Title: A quantum circuit framework for extended Wigner's friend scenarios: logical and causal reasoning without objective events

Speakers: V. Vilasini

Series: Quantum Foundations, Quantum Information

Date: September 16, 2024 - 2:10 PM

URL: https://pirsa.org/24090138

A quantum circuit framework for extended Wigner's friend scenarios: logical and causal reasoning without objective events

V. Vilasini
Inria Université Grenoble Alpes and ETH Zürich

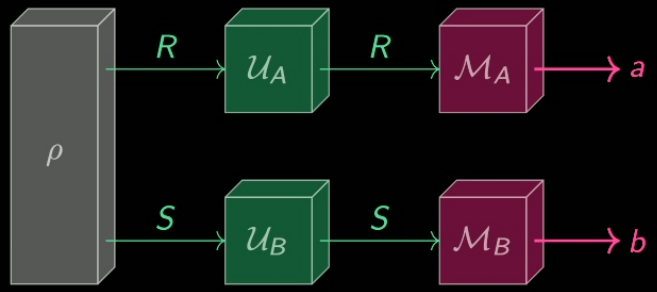
Causalworlds, Perimeter Institute 2024

Joint work with Mischa Prebin Woods (Inria, Université Grenoble Alpes)

Vilasini and Woods 2022, arXiv:2209.09281 (soon to be updated with generalised results) and works in preparation

Motivation: standard use of quantum theory vs Wigner's Friend Scenarios

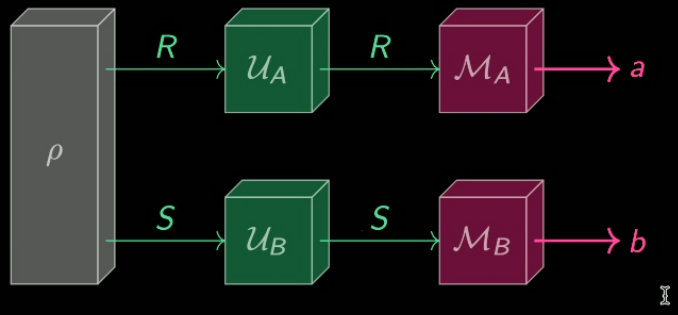
Standard use of quantum theory: causality and logic



$$P(a, b|\rho, \mathcal{U}_A, \mathcal{U}_B, \mathcal{M}_A, \mathcal{M}_B)$$

- Agents not part of the boxes and wires in the circuit

Standard use of quantum theory: causality and logic



$$P(a, b|\rho, \mathcal{U}_A, \mathcal{U}_B, \mathcal{M}_A, \mathcal{M}_B)$$

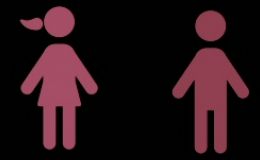
- Agents not part of the boxes and wires in the circuit
- Objective distinction: classical variables vs physical systems
- Objective measurement probabilities (Born rule)
- Implies consistent logic for statements about outcomes:

$$a = 1 \Rightarrow b = 1 \ldots \not\Rightarrow a = 0$$

Most causality frameworks: Quantum networks, acyclic and cyclic causal models, "indefinite causal order" processes etc.

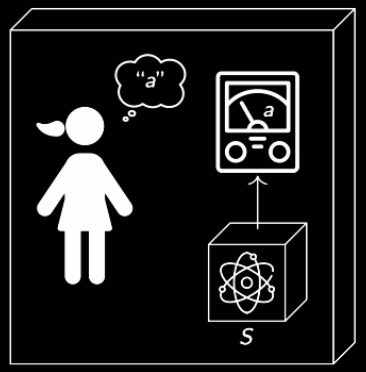
Standard use of quantum theory

"effectively classical" | fully quantum



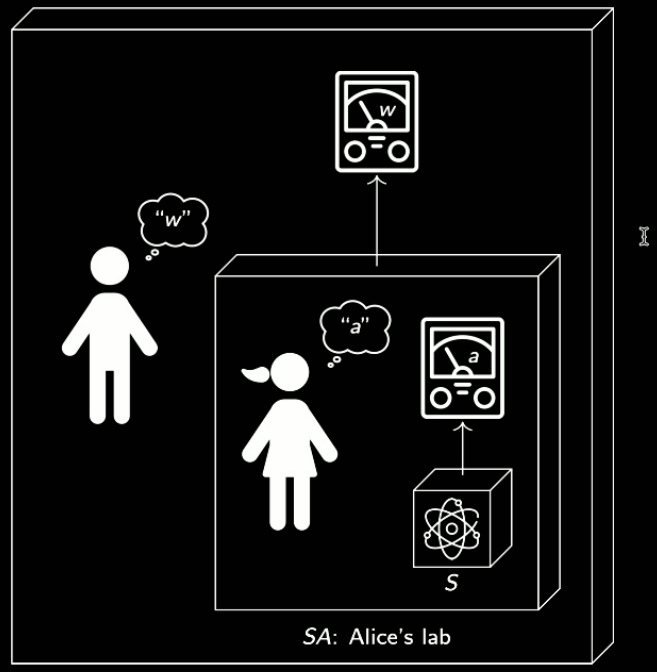
Agents and their labs as systems of quantum theory?

