The measurement problem is the measurement problem is the measurement problem

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Recently, it has been stated that single-world interpretations of quantum theory are logically inconsistent. The claim is derived from contradicting statements of agents in a setup combining two Wigner’s-friend experiments. Those statements stem from applying the measurement-update rule subjectively, i.e., only for the respective agent’s own measurement. We argue that the contradiction expresses the incompatibility of collapse and unitarity — resulting in different formal descriptions of a measurement — and does not allow to dismiss any specific interpretation of quantum theory.

I. INTRODUCTION

The mathematical formalism of quantum theory has been celebrated for its success; it has been well-tested and, so far, not been falsified — even in cases where its predictions are counter-intuitive and paradoxical. Nevertheless, there are ongoing controversies: On the one hand, there are various attempts to resolve the conflict of the apparent collapse during a measurement with the unitarity evolution. On the other hand, controversial discussions are led on how to understand and to interpret the formalisms.

The authors of claim to have proven that single-world interpretations of quantum theory cannot be self-consistent. They consider a combination of two Wigner’s-friend gedankenexperiments and derive a contradiction regarding the statements of the agents involved. The contradiction is, actually, a result of the quantum-mechanical description of the measurement: The agents in the setup attribute a collapse merely to their own measurement. We subsequently refer to this as subjective collapse. It is, however, subjective only in the case of encapsulated observers where unitarity and collapse are conflicting, see Agents measuring the same quantum system — not each other’s memories — can objectively agree on a collapse occurring in every measurement.

In our opinion, the subjective-collapse model, as Everett’s relative-state model or other collapse models such as GRW, is a mathematical formalism and not an interpretation. All the above formalisms yield the same predictions on experiments until one considers encapsulated observers; and then — if ever possible — a Wigner’s-friend experiment will have to decide among them.

In, the authors introduce a framework of so-called stories and plots that captures “what could be said” — in particular about entities in a physical experiment; the contradiction in question is obtained in this framework. We argue that the use of the framework to rule out certain interpretations of quantum theory as done in is debatable. This doubt has been supported recently by a consistent description of the setup in terms of a generalised version of Bohmian mechanics.

We first discuss the story-plot framework and hope to clarify how it relates to classical information. We critically examine the notion of “many worlds” established in the framework. Furthermore, we examine the original Wigner’s-friend experiment and formulate a contradiction analogous to that in in terms of stories and plots. Said contradiction, therefore, can be seen to reflect the measurement problem. Finally, we consider the setup in and explicitly show how the contradiction arises from the subjective collapse.

II. THE STORY- PLOT FRAMEWORK

The framework addresses the question what can possibly be said about a physical experiment. A simple example from quantum physics is the Stern-Gerlach setup, depicted in Fig. After recapitulating the framework in we discuss in how the compatibility constraint in relates to interoperability — the ability to copy information — and how their definition of “many worlds” is in conflict with the definiteness of measurement results. The latter relates to the distinguishability of the information obtained by the measurement. Finally, in we argue that the set of possible stories about a quantum-mechanical experiment can be formally represented by joint, conditional probability distributions.

A. Events, Stories, and Plots

In, a story s is defined as “an account of events that occur.” Neither of the terms “event,” “occur,” and “real” is unambiguous in this context, in particular if there is no further specification of the theoretical foundation. We will generalize the concept slightly and take a story to be a priori “anything that can be stated.” Statements (or accounts or stories) can be encoded in a finite bit string. These bit strings carry classical information that is preserved when copied — we will term this feature interoperability — and is based on a notion of distinguishability, i.e., different stories can be told apart from one another. Thus, stories are entities of classical information, even though we might talk about quantum
systems.
A possible story is for instance

“The source emits a photon in the state $|\phi\rangle = \alpha|0\rangle + \beta|1\rangle$ which is measured in the basis $\{0\}, \{1\}$ and yields the outcome 0.”

Another example is

“If a source emits a photon in the state $|\phi\rangle = \alpha|0\rangle + \beta|1\rangle$, a measurement in the basis $\{0\}, \{1\}$ might yield the outcome 0 or the outcome 1.”

