When Everett observes Greenberger, Horne, and Zeilinger meeting Wigner's friend

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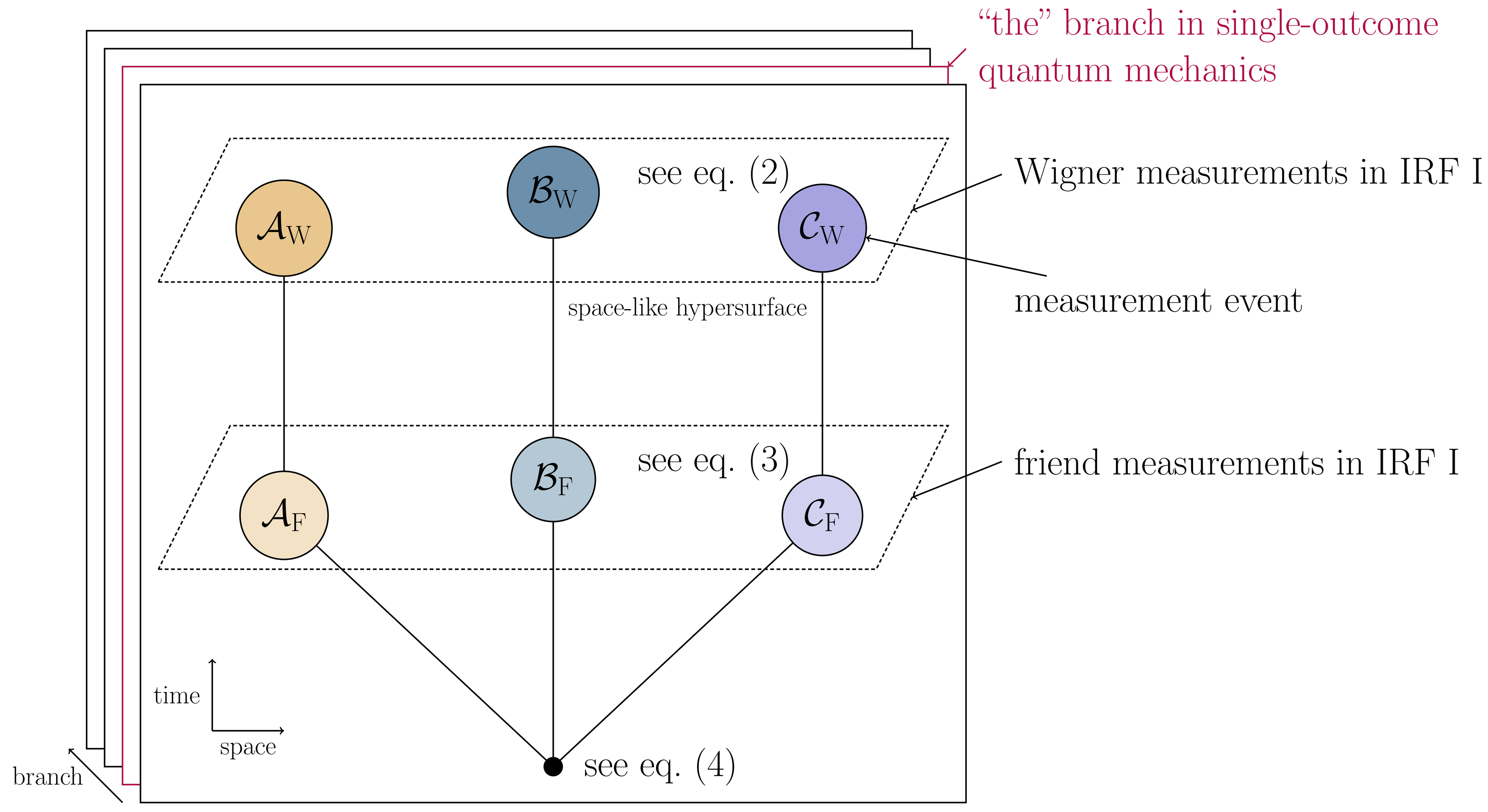
Abstract

Leegwater[1] raises a paradox where combining the GHZ paradox[2] with the Wigner's friend scenario[3] reveals an inconsistency between single-outcome unitary quantum mechanics and relativity. We offer a positive solution within an Everettian perspective — there is no paradox and unitary quantum mechanics is consistent over different inertial reference frames.