Wigner's thought-experiment



Wigner, Remarks on the Mind-Body Question, 1961.

Wigner's thought-experiment

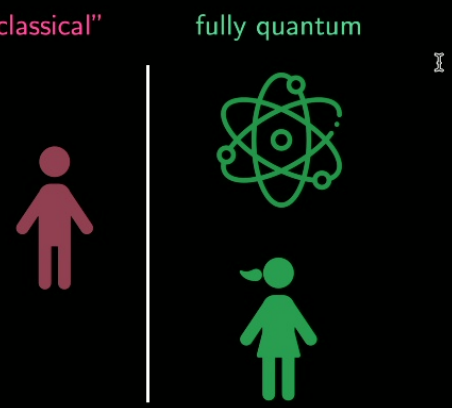


Wigner, Remarks on the Mind-Body Question, 1961.

Extended Wigner's Friend Scenarios (EWFS): Multi-partite protocols where agents can

- model other agents' lab as unitarily evolving closed q. systems
- have full quantum control over lab of another agent

EWFS involve universal use of quantum theory



⚠ No-go theorems: radical challenges posed by EWFS for logic, absoluteness of observed events, causality...

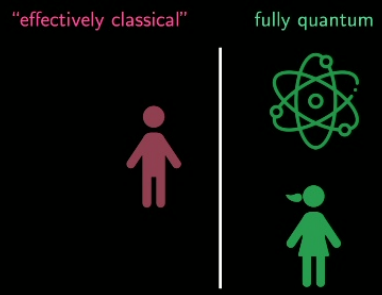
Frauchiger and Renner, 9, 3711 Nat. Comm. 2018. Brukner, 20, 350 Entropy 2018. Bong et. al., 16, 1199-1205, Nat Phys 2020. Yīng et. al. arXiv:2309.12987.

? Sound logical and causal reasoning in EWFS w/o assuming objective classical outcomes?

? Can we explain the emergence of objective classical measurement outcomes in existing experiments?

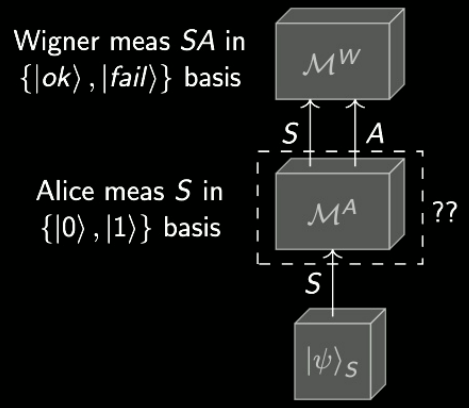
☺ This work: Yes via a quantum circuit framework for EWFS

🔑 Key ingredient: operational formulation of Heisenberg cuts



Agents ≠ conscious human beings. Can be quantum computers!

Wigner's thought-experiment: unitarity vs projection postulate



$|\psi\rangle_S = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)_S$

$|ok/fail\rangle = \frac{1}{\sqrt{2}}(|00\rangle \mp |11\rangle)$

Unitarity $\mathcal{M}^A_{unitary}$

$|\psi\rangle_S \mapsto \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)_{SA} = |fail\rangle_{SA}$

$\Rightarrow P(w = ok|\mathcal{M}^A_{unitary}) \overset{!}{=} 0$

Projection $\mathcal{M}^A_{projection}$

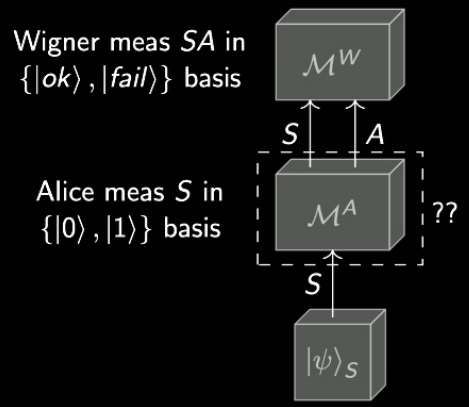
$|\psi\rangle_S \mapsto |00\rangle_{SA}$ or $|11\rangle_{SA}$ or mixture

$\Rightarrow P(w = ok|\mathcal{M}^A_{projection}) > 0$

Ambiguity of the postulates has empirical consequences in WFS

Wigner, Remarks on the Mind-Body Question, 1961.
Baumann and Wolf, Quantum 2, 99, 2018.

