Title: The preparation problem

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Abstract:

The effects of closed timelike curves (CTCs) in quantum dynamics, and its consequences for information processing have recently become the subject of a heated debate. Deutsch introduced a formalism for treating CTCs in a quantum computational framework. He postulated a consistency condition on the chronology-violating systems which led to a nonlinear evolution on the systems that come to interact with the CTC. This has been shown to allow tasks which are impossible in ordinary linear quantum evolution, such as computational speed-ups over (linear) quantum computers, and perfectly distinguishing non-orthogonal quantum states.

Bennett and co-authors have argued, on the other hand, that nonlinear evolution allows no such exotic effects. They argued that all proofs of exotic effects due to nonlinear evolutions suffer from a fallacy they called the " linearity trap". Here we review the argument of Bennett and co-authors and show that there is no inconsistency in assuming linearity at the level of a classical ensemble, even at the presence of nonlinear quantum evolution. In fact, this is required for the very existence of empirically verifiable nonlinear evolution. The arguments for exotic quantum effects are thus seen to be based on the necessity for a fundamental distinction between proper and improper mixtures in the presence of nonlinear evolutions. We show how this leads to an operationally well-defined version of the measurement problem that we call the "preparation problem".

The preparation problem

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“The measurement problem refers to a set of people”

- Hideo Mabuchi

Paradoxes of time travel

- Inconsistent histories
  - Some initial conditions lead to contradictions; e.g. time traveller goes back in time and kills his grandfather before he was born.
- Information paradox
  - Information created from nowhere; e.g. a girl receives plans to build a time machine from an older woman, grows up, builds the time machine, goes back in time and gives her young self the plans to build a time machine.

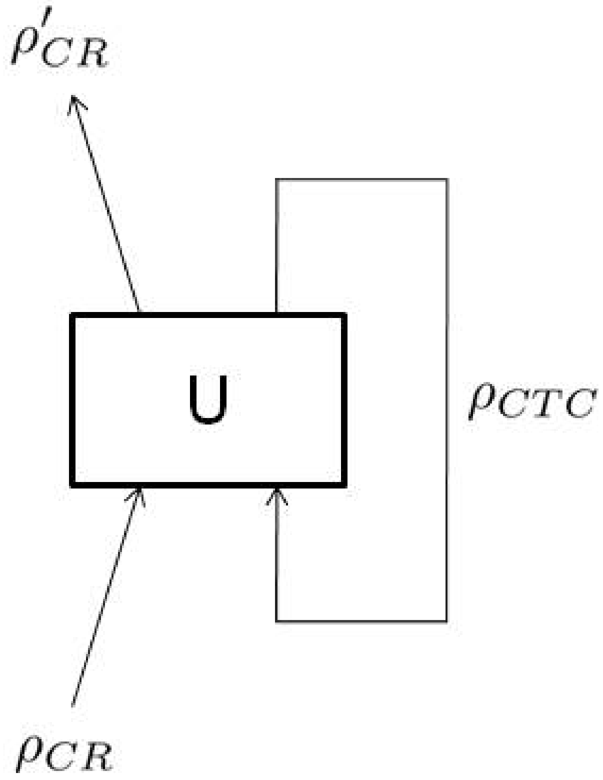
Deutsch's model

- Consistency constraint:

$$\rho_{\mathrm{CTC}} = \mathrm{Tr}_{\mathrm{CR}}(U\rho_{\mathrm{CR}} \otimes \rho_{\mathrm{CTC}} U^{\dagger})$$

- Output:

$$\rho'_{\mathrm{CR}} = \mathrm{Tr}_{\mathrm{CTC}}(U\rho_{\mathrm{CR}} \otimes \rho_{\mathrm{CTC}} U^{\dagger})$$



Some implications of Deutsch's model

- Solves grandfather paradox (solution always exist, although not unique).
- Does NOT solve information paradox → Deutsch conjectures principle to select solution with maximal entropy ("evolutionary principle").