While the first has a factual character, the second accounts for different possible outcomes. Both are elements in the set of all possible stories, $\Sigma$. If the setting of the story (e.g., the experimental setup) is known, and the content has enough structure, by interoperability, one can represent it more concisely with a set of ordered tuples of parameters — each tuple capturing one of the instances of information. From now on we assume — as in [7] — that stories have some temporal structure. As the story is finite, it can represent, for instance, real numbers only up to some finite precision. One might nonetheless take the values of the parameters embedded in a continuous space and, therefore, the sets in the Cartesian product $V$ to be real. The set of all possible events given the temporal structure and some Cartesian product $V$ is then

$$E = \{(t, x) \in T \times V \}.$$  

(1)

A deduction function maps stories into the power set $\mathcal{P}(E)$ and assigns to each story a set of events, called a plot:

$$d_E : \Sigma \rightarrow \mathcal{P}(E)$$

$$s \mapsto d_E(s) =: s^E \subseteq E.$$

The deduction function depends on the underlying event set. Some information of the story $s$ might get lost in its representation by events, $d_E(s)$. While in [7], $d_E$ is taken to be a partial function, we rather map stories that are meaningful with respect to the event set $E$ to the empty set.

B. Critique of the Story-Plot Framework

a. Compatibility and interoperability

By interoperability one can require different plots for different event sets stemming from the same story to be in some sense compatible. Two event sets $E$ and $F$ encompass the same information about a story $s$, if the plots $d_E(s)$ and $d_F(s)$ can be related bijectively. If, however, $F$ captures only a part of the information captured by $E$, i.e., $V_E = V_F \times W$ for some set $W$, then for any $(t, x) \in d_F(s)$, there has to exist a corresponding $(t, x, y) \in d_E(s)$, that is

$$(t, x) \in d_F(s) \iff \exists y \in W : (t, x, y) \in d_E(s).$$

(2)

Generally, if two event sets $E$ and $F$ have some “overlap,” i.e., there exist sets $W_E$ and $W_F$ such that $V_E \times W_E = V_F \times W_F$, then the compatibility condition is

$$\exists z \in W_F : (t, x, z) \in d_E(s) \iff \exists y \in W_E : (t, x, y) \in d_E(s).$$

(3)

This is the compatibility constraint introduced in [7] and demands different plots to be copies of the information of the same corresponding story. It is possible due to the interoperability of classical information.

b. Many worlds and distinguishability

Stories allow for multiple events happening at the same time, as illustrated in the following examples.

“Alice and Bob perform their respective measurements.”

“Alice measures either 0 or 1.”

In the first story two a priori uncorrelated events happen “at the same time,” by which we rather mean that we cannot distinguish which one happened before the other. The second story refers to multiple possible results. Both stories have plots with at least two events

$$(t, x_1), (t, x_2) \in d_E(s)$$

with the same time parameter $t$. While in the first story those two events are related by AND for two independent measurements, the latter contains events that are connected by OR. From the plots alone, it cannot be deduced how two events with the same time parameter are related to one another. In [7], the authors allow for AND-connected events in stories about one single measurement and refer to this as many worlds. This, however, is in conflict with the definiteness of measurement outcomes, in the sense that each single instance of
a measurement gives exclusively one result. The ability to infer distinguishable, classical information from it might be seen as the defining property of a measurement. The *distinguishability* of classical information — a classical bit is either 0 or 1 — then requires, by definition, measurement outcomes to be definite from the point of view of a given observer. Relating two events describing results for a single measurement with AND is then a contradiction in itself. The statement “Alice measures 0 and 1” does not describe a measurement in the above sense, since it does not describe Alice inferring a classical bit. In our understanding, two events in a plot of a story about *one measurement*, therefore, have to be connected by OR. Connecting such events by AND is questionable.

In a many-worlds interpretation, a tree such as shown in Fig. 3 is commonly used to depict the multiverse [13]. Such a tree illustrating all possible results — i.e., the “multiverse” —, can also be constructed for collapse models. The probability weights associated to the branches in the different formalisms can, however, differ. Whatever the interpretation, statements regarding actual measurement results of an experiment refer to *one particular branch* of the multiverse. Within one such branch, there are no AND-related outcomes for a single measurement.