Wigner's thought-experiment: apparent paradox



$|\psi\rangle_S = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)_S$

$|ok/fail\rangle = \frac{1}{\sqrt{2}}(|00\rangle \mp |11\rangle)$

Unitarity $\mathcal{M}^A_{unitary}$: $x_A = 0$

$|\psi\rangle_S \mapsto \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)_{SA} = |fail\rangle_{SA}$

$\Rightarrow P(w = ok | x_A = 0) = 0$

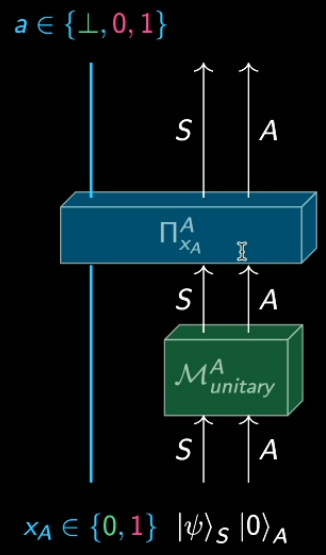
Projection $\mathcal{M}^A_{projection}$: $x_A = 1$

$|\psi\rangle_S \mapsto |00\rangle_{SA}$ or $|11\rangle_{SA}$ or mixture

$\Rightarrow P(w = ok | x_A = 1) > 0$

- Predictions do depend on $x_A \in \{0, 1\}$
- "Paradox" if we ignore x_A: $P(w = ok) = 0$ and > 0.

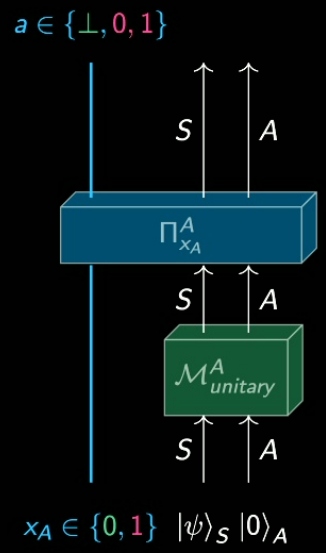
Explicit description of $\mathcal{M}_A$ (unitarity vs projection postulate)



Setting-dependent projectors

$$\Pi^A_{x_A=0} = \mathcal{I} \text{ (no classical record } a = \perp)$$
$$\Pi^A_{x_A=1} = \{|00\rangle\langle 00|, |11\rangle\langle 11|\} \text{ (non-trivial record } a \in \{0, 1\})$$

Explicit description of $\mathcal{M}_A$ (unitarity vs projection postulate)