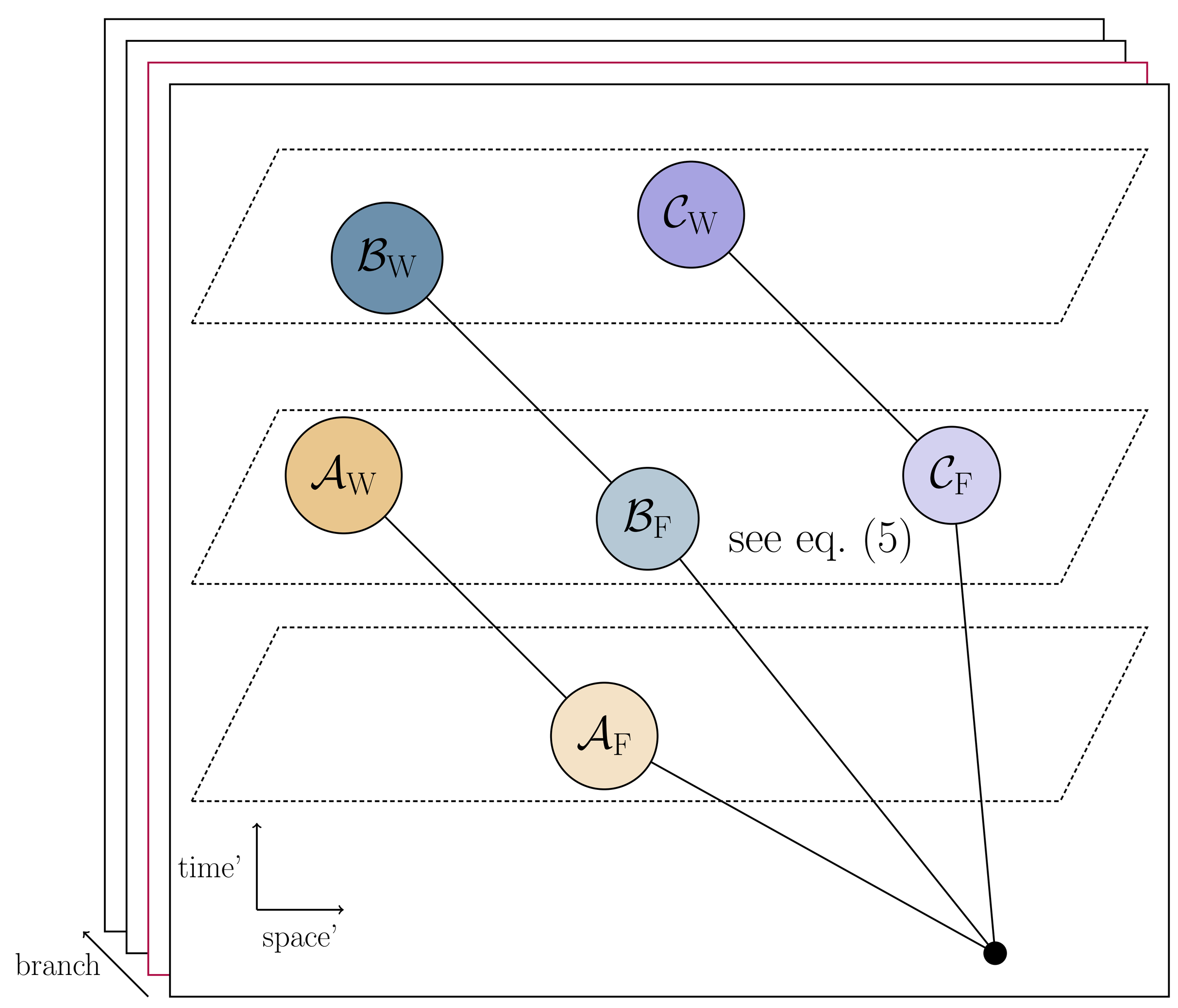
Introduction

- GHZ paradox:[2]
  - qubit measurements in $\hat{x}\hat{x}\hat{x}$ basis inconsistent to $\hat{x}\hat{y}\hat{y}$ (or circular permutations),
  - a resolution: these measurements cannot be simultaneously realised (counterfactual defense).
- Wigner's friend:[3]
  - friend measures qubit,
  - Wigner measures friend and their laboratory (feasibility might be questioned[4]),
  - varying interpretations as to when "collapse" occurs.
- Leegwater:[1] GHZ + Wigner's friend → paradox (perspective of super-ontological observer).
- Proposal: many-worlds inspired local solution valid across inertial reference frames (perspective of super-ontological super-observer).

