No Superluminal Causal Influence in QFT with a Local Measurement Theory

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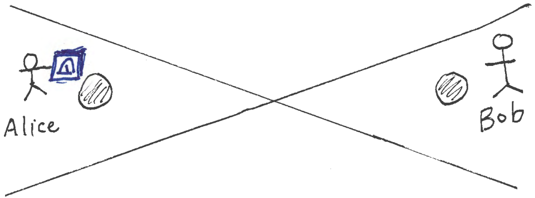
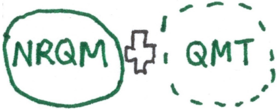
The Big Picture



SL1?: Does Alice's measurement affect Bob's system properties?



YES (apparently). Diagnoses:

1. correct interpretation of QM is compatible with relativity (e.g., neo-Bohr, Everett, ...)
2. QM and relativity incompatible
3. non-relativistic QM is non-relativistic!

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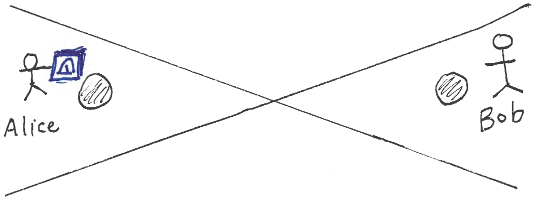

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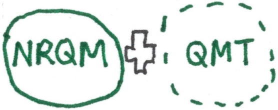

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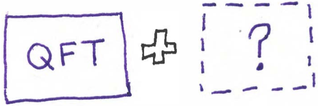

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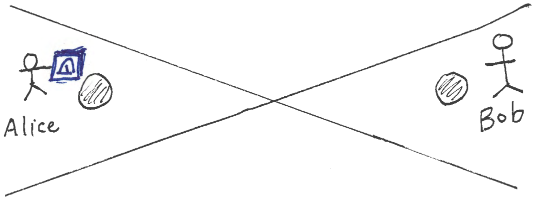

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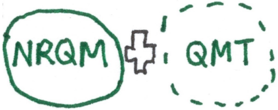

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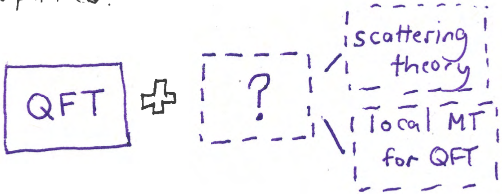
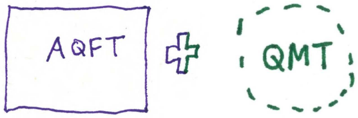


DF and MP, "Note on episodes in the history of modelling measurements in local spacetime regions using QFT," *EPJH*

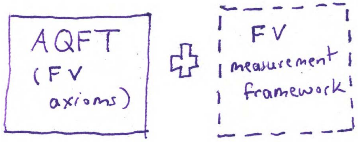
Outline

1. Review: Reeh-Schlieder Theorem with QMT

   Apparent implication: local selective measurements can have superluminal effects



2. Fewster-Verch (FV) Local Measurement Framework for AQFT



3. Reeh-Schlieder Theorem with FV Local Measurement Framework for QFT

   The Resolution: Using relativistic local measurement theory removes the appearance of superluminal causal influence

4. Conclusions

Reeh-Schlieder Theorem (Reeh & Schlieder 1961)

$O \mapsto \mathcal{A}(O)$: net of local algebras of observables for $O \subset M$, Minkowski spacetime

ω: vacuum state

Concrete GNS representation: $(\mathcal{H}_\omega, \pi_\omega)$ with net $O \mapsto \mathfrak{R}(O)$ of von Neumann algebras and vacuum vector Ω.

Assume (Spectrum Condition) and (Weak Additivity).

Reeh-Schlieder theorem: For O any open causally convex region, Ω is *cyclic* for the local algebras $\mathfrak{R}(O)$, i.e., vectors of the form $A\Omega$ where $A \in \mathfrak{R}(O)$ are *dense* in $\mathcal{H}_\omega$.