- Computational speed-up over (linear) quantum computers;
- Distinguish non-orthogonal states

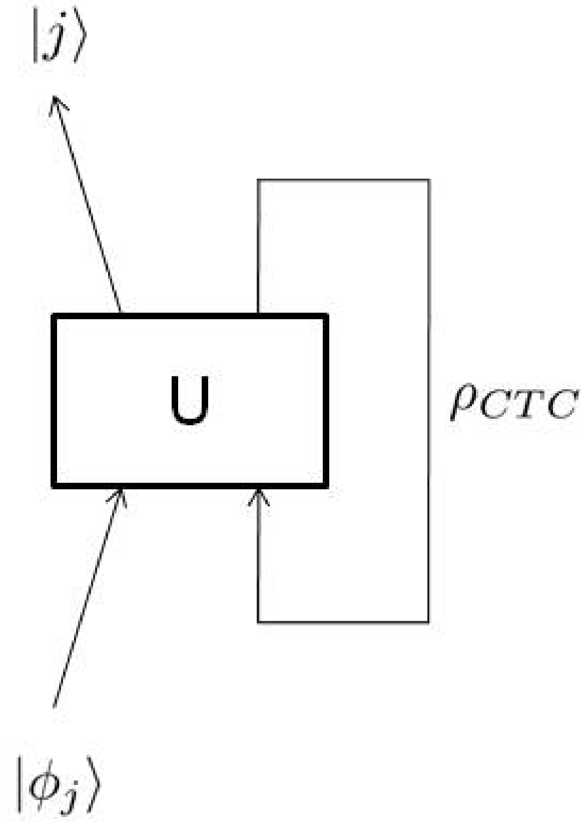
- Superluminal signaling?

Distinguishing non-orthogonal states

- Brun et al. [PRL 102, 210402 (2009)] have shown that for any set of (not necessarily orthogonal) input states there exists U such that the unique solution of Deutsch's model maps those states onto an orthogonal set.

E.g., $|0\rangle \rightarrow |0\rangle$

$|+\rangle \rightarrow |1\rangle$



Postselected CTCs

- Bennett-Schumacher-Svetlichny-Lloyd
- Information flow in analogy with postselected teleportation
- Also leads to nonlinear evolution
- BUT… needs auxiliary assumptions to solve the grandfather paradox

The “linearity trap”

- **Bennett *et al.*** [Phys. Rev. Lett. 103, 170502 (2009)] argued that CTCs (or general nonlinear theories) do not lead to exotic effects such as distinguishing non-orthogonal states.
  - Calculations that show distinguishability of non-orthogonal states use linearity of classical mixtures.
  - One should not assume linearity in a nonlinear theory: “linearity trap”.

The prescription of Bennett et al.

1. Rob prepares one of two non-orthogonal states, gives it to Alice and keeps a record:

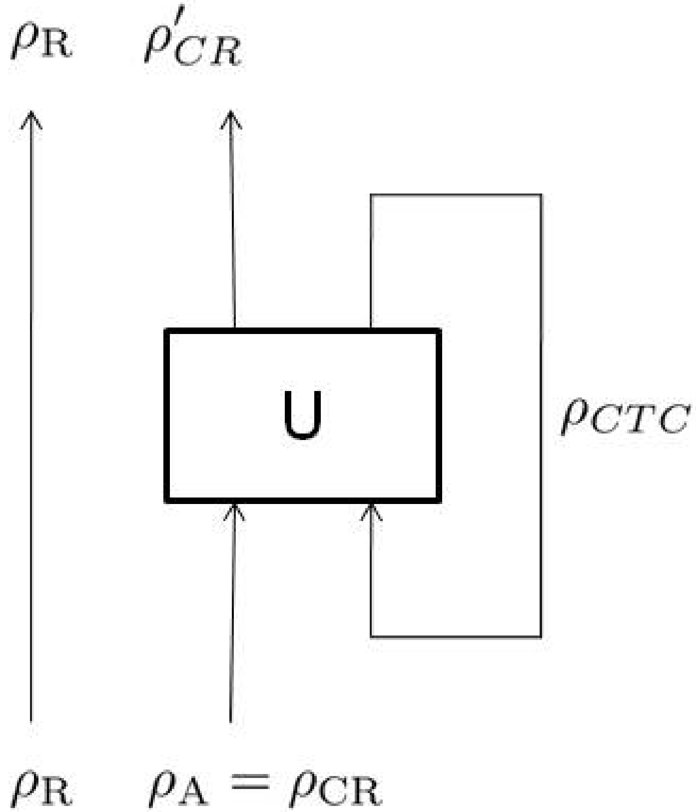
$$\rho_{\mathrm{RA}} = \sum_j p_j |j\rangle\langle j|_{\mathrm{R}} \otimes |\phi_j\rangle\langle\phi_j|_{\mathrm{A}}$$