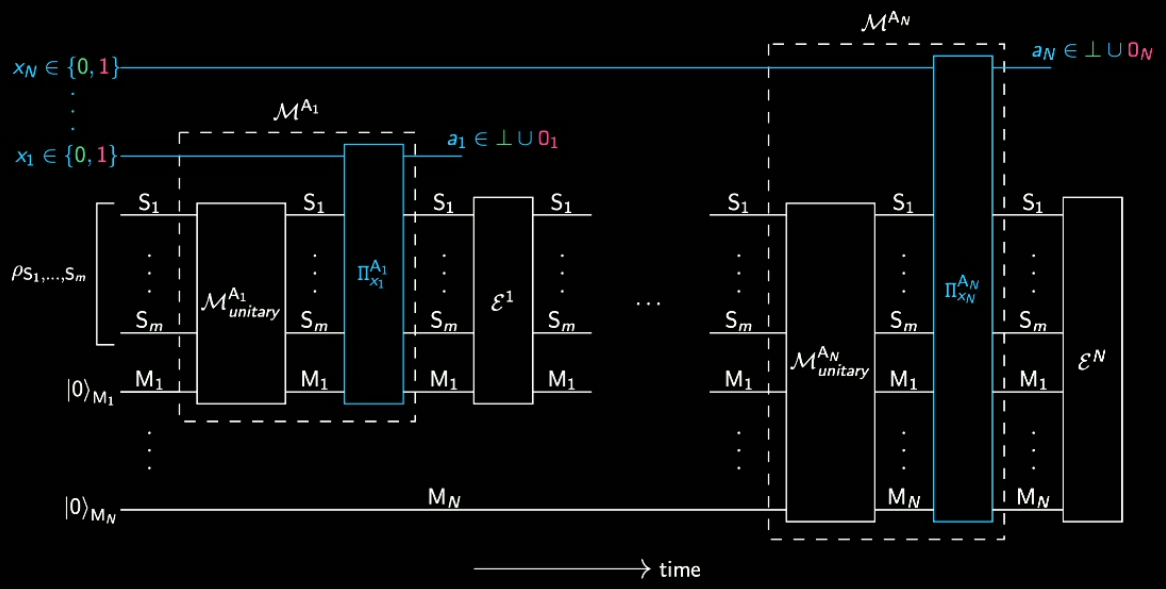


Setting-dependent projectors

$$\Pi^A_{x_A=0} = \mathcal{I} \text{ (no classical record } a = \perp)$$
$$\Pi^A_{x_A=1} = \{|00\rangle\langle 00|, |11\rangle\langle 11|\} \text{ (non-trivial record } a \in \{0, 1\})$$

Setting $x_A \in \{0, 1\}$ formalises Heisenberg cut for agent A

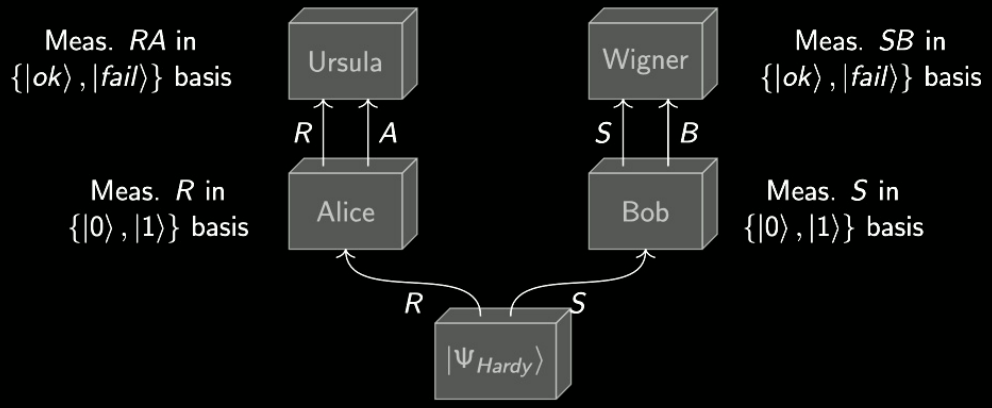
Generalises to arbitrary WFS over N agents $A_1, ..., A_N$, performing arbitrary quantum operations on each other's labs/memories



An augmented circuit for a general EWFS

Quantum theory is logically and causally consistent: simple resolution to EWFS paradoxes

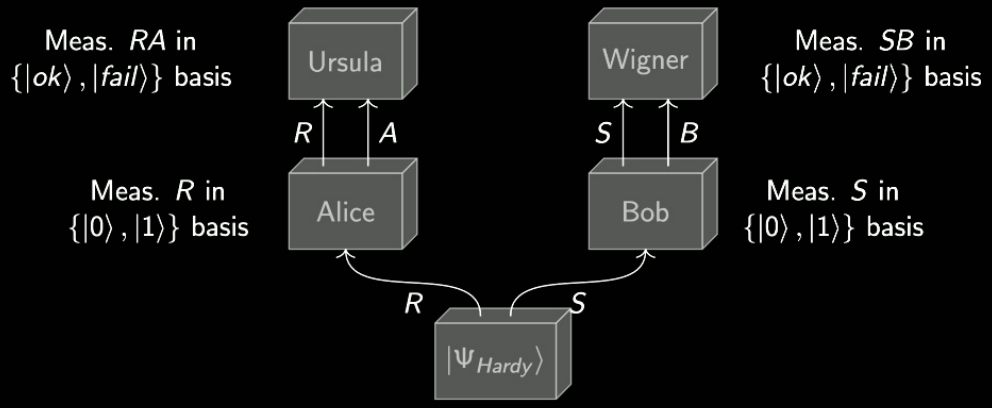
Frauchiger-Renner's apparent paradox (quick overview)



- Claim: Born rule + unitarity + classical logic $\Rightarrow$ PARADOX
- Reasoning: Post-select on run where $u = w = ok$

Frauchiger and Renner, 9, 3711 Nat. Comm. 2018. Pusey, Masanes (talks). Nurgalieva and del Rio, EPTCS 287, 2019.