**C. Plots and Quantum Theory**

In quantum mechanics, Born’s rule relates the measurement outcomes with subspaces in a sample space $\Omega$ and a corresponding probability distribution $P$. By definiteness of the outcomes we assume that $\Omega$, in a single measurement, falls into a disjoint union of at least two subsets $\Omega = \bigcup_k V_k$, $V_k \cap V_l = \emptyset \forall \ k \neq l$, where each correspond to different measurement results and subsequently to different events. Stating disjointness is then equivalent to saying that two results cannot occur simultaneously, i.e.,

$$P(V_k \cap V_l) = 0 \ \forall \ k \neq l.$$  

Consider a quantum experiment with multiple parties measuring each part of a density matrix $\rho$ on $\mathcal{H}_{W_1} \otimes \mathcal{H}_{W_2} \cdots$. The overall probability distribution $P(w_1, w_2, \ldots) = \text{Tr}(\rho \pi_{w_1} \otimes \pi_{w_2} \cdots)$ encodes all possible combinations of measurement results. Each party that knows the entire setup and thus $\rho$, can compute her own probability distribution $P_k(w_k) = \text{Tr}_{W_k}(\rho \mathbb{1} \otimes \pi_{w_k})$, where $\text{Tr}_{W_k}$ is the partial trace over all other parties. The conditional probability distribution $P(w_1, \ldots, w_k-1, w_{k+1}, \ldots | w_k)$ reflects the party’s knowledge about the other results, given her own outcome.

All plots corresponding to a quantum experiment then relate to the joint probability distribution and can only contain OR-related events referring to different results of one measurement.

![FIG. 3. The source $S$ emits a quantum state (e.g., a qubit) $|\phi\rangle$, which is measured by the friend in some basis (e.g., $\{|\uparrow\rangle, |\downarrow\rangle\}$). Wigner then measures the joint system of the state emitted by the source and the friend’s memory.](image)

**III. WIGNER’S FRIEND**

The setup of the original Wigner’s-friend experiment is depicted in Fig. 3. An observer — the friend $F$ — performs a measurement $M_F$ on the quantum system emitted by the source $S$. Both the source and the friend constitute a joint quantum system which is then measured by a superobserver — Wigner $W$ — with a projective measurement $M_W$. We say, Wigner has full quantum control over the friend’s lab.

According to textbook quantum mechanics, the friend’s measurement induces a collapse to the eigenvector associated with the observed measurement result. To Wigner, however, the source and the friend’s memory appear as one big quantum system, which supposedly evolves unitarily, i.e., without a collapse. If the friend’s measurement does not induce a collapse, does he actually obtain a definite measurement result? Deutsch’s variant of the experiment [14] addresses this issue. The friend raises a flag stating whether he observed a definite outcome or not.

We differentiate between three models. The *no-collapse* model, which can be associated with Everett’s relative-state formalism [9], removes the collapse completely. The *objective collapse* model refers to theories assuming a collapse in every measurement. In that case, even for Wigner the evolution of the joint system is not unitary due to the friend’s measurement. Finally, the *subjective collapse* model, with each agent assuming a collapse merely in his own measurement, is labelled as standard quantum theory in [7]. While in the first two all agents make consistent predictions about all measurements, the latter allows Wigner and his friend to make predictions that contradict each other. One further has to assume that the friend can actually test his predictions about Wigner’s result. The possibility of communication between encapsulated observers is questionable. In that sense, the subjective collapse might be sufficient if the “wrong” prediction cannot be tested.

**A. Everettian Description of the Experiment**

According to Everett, the friend’s measurement is an isometry, correlating his memory state with the differ-
ent elements of the measurement basis \( \{ | m^{(i)}_F \rangle \}_i \),

\[
V_F : \mathcal{H}_S \to \mathcal{H}_S \otimes \mathcal{H}_F \\
|m^{(i)}_F \rangle \mapsto | m^{(i)}_F \rangle \otimes | z_i \rangle \quad \forall i,
\]

where \( \{ | z_i \rangle \}_i \) is an orthogonal set in the memory system recording the result. Consistently, we can model Wigner’s measurement with an isometry \( \rho_{\text{mem}} = \text{Tr}_S \left( V_W V_F | \psi_S \rangle \langle \psi_S | V_F^\dagger V_W^\dagger \right) \),

where \( | \psi_S \rangle \in \mathcal{H}_S \) is the state emitted by the source. The density matrix \( \rho_{\text{mem}} \) encodes possible correlations between the memory states of Wigner and his friend. To compute it one merely needs to know the two measurement bases, the one of the friend and the one of Wigner. We assume that the source emits a superposition \( | \psi_S \rangle = \frac{1}{\sqrt{2}} (| \uparrow \rangle + | \downarrow \rangle) \), that is measured by the friend in the basis \( \{ | \downarrow \rangle, | \uparrow \rangle \} \) before Wigner measures the joint system in a product basis \( \{ | \uparrow \rangle \otimes | u \rangle, | \downarrow \rangle \otimes | d \rangle \} \).