2. Alice takes the partial trace over Rob's record (unknown to her):

$$\rho_{\mathrm{A}} = \mathrm{Tr}_{\mathrm{R}}(\rho_{\mathrm{RA}}) = \sum_j p_j |\phi_j\rangle\langle\phi_j|_{\mathrm{A}}$$

3. Since this input state does not depend on Rob's record, the CTC will give the same (generally mixed) output every time.

4. => Alice can't tell which state Rob prepared.



A contradiction with verifiability

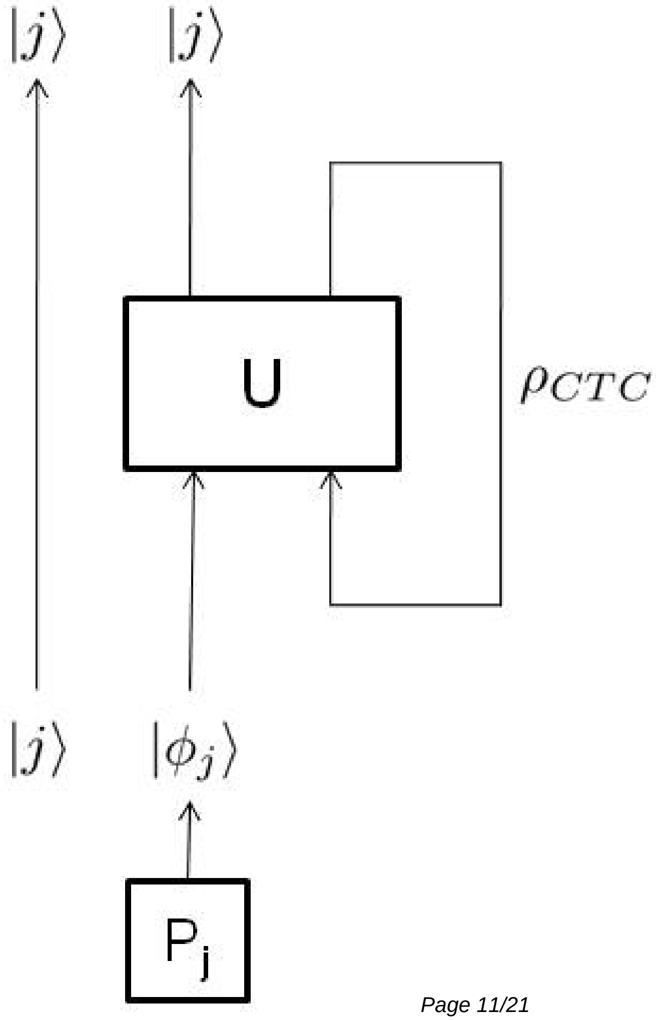
1. By assumption, the CTC *does* perform the nonlinear evolution for pure states:

$$|\phi_j\rangle \rightarrow |j\rangle$$

2. If Rob can *verify* this claim, he should be able to *prepare* those states and verify through tomography that the output is the corresponding one.