Frauchiger-Renner's apparent paradox (quick overview)



- Claim: Born rule + unitarity + classical logic $\Rightarrow$ PARADOX
- Reasoning: Post-select on run where $u = w = ok$

$$u = ok \wedge w = ok \Rightarrow b = 1 \Rightarrow a = 1 \Rightarrow w = fail$$

Frauchiger and Renner, 9, 3711 Nat. Comm. 2018. Pusey, Masanes (talks). Nurgalieva and del Rio, EPTCS 287, 2019.

FR paradox disappears once we account for settings/"H-cuts"

FR's statements

- $u = ok \Rightarrow b = 1$ "$P(b = 1|u = ok) = 1$"
- $b = 1 \Rightarrow a = 1$ "$P(a = 1|b = 1) = 1$"
- $a = 1 \Rightarrow w = fail$ "$P(w = fail|a = 1) = 1$"
- $P(u = w = ok) = \frac{1}{12} > 0$

Explicit statements in our framework

- $u = ok \wedge (x_A = 0, x_B = 1) \Rightarrow b = 1$
- $b = 1 \wedge (x_A = 1, x_B = 1) \Rightarrow a = 1$
- $a = 1 \wedge (x_A = 1, x_B = 0) \Rightarrow w = fail$
- $P(u = w = ok|(x_A = 0, x_B = 0)) = \frac{1}{12} > 0$

Cannot be chained together by any axiom of classical logic

General result: Completeness, consistency and causality

Theorem (informal): An augmented circuit for an EWFS

1. Encodes all predictions that can made in that EWFS
2. Never leads to contradictory predictions
3. Predictions indep of settings/H-cuts outside causal past

- Objective part: Augmented circuit has a well-defined operational causal structure that all agents agree on.

Root of apparent inconsistencies: ignoring H-cut dependence

- outcome probabilities of one mmt are independent of another mmt's setting (/H-cut) $x \in \{0, 1\}$ (unitary vs projection)

General result: Completeness, consistency and causality

Theorem (informal): An augmented circuit for an EWFS

1. Encodes all predictions that can made in that EWFS
2. Never leads to contradictory predictions
3. Predictions indep of settings/H-cuts outside causal past

- Objective part: Augmented circuit has a well-defined operational causal structure that all agents agree on.
- Allows subjectivity: each prediction is relative to a choice of settings (priors/inputs), need not be same for all agents.

Root of apparent inconsistencies: ignoring H-cut dependence

- outcome probabilities of one mmt are independent of another mmt's setting (/H-cut) $x \in \{0, 1\}$ (unitary vs projection)

Theorem: (informal) Inconsistent predictions arise only if $\mathbf{I}$ has been assumed in an EWFS where it fails.

Refined understanding of FR for quantum theory (QT):

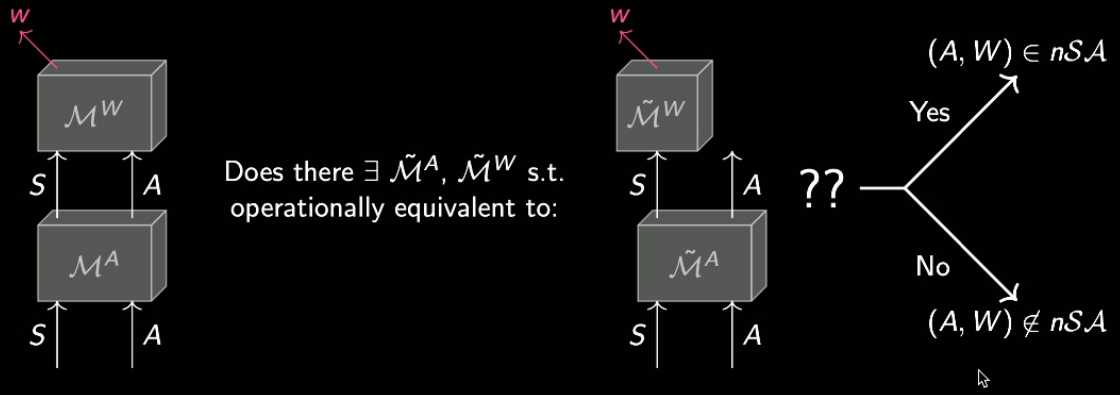
FR: Cut-independent QT+logic $\Rightarrow$ paradox in one EWFS
Here: Cut-dependent QT+logic $\Rightarrow$ consistency in all EWFS

Frauchiger and Renner, 9, 3711 Nat. Comm. 2018.