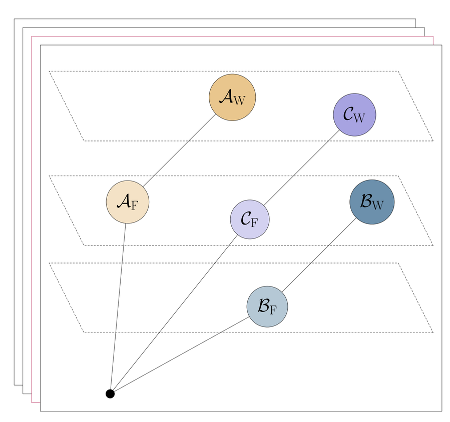
Inertial Reference Frame (IRF) I



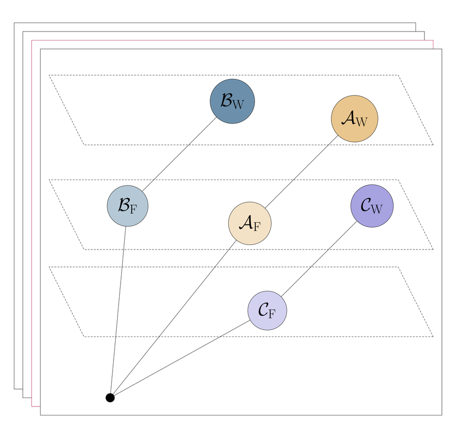
Inertial Reference Frame IIa



IRF IIb



IRF IIc



Perspective of super-ontological observer

- Experiments have single outcomes.
- GHZ + Wigner's friend → paradox: $\hat{x}\hat{x}\hat{x}$ and $\hat{x}\hat{y}\hat{y}\ldots$ measurements take place in same reality but in different reference frames (counterfactual defense doesn't work).

Perspective of a super-ontological super-observer

- Reality consists of multiple branches and branch combination is a physical event.
- Wigners measure their friends (qubit and laboratory) in rotated basis:

$$|\pm\hat{x}\rangle_{\mathrm{lo_l}} = \varphi|\mp\hat{y}\rangle_{\mathrm{lo_l}} + \varphi^*|\pm\hat{y}\rangle_{\mathrm{lo_l}} \quad (\varphi = \exp(i\pi/4)). \tag{1}$$

Solution: several ways of writing the GHZ state.

$\hat{x}\hat{x}\hat{x}$ form (best description at distant future):

$$|+\hat{x}\rangle_{\mathrm{ao_a o_{ao_a}}}|+\hat{x}\rangle_{\mathrm{bo_b o_{bo_b}}}|+\hat{x}\rangle_{\mathrm{co_c o_{co_c}}} + |+\hat{x}\rangle_{\mathrm{ao_a o_{ao_a}}}|-\hat{x}\rangle_{\mathrm{bo_b o_{bo_b}}}|-\hat{x}\rangle_{\mathrm{co_c o_{co_c}}} + |-\hat{x}\rangle_{\mathrm{ao_a o_{ao_a}}}|+\hat{x}\rangle_{\mathrm{bo_b o_{bo_b}}}|-\hat{x}\rangle_{\mathrm{co_c o_{co_c}}} + |-\hat{x}\rangle_{\mathrm{ao_a o_{ao_a}}}|-\hat{x}\rangle_{\mathrm{bo_b o_{bo_b}}}|+\hat{x}\rangle_{\mathrm{co_c o_{co_c}}}. \tag{2}$$

$\hat{y}\hat{y}\hat{y}$ form (best description after friend measurement in IRF I):

$$\varphi|+\hat{y}\rangle_{\mathrm{ao_a}}|+\hat{y}\rangle_{\mathrm{bo_b}}|+\hat{y}\rangle_{\mathrm{co_c}} + \varphi^*|-\hat{y}\rangle_{\mathrm{ao_a}}|+\hat{y}\rangle_{\mathrm{bo_b}}|+\hat{y}\rangle_{\mathrm{co_c}} + \varphi|-\hat{y}\rangle_{\mathrm{ao_a}}|-\hat{y}\rangle_{\mathrm{bo_b}}|+\hat{y}\rangle_{\mathrm{co_c}} + \varphi^*|+\hat{y}\rangle_{\mathrm{ao_a}}|-\hat{y}\rangle_{\mathrm{bo_b}}|+\hat{y}\rangle_{\mathrm{co_c}} + \varphi|-\hat{y}\rangle_{\mathrm{ao_a}}|+\hat{y}\rangle_{\mathrm{bo_b}}|-\hat{y}\rangle_{\mathrm{co_c}} + \varphi^*|+\hat{y}\rangle_{\mathrm{ao_a}}|+\hat{y}\rangle_{\mathrm{bo_b}}|-\hat{y}\rangle_{\mathrm{co_c}} + \varphi|+\hat{y}\rangle_{\mathrm{ao_a}}|-\hat{y}\rangle_{\mathrm{bo_b}}|-\hat{y}\rangle_{\mathrm{co_c}} + \varphi^*|-\hat{y}\rangle_{\mathrm{ao_a}}|-\hat{y}\rangle_{\mathrm{bo_b}}|-\hat{y}\rangle_{\mathrm{co_c}}. \tag{3}$$