3. Rob should be able to verify that evolution even if Alice doesn't know which state he prepared.

4. => *For the purpose of calculating nonlinear quantum evolution,* Alice can't use density matrices to represent her partial knowledge of the input state. [Cavalcanti and Menicucci, arXiv:1004.1219]



Linearity of classical mixtures vs. linear evolution

- Bennett et al. conflate two different kinds of linearity:

$$\mathcal{E}(|\phi_0\rangle + |\phi_1\rangle) = \mathcal{E}|\phi_0\rangle + \mathcal{E}|\phi_1\rangle$$

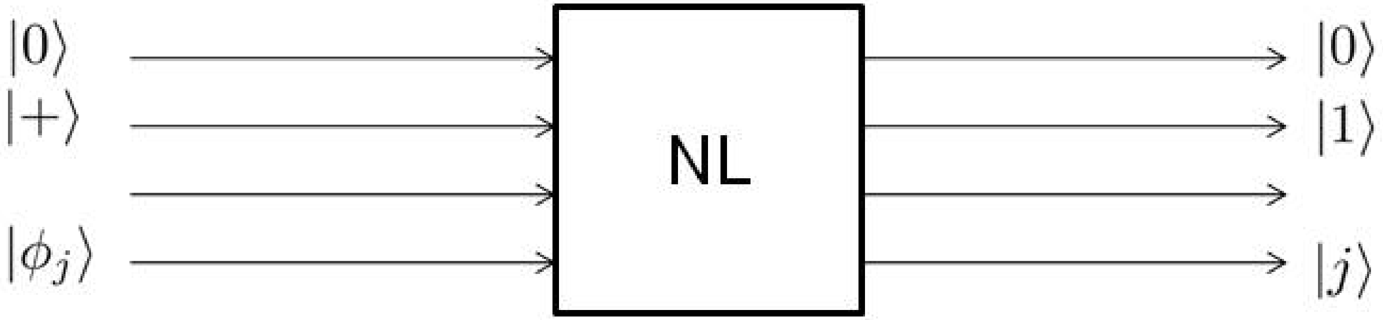
$$\mathcal{E}\{p_j, |\phi_j\rangle\} = \{p_j, \mathcal{E}|\phi_j\rangle\}$$

- While the first kind of linearity fails on Deutsch's model, the second kind does not necessarily fail.
    - Verifiable nonlinear quantum evolution implies failure of density matrix representation for proper mixtures.

E. Cavalcanti and NCM, arXiv:1004.1219 [quant-ph]

Nonlinear boxes

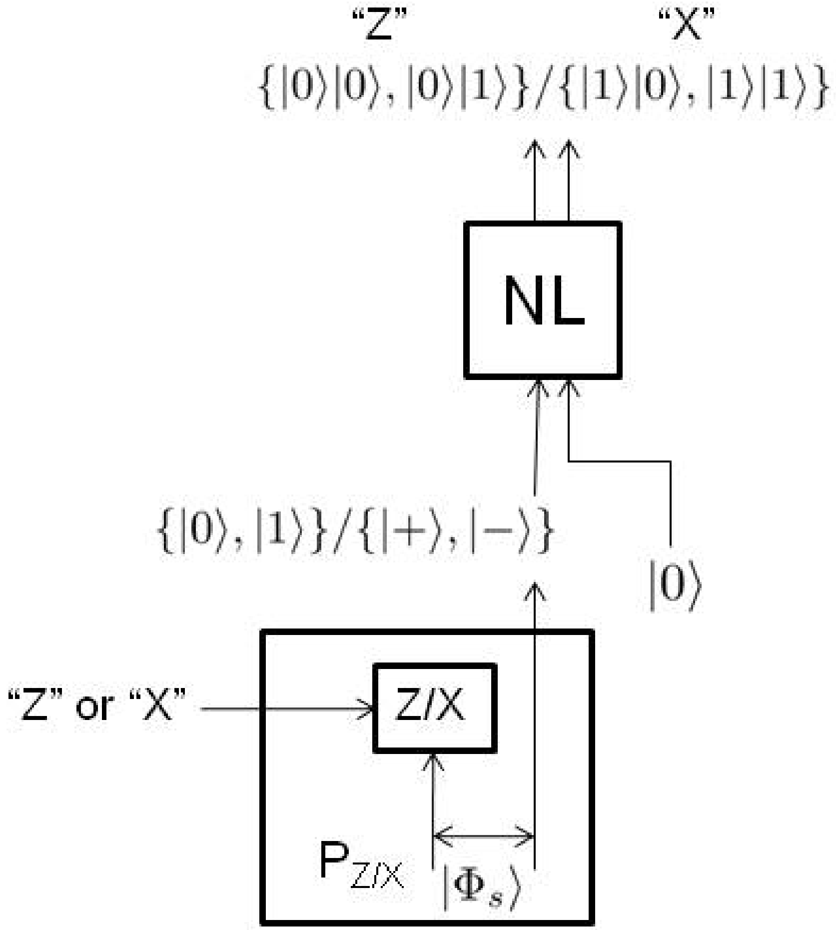
- Consider a general class of theories which allow the existence of "nonlinear boxes"
  - Output state is a general nonlinear map from the input state (and in particular may discriminate between different ensembles of the same density matrix)