Emergence of objective measurement events

? How does the perceived objectivity of measurement events and classical records emerge?

- New concept: *non-superagent structure* $n\mathcal{SA}$



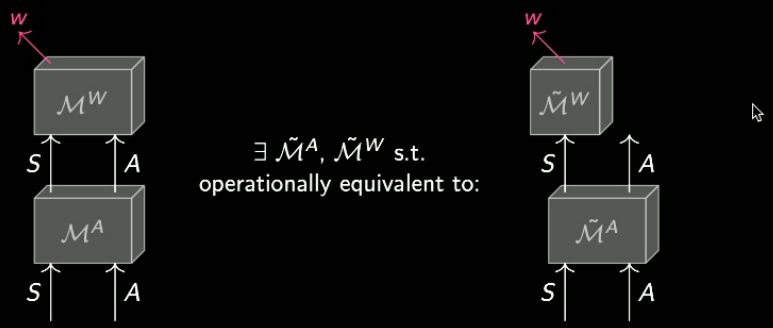
- Precise distinction: standard vs WF-type experiments. In standard quantum exp, $(A_i, A_j) \in n\mathcal{SA}\ \forall\ i, j$.

Objective, H-cut independent predictions, classical facts emerge

Theorem: In any EWFS corresponding to a standard q. exp.

1. All predictions become setting-independent e.g., $P(w|x_A = 0) = P(w|x_A = 1) := P(w)$.
2. Augmented circuit reduces to a standard form quantum circuit without settings.

Interpretation: Stable classical records can be extracted (open quantum system, decoherence, information leakage etc.)

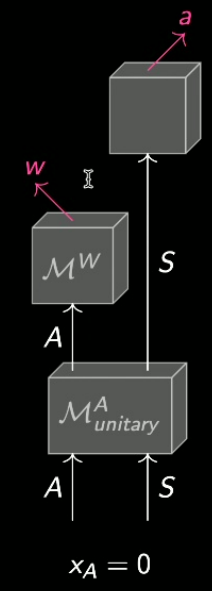


Causality and bubbles of objectivity despite non-absolute events

Example 1: Wigner asks Alice her outcome

$(Alice, Wigner) \in nSA$

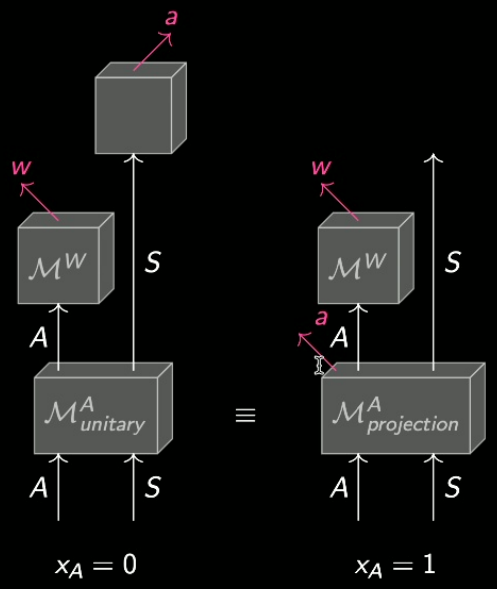
$(Wigner, Alice) \in nSA$



$x_A = 0$

Example 1: Wigner asks Alice her outcome

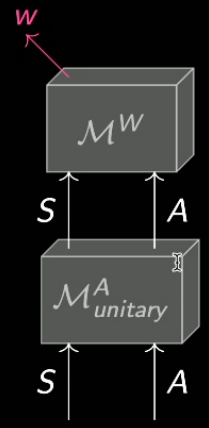
$(Alice, Wigner) \in nSA$
$(Wigner, Alice) \in nSA$



Alice and Wigner share a "bubble" of objectivity: observations explained by a $P(aw)$ independent of x_A

Terminology inspired by the term "Wigner bubble" introduced in: Cavalcanti Found Phys 51, 39 (2021).

