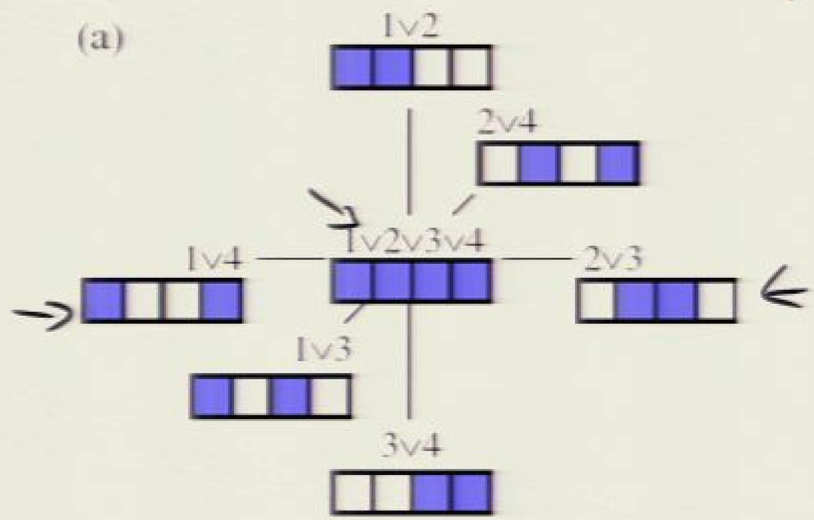

- Range of epistemic solutions exist,
- but no ontic solution (paradox)
- Is the paradox 'contained'?

Paradoxes with classical systems

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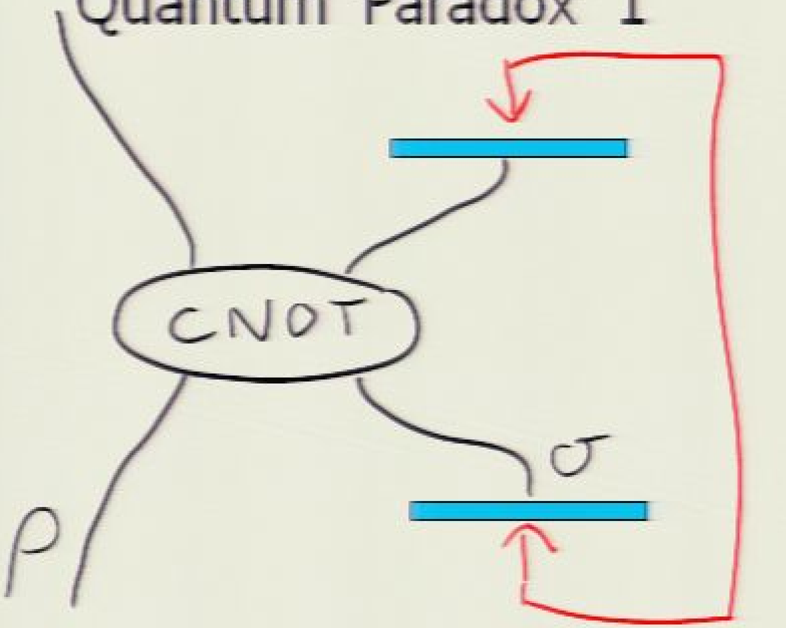

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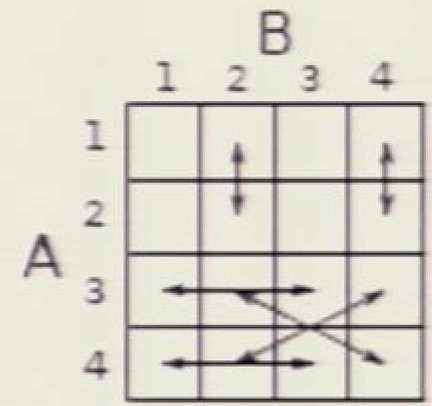