- Not enough to specify transformation on a basis
  - Are there finitely or infinitely many "inequivalent" nonlinear boxes? (what about for specific purposes: computation, cloning, signaling, etc.)

Faster-than-light signaling?

- Gisin has argued that nonlinear evolution can lead to signaling
- Relation to steering

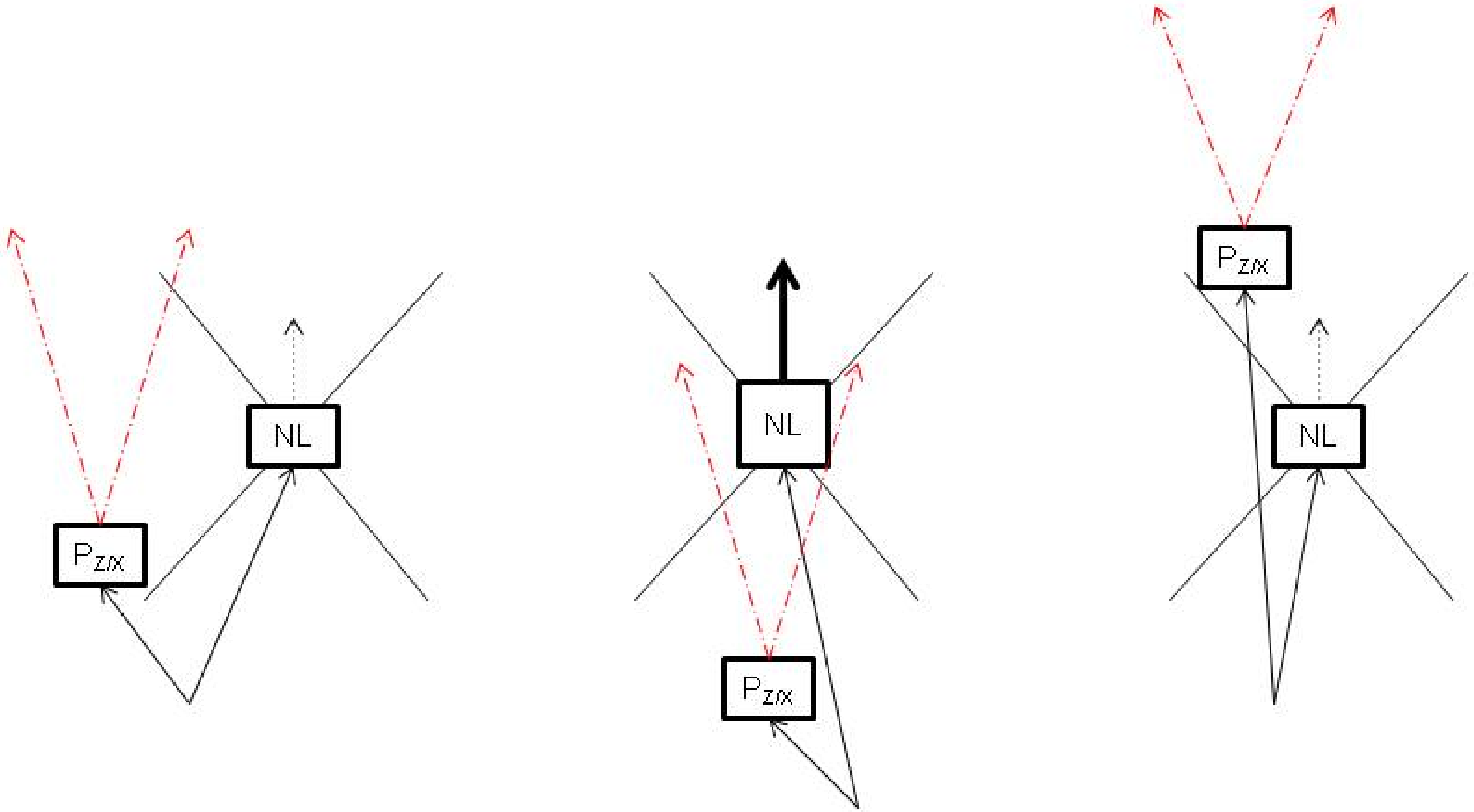