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Problem: Because $A \in \mathfrak{R}(O)$ represent local selective measurement operations, "it looks as though entirely physical operations in O can change the global state, in particular the vacuum, to any desired state!" (Clifton & Halvorson 2001)

"by acting on the vacuum with suitable operations in a terrestial laboratory, an experimenter can create the Taj Mahal on (or even behind) the Moon!" (attributed to Werner in Verch (2006), "Vacuum Fluctuations, Geometric Modular Action and Relativistic Quantum Information Theory")

Responses to Reeh-Schlieder Theorem

1. Pragmatic: This is not a practical method for constructing Taj Mahal behind the moon because vacuum correlations fall off asymptotically with distance. (Verch, Fewster, Rejzner)
2. Selective measurement operations are not (entirely) physical operations. (Redhead; Clifton & Halvorson)
3. Compatibility with relativity theory requires only prohibition on superluminal *signalling*; superluminal causal influence is okay. (Valente)
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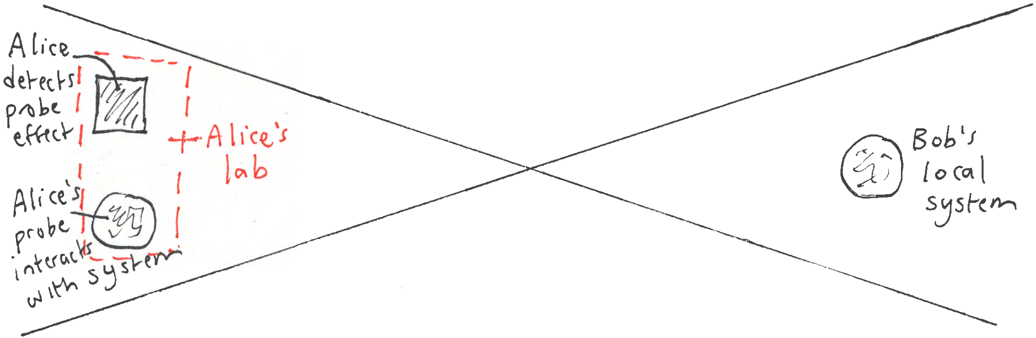
5. Earman & Valente (2014): "The first option would challenge the assumption that if $A \in \mathfrak{R}(O)$ is self-adjoint then it is measurable by an operation performed in O. We will not discuss this option here.": Suggestive!

   Our diagnosis: need a representation of local measurement operations suited to AQFT

Physical Model of Local Measurement

(common to both QMT and FV measurement framework)



Mathematical Physics Model of Local Measurement using AQFT

QMT: model system, probe(s), and interactions between them using NRQM

FV Measurement Framework for AQFT: model system, probe, and interactions between them using AQFT

(Aside: Clearly no one is solving all aspects of the Measurement Problem)

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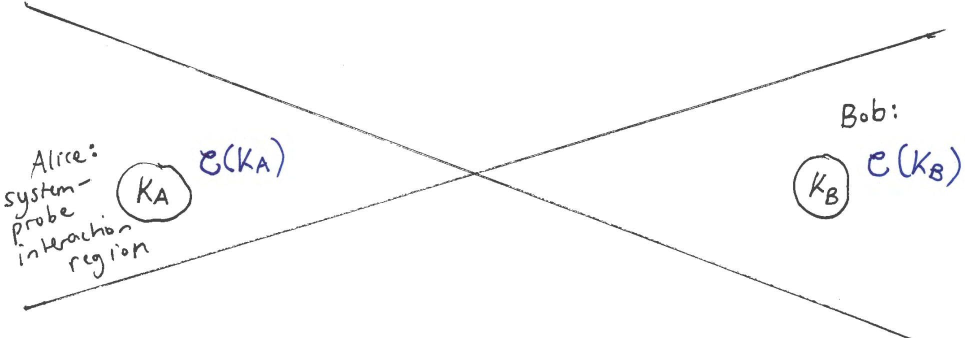
(i) Local "observables" (which represent properties): $O \mapsto \mathscr{C}(O)$, net representing local observables of coupled system-probe



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(i) Local "observables" (which represent properties): $O \mapsto \mathscr{C}(O)$, net representing local observables of coupled system-probe

(ii) Local Measurement Representation Assumption: system and probe interact only in region $K_A \Rightarrow$ **coupled** algebra $\mathscr{C}$ is *isomorphic* to **uncoupled** algebra $\mathscr{U} = \mathscr{S} \otimes \mathscr{P}$ outside the causal hull of K_A
$\Rightarrow$ Define *Local Scattering Isomorphism* Θ: $\mathscr{U}(M) \to \mathscr{U}(M)$

Representation of Local Measurement Operations in FV framework

FV's Question: How to represent *local measurement operations* using this framework?