$\hat{z}\hat{z}\hat{z}$ form (best description at origin):

$$|+\hat{z}\rangle_{\mathrm{a}}|+\hat{z}\rangle_{\mathrm{b}}|+\hat{z}\rangle_{\mathrm{c}} + |-\hat{z}\rangle_{\mathrm{a}}|-\hat{z}\rangle_{\mathrm{b}}|-\hat{z}\rangle_{\mathrm{c}}. \tag{4}$$

$\hat{x}\hat{y}\hat{y}$ form (best description after friend measurement in IRF IIs):

$$|-\hat{x}\rangle_{\mathrm{ao_a o_{ao_a}}}|+\hat{y}\rangle_{\mathrm{bo_b}}|+\hat{y}\rangle_{\mathrm{co_c}} + |+\hat{x}\rangle_{\mathrm{ao_a o_{ao_a}}}|-\hat{y}\rangle_{\mathrm{bo_b}}|+\hat{y}\rangle_{\mathrm{co_c}} + |+\hat{x}\rangle_{\mathrm{ao_a o_{ao_a}}}|+\hat{y}\rangle_{\mathrm{bo_b}}|-\hat{y}\rangle_{\mathrm{co_c}} + |-\hat{x}\rangle_{\mathrm{ao_a o_{ao_a}}}|-\hat{y}\rangle_{\mathrm{bo_b}}|-\hat{y}\rangle_{\mathrm{co_c}}. \tag{5}$$

Glossary

- Super-ontological observer: outside ontology, single branch.
- Super-ontological super-observer: outside ontology, multiple branches
- $|\ \rangle_{\mathrm{l}}$: state of qubit l; $|\ \rangle_{\mathrm{o_l}}$: state of (friend level) observer $\mathrm{o_l}$ for qubit l; $|\ \rangle_{\mathrm{o_{lo_l}}}$: state of (Wigner level) observer $\mathrm{o_{lo_l}}$ for qubit and laboratory $\mathrm{lo_l}$.
- Branch combination: observer measuring a superposition of two branches — for example, if observer $\mathrm{o_{lo_l}}$ measured the system $\mathrm{lo_l}$ in eq. (1) in the rotated basis.
- Events $\mathcal{X}_{\mathrm{F}}$ refer to mesoscopic measurements by friend systems; $\mathcal{X}_{\mathrm{W}}$ refer to macroscopic measurements by Wigner systems.

Super-ontological super-observer in IRF I

1. Friend measurements:
   (a) a, b, and c (in GHZ state) reach events $\mathcal{A}_{\mathrm{F}}$, $\mathcal{B}_{\mathrm{F}}$, and $\mathcal{C}_{\mathrm{F}}$,
   (b) and are observed by $\mathrm{o_a}$, $\mathrm{o_b}$, and $\mathrm{o_c}$ respectively in $\hat{y}$ basis.
2. Wigner measurements:
   (a) observers $\mathrm{o_{ao_a}}$, $\mathrm{o_{bo_b}}$, and $\mathrm{o_{co_c}}$ observe qubit-laboratory systems $\mathrm{ao_a}$, $\mathrm{bo_b}$, and $\mathrm{co_c}$
   (b) at events $\mathcal{A}_{\mathrm{W}}$, $\mathcal{B}_{\mathrm{W}}$, and $\mathcal{C}_{\mathrm{W}}$, respectively, in the $\hat{x}$ basis (eq. (1)).

Super-ontological super-observer in IRF IIa

Sequence of events:

1. observer $\mathrm{o_a}$ observes qubit a in the $\hat{y}$ basis at event $\mathcal{A}_{\mathrm{F}}$,
2. events $\mathcal{A}_{\mathrm{W}}$, $\mathcal{B}_{\mathrm{F}}$, and $\mathcal{C}_{\mathrm{F}}$ take place simultaneously where the observers $\mathrm{o_{ao_a}}$, $\mathrm{o_b}$, and $\mathrm{o_c}$ measure in the $\hat{x}$, $\hat{y}$, and $\hat{y}$ basis, respectively,
3. observers $\mathrm{o_{bo_b}}$ and $\mathrm{o_{co_c}}$ measure qubit-laboratory systems $\mathrm{bo_b}$, and $\mathrm{co_c}$ in the $\hat{x}$ basis at events $\mathcal{B}_{\mathrm{W}}$ and $\mathcal{C}_{\mathrm{W}}$ respectively.

Similarly for IRFs IIb and IIc.

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