The corresponding density matrix

\[
\rho_{\text{mem}}^{(1)} = \frac{1}{2} (| u \rangle \langle u | + | d \rangle \langle d |) \quad (\text{6})
\]

shows that Wigner will know the measurement result of the friend. Alternatively, Wigner can measure in the superposition basis \( \{ | \phi^\pm \rangle \} = \sqrt{1/2} (| \uparrow \rangle \pm | \downarrow \rangle) \otimes | d \rangle \) resulting in memory state

\[
\rho_{\text{mem}}^{(2)} = \frac{1}{2} (| u \rangle \langle u | + | d \rangle \langle d |) \otimes | + \rangle \langle + | , \quad (\text{7})
\]

where \( | + \rangle \) corresponds to Wigner observing the joint system to be in state \( | \phi^+ \rangle \). As the density matrix is a product, Wigner cannot extract any information about the friend’s measurement result. To incorporate a collapse in this formalism, one needs the source with the measured state. If the friend’s result was \( u \), the memory state would be

\[
\rho_{\text{mem}}^{\text{clps}} = \text{Tr}_S \left( V_W V_F | \uparrow \rangle \langle \uparrow | V_F^\dagger V_W^\dagger \right) \quad (\text{8})
\]

\[
= \text{Tr}_S \left( V_W V_F | \uparrow \rangle \langle \uparrow | \otimes | u \rangle \langle u | V_W^\dagger V_W \right).
\]

If Wigner then measured in the superposition basis, he would measure \( | \phi^- \rangle \) with non-zero probability in case of a collapse.

### B. The Experiment in the Story-Plot Framework

The friend will account for his measurement with a plot

\[
s^F = \{(t_1, z)\} \quad (\text{9})
\]

containing a single event and \( z \) being the measurement result he observed. The underlying event set is \( E = \{ T \times \{ 0, 1 \} \} \). Wigner, on the other hand, has a plot

\[
s^W_0 = \{(t_2, u)\}, \quad (\text{10})
\]

where \( w \) is the outcome Wigner observed in his measurement on the combined system. Compatibility constraints arise when Wigner and his friend deduce something from their measurements. Generally, their plots will then be of the form

\[
s^F = \{(t_0, e), (t_1, z'), (t_2, y_w)\},
\]

where \( e \) and \( y_w \) describe what the friend can deduce about the source and Wigner’s results. Wigner’s plot will be

\[
s^W = \{(t_0, e'), (t_1, y_f), (t_2, w')\},
\]

where \( e' \) and \( y_f \) describe Wigner’s deductions. Using the same shortened notation as in \( \rho_{\text{mem}} \), compatibility would then require that

\[
(t_1, z', \star) \in s^F \iff (t_1, z = z', \star) \in s^W \quad (\text{13})
\]

\[
(t_2, \star, w = w') \in s^F \iff (t_2, \star, w') \in s^W, \quad (\text{14})
\]

which means that if one party can deduce the outcome of the other party’s measurement with certainty, this should be what that party observes. Deductions will in the following be written as equalities, while observed quantities are represented by their value.

In Deutsch’s version of the Wigner’s-friend experiment, the friend and Wigner communicate an additional bit \( x \), encoding whether the friend observed a definite outcome or not. Assume that they further have to answer the question “Can Wigner measure \( | \phi^- \rangle \) encoded in another bit \( y \).” This introduces further compatibility constraints

\[
(t_1, \star, x') \in s^F \iff (t_1, \star, x = x') \in s^W \quad (\text{15})
\]

\[
(t_2, \star, y = y') \in s^F \iff (t_2, \star, y') \in s^W, \quad (\text{16})
\]

The subjective-collapse model gives rise to the contradiction depicted in Fig. 4.
IV. THE FRAUCHIGER/RENNER PROTOCOL

The setup introduced in [7] allows to establish contradicting predictions, as for the Wigner’s-friend experiment above, more strikingly and in a single-run. It consists of two standard Wigner’s-friend experiments, where the friend in the first acts as the source for the second. The setup is given by the following protocol.