- However, conclusion depends on whether the black-box $P_{Z/X}$ *prepares* a pure state (for the purpose of nonlinear evolution) or not. Two alternatives:

  a) The output of $P_{Z/X}$ is a pure state
     → signaling

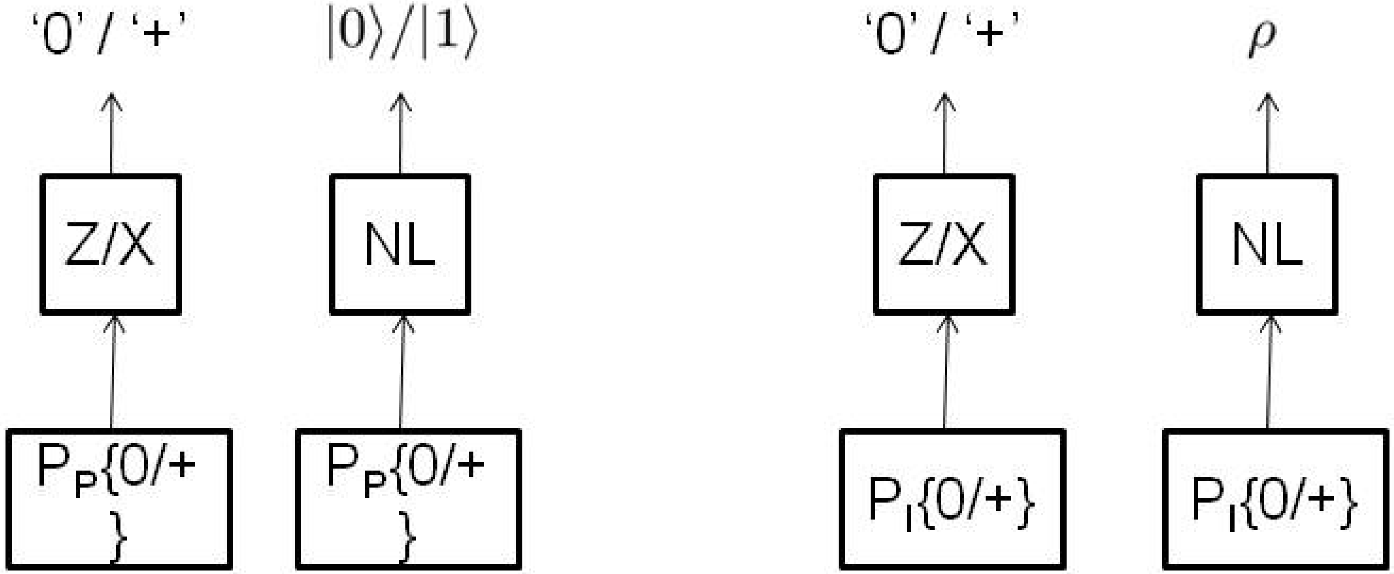
  b) The output of $P_{Z/X}$ is a mixed state (improper mixture). [Ralph and Myers (2010)]
     → "Preparation problem": how do we prepare pure states?

Measuring speed of collapse?