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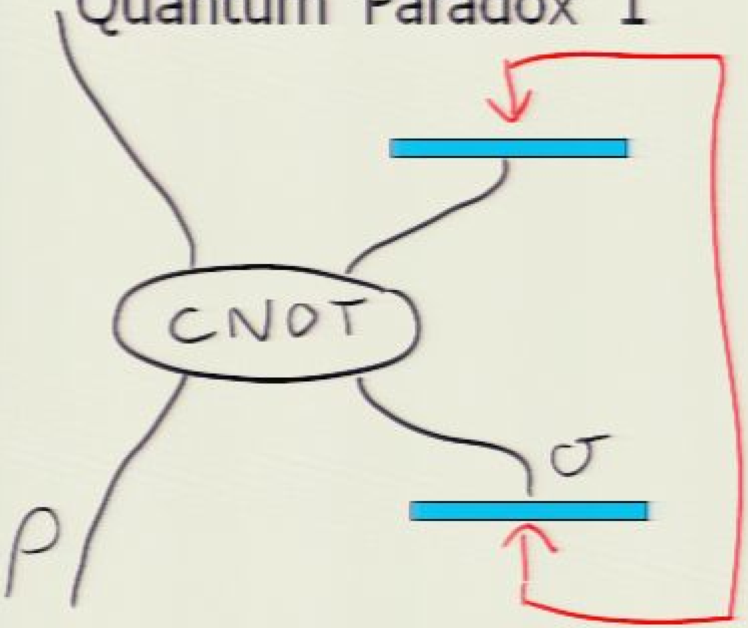

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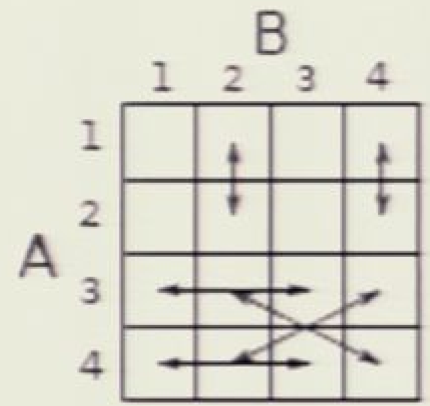

- A number of epistemic solutions
- Ontic solutions **only** if the non-CTC system is in ontic state 1 or 2
- **Lesson:** paradoxes exist, but can be hidden by the epistemic constraint

Combining ontic consistency with the epistemic constraint

- We enforce consistency conditions on the ontic state
- We require the epistemic constraint to be preserved
- Do we ever reach a contradiction?

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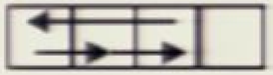
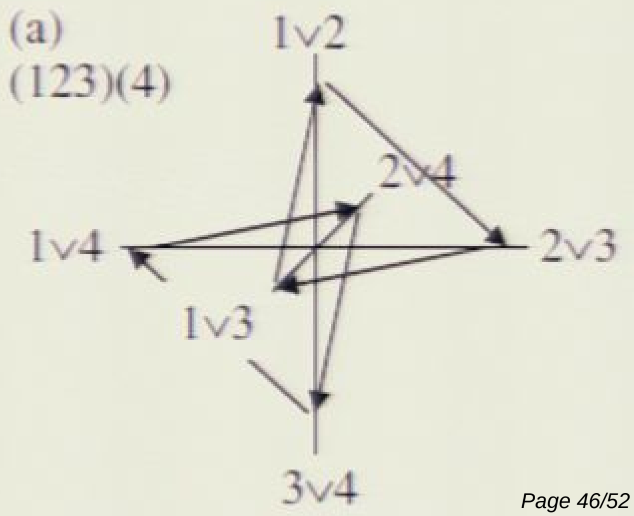
- Transformation $(123)(4)$: 
- Ontic consistency: must be 4