FV's Answer: Proceed by analogy to QMT **EXCEPT** apply (i) Local "observables" and (ii) Local Measurement Representation Assumption

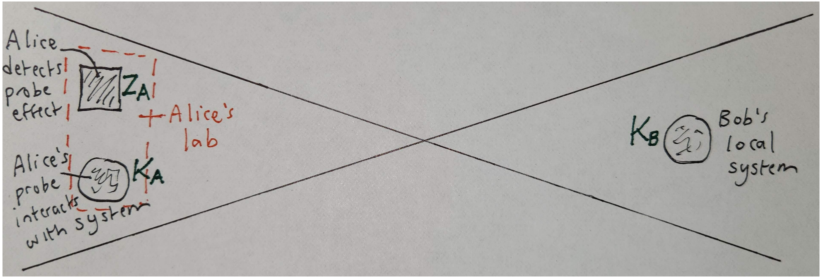
- Define a measurement scheme, instruments, and state update rules by following Chapter 10 of Busch et al. *Quantum Measurement* step by step

State update rule for local selective measurement in FV framework:

$$\omega_s'(S) = \frac{(\Theta^*(\omega \otimes \sigma))(S \otimes P)}{\omega(\varepsilon_\sigma(P))} \tag{1}$$

$\varepsilon_\sigma(P)$: system observable induced by probe effect P, with probe prepared in state σ

No Superluminal Causal Influence: Counterfactual Analysis I



(SLI?): Does Alice's intervention on the system by (i) introducing a probe that interacts locally with the system in K_A and (ii) detecting the probe effect in Z_A bring about a change in the local system properties in Bob's region K_B?

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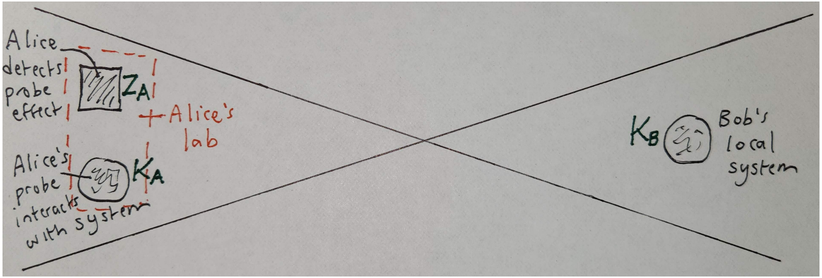

(SLI?): Does Alice's intervention on the system by (i) introducing a probe that interacts locally with the system in K_A and (ii) detecting the probe effect in Z_A bring about a change in the local system properties in Bob's region K_B?

(SLI counterfactual?): If Alice had not performed an intervention on the system by (i) introducing a probe that interacts locally with the system in K_A and (ii) detecting the probe effect in Z_A, would the local system properties in Bob's region K_B have been different?

No Superluminal Causal Influence: Counterfactual Analysis II

Counterfactual Scenario: Alice does not perform a local measurement ($\mathscr{U}(M)$ and $\omega \otimes \sigma$)

Actual Scenario, Part (i): Alice introduces a probe that interacts with system in K_A

Evaluate this counterfactual using the representation of the dynamics given by the FV framework:

- Θ: essentially, tracks how the system-probe interaction changes the assignment of elements of $\mathscr{U}$ to regions in M^+
- Application of Relativistic Heisenberg Picture Dynamics: Does a particular physical property get represented by $X \in \mathscr{U}(K_B)$ in the Counterfactual Scenario and some *other* algebra element $X' \in \mathscr{U}(K_B)$ in the Actual Scenario?

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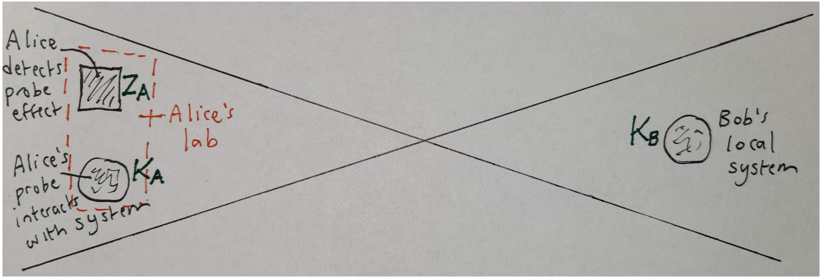
  Answer: **NO**

  Prop. 3.1(b) (FV (2020)) For system observables associated with $L \subset K_A^\perp$ (such as K_B), $\Theta(A \otimes B) = A \otimes B$.

No Superluminal Causal Influence: Counterfactual Analysis III



Counterfactual Scenario: Alice does not perform a local measurement ($\mathscr{U}(M)$ and $\omega \otimes \sigma$)

Actual Scenario, Parts (i) and (ii): Alice (i) introduces a probe that interacts with system in K_A **and (ii) detects the probe effect in** Z_A

The system and probe are uncoupled in region Z_A, so the system is unaffected by whatever Alice does to the probe in this region.