The preparation problem

- Verifiable nonlinear evolution without signaling requires two kinds of preparation devices: *proper and improper*



Problem: what kinds of processes are proper preparations? (Von Neumann measurement with post-selection is an improper preparation)

Candidate 1* for proper preparation

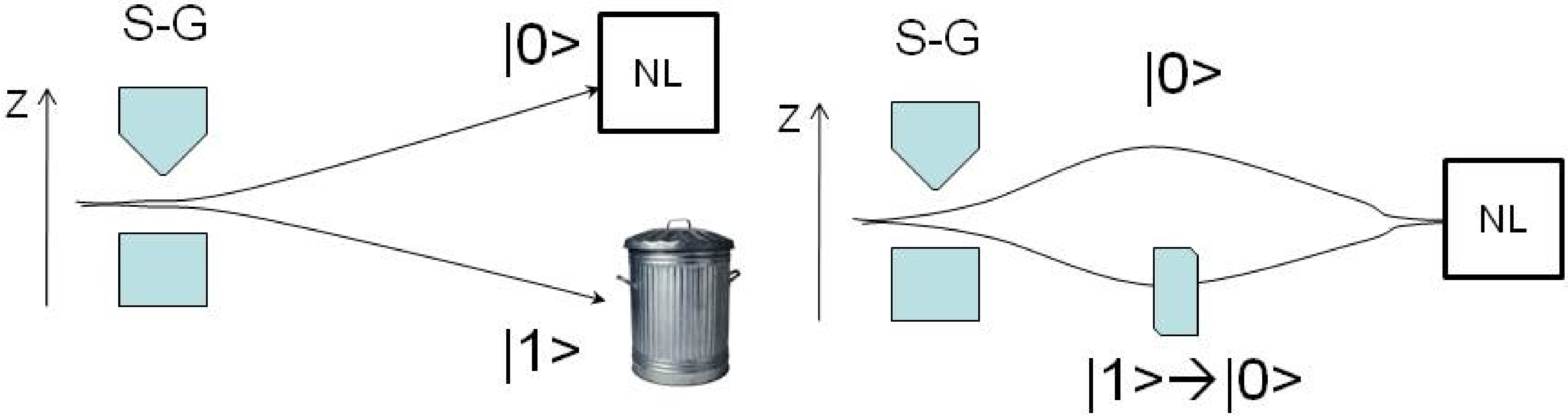
- Cooling to a ground state

- However, a careful examination of such process mediated by unitary evolution would show that one initially needs information about states of the environment, references frames, etc, to shuffle entropy around. (Entropy of the global system cannot decrease by unitary evolution.)

→ Infinite regress

*suggested by Tim Ralph

Candidate 2* for proper preparation



- However, argument implicitly requires macroscopic reference frames for direction of Stern-Gerlach device and transformation devices. Full quantum-mechanical treatment would produce improper mixture or lead to infinite regress.

*suggested by David Pegg

Ontic vs. epistemic states

- Wallman and Bartlett [arXiv:1005.2438] have argued that Deutsch's model requires an *ontic* view of the quantum states inside the CTC. They apply a consistency condition to ontic states of Spekkens' toy theory and show that paradoxes remain.