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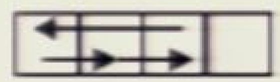
- Transformation $(123)(4)$: 
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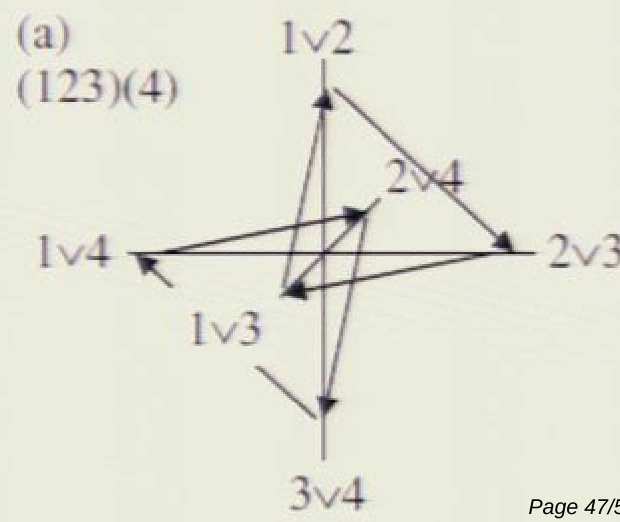
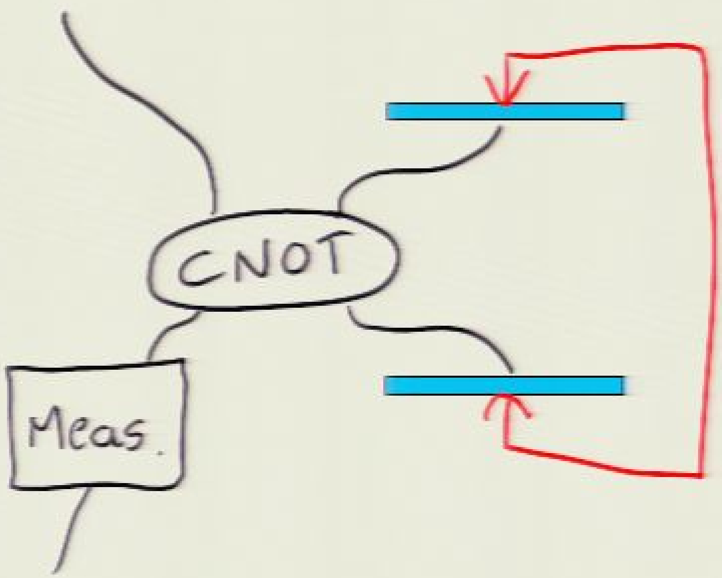
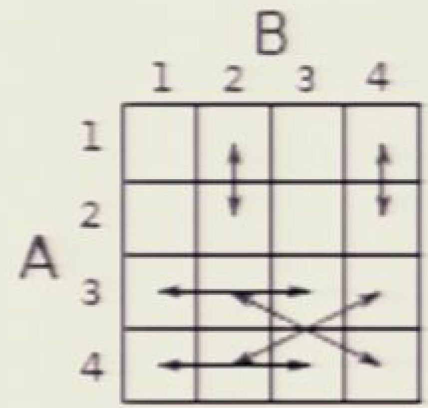
- Violation of knowledge-balance but only for a particle in the CTC



Combining ontic consistency with the epistemic constraint

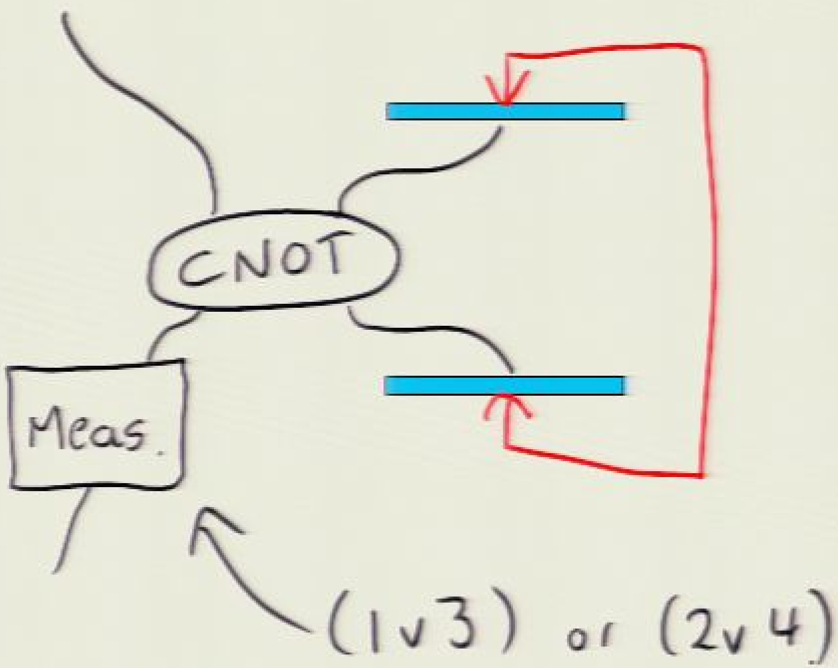
- Can we violate the knowledge-balance principle for a system that does not travel through the CTC?

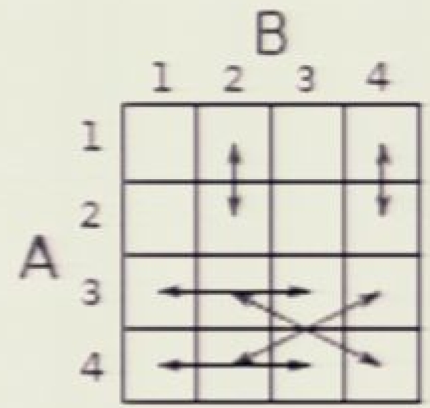




Combining ontic consistency with the epistemic constraint

- Can we violate the knowledge-balance principle for a system that does not travel through the CTC?





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- No need to throw out linearity – revisit our QI conclusions?