Example 2: Wigner "Hadamards" Alice's lab

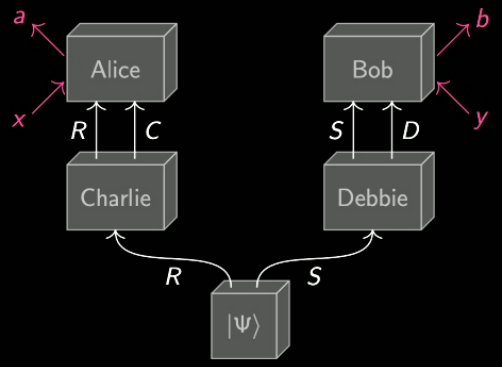


$(Alice, Wigner) \notin n\mathcal{SA}$
$(Wigner, Alice) \in n\mathcal{SA}$

Alice and Wigner do not share a "bubble" of objectivity

AoE $\Rightarrow$ valid joint distribution on outcomes of all agents

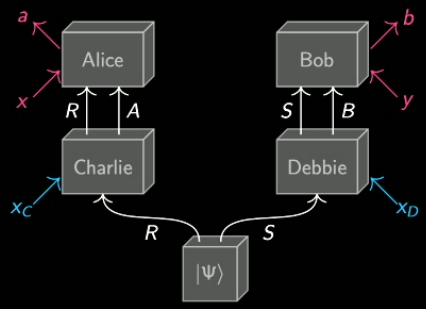
Local Friendliness (LF) theorem: quantum predictions $P_{LF}(ab|xy)$ in this EWFS cannot be explained by any theory respecting AoE (under assumptions about causality and free choice).



$x = 0$: Alice asks Charlie his outcome (example 1)
$x = 1$: Alice "Hadamards" Charlie's lab (example 2)

Bong et. al., 16, 1199-1205, Nat Phys 2020.

Augmented circuit also includes "H-cut settings" and recovers the quantum predictions $P_{LF}(ab|xy)$



$$P_{LF}(ab|xy) = P(ab|xy, x_C = x_D = 0)$$

AoE relaxed: Predictions need not arise from a $P(abcd)$ in general.

For different physical settings, predictions can be explained by

1. $x = 0, y = 0$: $P(abcd)$ $(x_C = 1, x_D = 1)$.
2. $x = 0, y = 1$: $P(abc)$ $(x_C = 1, x_D = 0)$.
3. $x = 1, y = 0$: $P(abd)$ $(x_C = 0, x_D = 1)$.

Implies well-defined operational quantum causal model on a directed acyclic graph explaining the predictions w/o AoE.

V. Vilasini and Mischa Woods (in preparation). V. Vilasini (in-preparation).

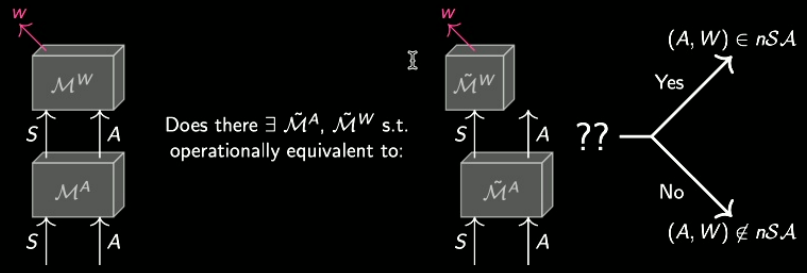
- General formalisation of H-cuts, super-agency, Wigner bubbles
- Completeness, consistency, causality w/o absolute events
- Consistent reasoning rules for quantum agents w/o giving up quantum theory or classical logic. FR paradoxes resolved.
- Explains how objectivity emerges in real-world experiments
- Operational quantum causal model for explaining quantum predictions in an EWFS (such as LF) without assuming AoE

Take home message: Sound causal and logical reasoning is possible at an operational level even if

- quantum theory were universally valid and,
- there is no absolute notion of measurement events

Quantum resource theory of genuine "WF-ness"?

$(A, W) \notin n\mathcal{SA}$ captures that Wigner has non-trivial quantum control over Alice's whole lab. (Link to H-cut dependence, AoE)



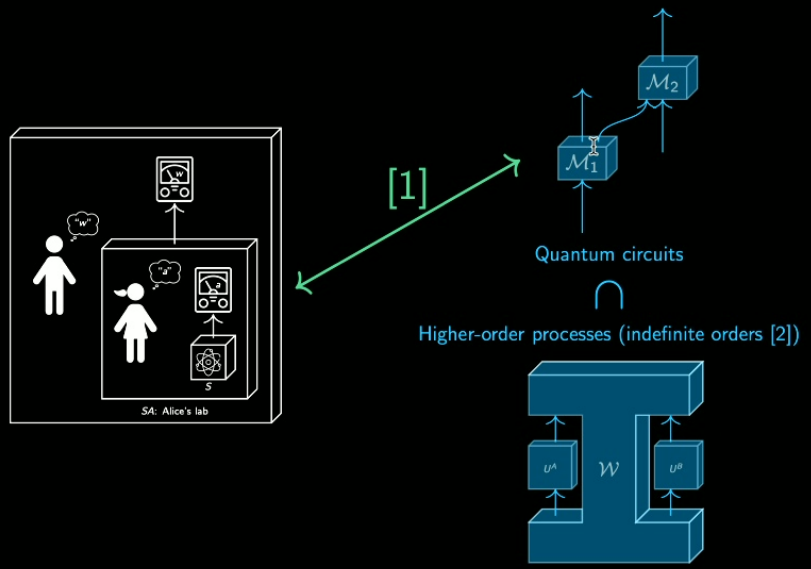
Fundamental resource that separates WF from standard experiments? Complementarity of Wigner's measurement on Alice's lab, contextuality of the scenario, information preservation of closed systems?