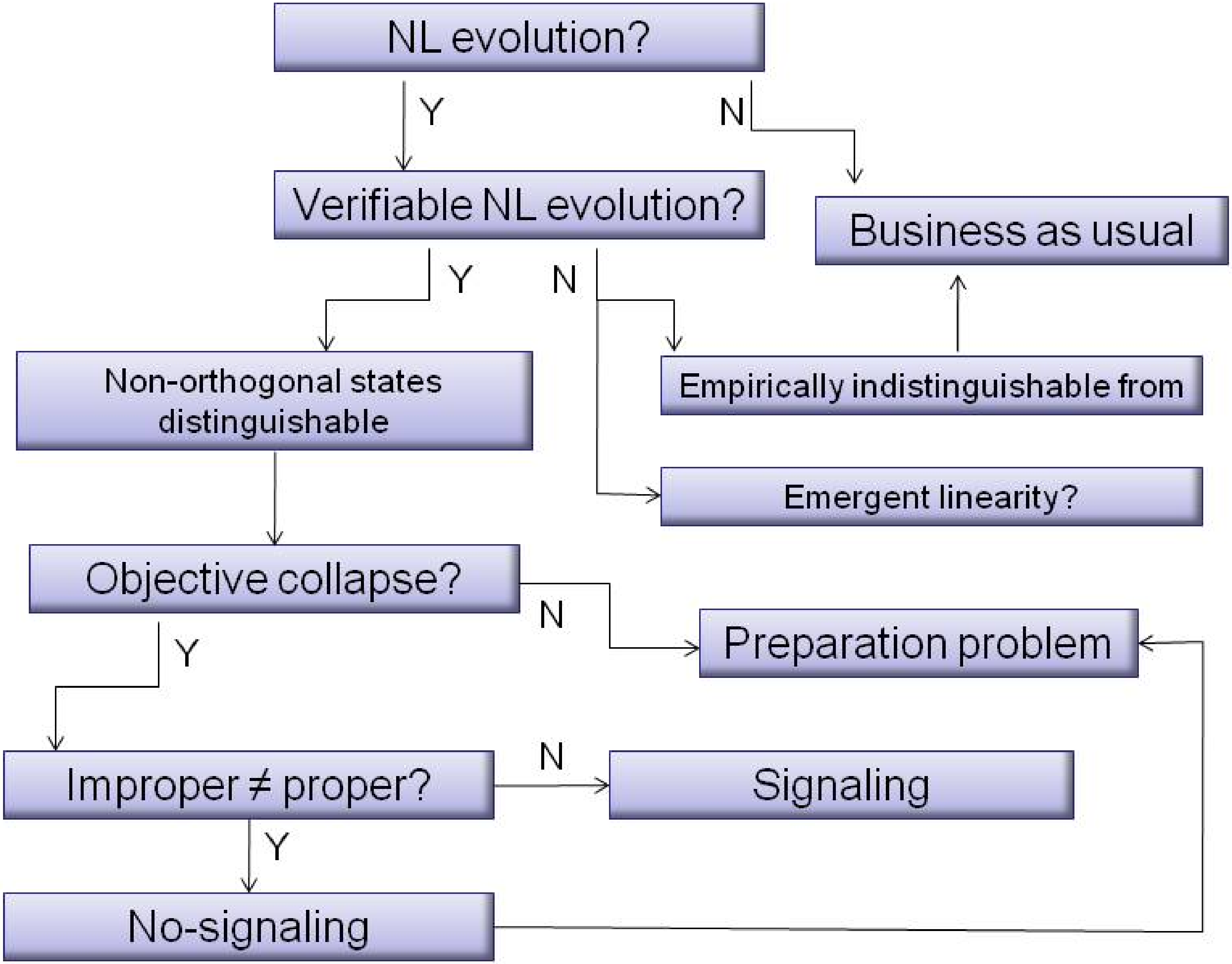
- Our analysis shows that Deutsch model also needs an ontic view of quantum states *also for the causality-respecting (asymptotically free) qubits.*

- As far as we know it is not *incoherent* to have an ontic view of quantum states (e.g. collapse models).

- CTCs could therefore provide an experimental test to discriminate between the ontic view and the epistemic view of quantum states.

Summary

- Recent quantum models for CTCs lead to nonlinear evolution;
- Arguments raised against them (linearity trap) are found wanting;
- Verifiable nonlinear evolution requires proper mixtures;
- That and no-signaling requires that improper ≠ proper mixtures;
- What processes lead to proper mixtures? → preparation problem
- Can the study of "nonlinear boxes" lead to interesting insights into foundations (see e.g. Popescu-Rorhlich boxes)



NL evolution?

Y

N

Verifiable NL evolution?

Business as usual

Y

N

Non-orthogonal states distinguishable

Empirically indistinguishable from

Emergent linearity?

Objective collapse?

N

Preparation problem

Y

Improper ≠ proper?

N

Signaling

Y

No-signaling