Reeh-Schlieder Theorem with FV framework I

FV: Selective state update rule for **special case of Bob's region, in which** $K_B \subset K_A^\perp$ **for any** $S \in \mathscr{S}(K_B)$, C*-algebras

$$\omega'_{FV}(S) = \frac{\omega(\sqrt{\varepsilon_\sigma(P)}S\sqrt{\varepsilon_\sigma(P)})}{\omega(\varepsilon_\sigma(P))} \tag{2}$$

QMT: Abstract algebraic version of generalized Lüders' selective state update rule for POVMs with a discrete set of outcomes $a_1, a_2, \ldots$ each associated with a positive operator A_i

$$\omega'_{GL}(B) = \frac{\omega(\sqrt{A_i}B\sqrt{A_i})}{\omega(A_i)} \tag{3}$$

Formally similar:

- FV $\varepsilon_\sigma(P)$: an element of system algebra $\mathscr{S}$
  (observable induced by probe effect P, with probe prepared in state σ)
- QMT A_i: an element of system algebra $\mathcal{A}$

Reeh-Schlieder Theorem with FV framework II

FV: Selective state update rule (for special case of K_B, C*-algebras)

$$\omega'_{FV}(S) = \frac{\omega(\sqrt{\varepsilon_\sigma(P)}S\sqrt{\varepsilon_\sigma(P)})}{\omega(\varepsilon_\sigma(P))} \tag{4}$$

QMT: Algebraic version of generalized Lüders' selective state update rule for POVMs with a discrete set of outcomes

$$\omega'_{GL}(B) = \frac{\omega(\sqrt{A_i}B\sqrt{A_i})}{\omega(A_i)} \tag{5}$$

Physical difference:

- FV $\varepsilon_\sigma(P) = (\eta_\sigma \circ \Theta)(1 \otimes P)$ is *not* just any positive operator in system algebra $\mathscr{S}$
  Θ: encodes information about K_A and relativistic dynamics (Time-Slice Property)
  selective state update rule for **local** observables and **local** measurement operations
- QMT A_i: a positive operator in system algebra $\mathcal{A}$
  selective state update rule for **local** observables BUT **not local** measurement operations

Reeh-Schlieder Theorem with FV framework III

Reeh-Schlieder theorem: For O any open causally convex region, Ω is *cyclic* for the local algebras $\mathfrak{R}(O)$, i.e., vectors of the form $A\Omega$ where $A \in \mathfrak{R}(O)$ are *dense* in $\mathcal{H}_\omega$.

Problem: Because $A \in \mathfrak{R}(O)$ represent local selective measurement operations, "it looks as though entirely physical operations in O can change the global state, in particular the vacuum, to any desired state!" (Clifton & Halvorson 2001)

Resolution using FV framework:[1]

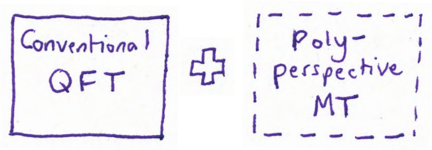
- local measurement operations are no longer identified with elements of local algebras
- local measurement operations are represented using induced observables $\varepsilon_\sigma(P)$, which are ***not*** arbitrary elements of local algebras
  $\Rightarrow$ blocks the inference that vacuum is cyclic for *local selective measurement operations*
- more substantively: the physical requirements that local measurement operations are confined to a local region and constrained by relativistic dynamics are built into the mathematical representation of local measurement operations

[1] Still have Bell-inequality violating correlations: see FV (2020) and Fewster York School notes

Connection to Polyperspective Formalism (next talk)

General Moral: We should expect QFT with a local measurement theory to rule out superluminal causal influence by local measurement operations.

Many differences between FV measurement framework and Polyperspective Formalism, but one similarity is that both rule out superluminal causal influence by local measurement operations (albeit in very different ways!).



Conclusions

- The Reeh-Schlieder theorem for AQFT appears to imply superluminal causal influence when QMT (for NRQM) is applied.
- This apparent problem of incompatibility with relativistic causality is resolved by instead applying the FV local measurement framework for AQFT.
  - elements of local algebras no longer do double-duty as representatives of local observables and (local) measurement operations
  - mathematical representation of local measurement operations incorporates physical requirements of locality and relativistic dynamics

Broader Outlook:

- securing compatibility between quantum theory and relativity theory is not a matter of finding the correct *interpretation* of NRQM; it is a matter of developing relativistic quantum *physics*