Initial work: Vilasini, Nurgalieva and del Rio. New J. Phys. 21, 113028, 2019. Nurgalieva and Vilasini. QPL 2023 talk, in-preparation

Info-theoretic and spatio-temporal events, causality in EWFS?

Wigner's Friends

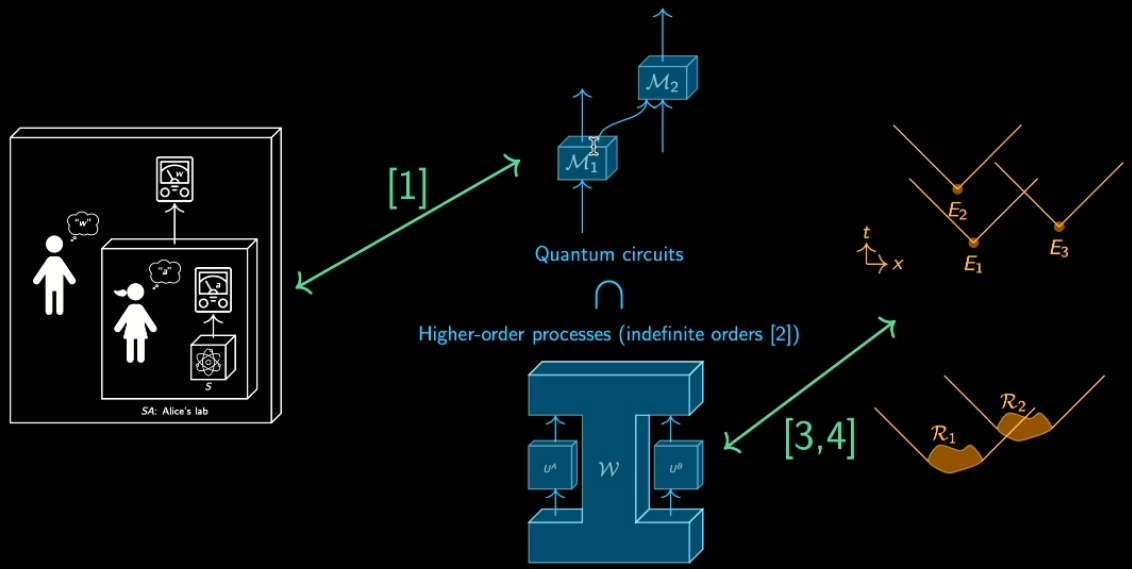
Info-th. causality



[1] Vilasini and Woods, arXiv:2209.09281.
[2] Hardy, arXiv:0509120. Oreshkov, Costa, Brukner, Nat. Com. 3, 1092, 2012. Chiribella et. al. PRA 88, 022318, 2013.

Info-theoretic and spatio-temporal events, causality in EWFS?

Wigner's Friends | Info-th. causality | Space-time



Scope for unified framework: new "genuinely" WF-like non-classical phenomena?

[1] Vilasini and Woods, arXiv:2209.09281.
[2] Hardy, arXiv:0509120. Oreshkov, Costa, Brukner, Nat. Com. 3, 1092, 2012. Chiribella et. al. PRA 88, 022318, 2013.
[3] Vilasini and Renner, PRL 133, 080201 and PRA 110, 022227, 2024. **(Renato Renner's talk on Friday)**
[4] Vilasini and Colbeck, PRL 129, 110401 and PRA 106, 032204, 2022.

- Resource behind genuine WF-like phenomena?

  (Initial work (link to contextuality): Nurgalieva, Vilasini. QPL 2023 talk, in-preparation)

- Causal models, higher-order processes, space-time in EWFS?

  (Ongoing work: combining this work + Vilasini, Renner, PRL 133, 080201 and PRA 110, 022227, 2024.)

- WF paradoxes, meas. problem beyond quantum theory?

  (Initial work: Vilasini, Nurgalieva, del Rio. NJP 2019. Ormrod, Vilasini, Barrett 2023, arXiv:2303.03353)

Thank you very much!