**Protocol 1.** The protocol assumes four parties, two friends, \( F_1 \) and \( F_2 \), and two super-observers, Wigner \( W \) and his assistant \( A \), with full quantum control over \( F_1 \) and \( F_2 \) respectively. The steps of the protocol are

0. At time \( t_0 \), a source emits a quantum coin in the superposition \( |\psi_c\rangle = \sqrt{\frac{1}{2}}|h\rangle + \sqrt{\frac{1}{2}}|t\rangle \) of head and tail.

1. At time \( t_1 \), the first friend \( F_1 \) measures the coin and prepares a spin state \( |\phi_a\rangle = |\downarrow\rangle \) if the result of the measurement was head and a spin state \( |\phi_a\rangle = \sqrt{\frac{1}{2}}(|\downarrow\rangle + |\uparrow\rangle) \) if the result was tail. The measurement is given by an isometry correlating the brain state \( |\phi_{F_1}\rangle \in \{|H\rangle,|T\rangle\} \) of \( F_1 \) with the different coin states.

2. At time \( t_2 \), the second friend \( F_2 \) measures the spin state in the basis \( \{|\uparrow\rangle,|\downarrow\rangle\} \). The measurement is given by an isometry correlating the brain state \( |\phi_{F_2}\rangle \in \{|U\rangle,|D\rangle\} \) of \( F_2 \) with the different spin states.

3. At time \( t_3 \), the assistant \( A \) measures the coin \( C \) and the brain state of \( F_1 \) in a basis

\[
\{|o\rangle = \sqrt{1/2}(|h, H\rangle - |t, T\rangle), |f\rangle = \sqrt{1/2}(|h, H\rangle + |t, T\rangle)\}.
\]

4. At time \( t_4 \), Wigner \( W \) measures the spin state \( S \) and the brain state of \( F_2 \) in a basis

\[
\{|O\rangle = \sqrt{1/2}(|\downarrow, D\rangle - |\uparrow, U\rangle), |F\rangle = \sqrt{1/2}(|\downarrow, D\rangle + |\uparrow, U\rangle)\}.
\]

5. At time \( t_5 \), Wigner and his assistant compare their results. If they both obtain the measurement result ok corresponding to \( |O\rangle \) and \( |o\rangle \) respectively, they halt, otherwise the restart with the first step.

V. DISCUSSION OF THE SUBJECTIVE-Collapse MODEL

We will now consider the predictions of the various agents about the other’s measurement result in the halting round of the protocol. The calculations are performed in the Everett formalism described above. The subscript on the probabilities indicates whether a collapse was considered, \( P_{\text{clps}} \), or not, \( P_{\text{ism}} \).

c. \( A \) about \( F_2 \) The knowledge of \( A \) about \( F_2 \) is given by the distribution

\[
P_{\text{ism}}(f_2 | a) = \frac{1}{N_a} \text{Tr} [V |\phi_{C}\rangle \langle \phi_{C}|V^\dagger \cdot |f_2\rangle \langle f_2| \otimes |a\rangle \langle a| \otimes I_{\text{rest}}]
\]

where \( V = V_A \cdot V_{F_1} \cdot V_{F_2} \) with the values

\[
\begin{array}{c|c|c}
f_2 & P_{\text{ism}}(f_2 | f) & P_{\text{ism}}(f_2 | o) \\
\hline
u & 0.2 & 1.0 \\
d & 0.8 & 0.0
\end{array}
\]

Thus, \( A \) can conclude that \( F_2 \) measures \( \uparrow \) upon obtaining \( o \).

d. \( F_2 \) about \( F_1 \) The knowledge of \( F_2 \) about \( F_1 \) is given by the distribution

\[
P_{\text{ism}}(f_1 | f_2) = \frac{1}{N_{f_2}} \text{Tr} [V |\phi_{C}\rangle \langle \phi_{C}|V^\dagger \cdot |f_1\rangle \langle f_1| \otimes |f_2\rangle \langle f_2| \otimes I_{\text{rest}}]
\]

where \( V = V_{F_1} \cdot V_{F_2} \) with the values

\[
\begin{array}{c|c|c}
f_1 & P_{\text{ism}}(f_1 | U) & P_{\text{ism}}(f_1 | D) \\
\hline
h & 0.0 & 0.5 \\
t & 1.0 & 0.5
\end{array}
\]

Then \( F_2 \) can conclude that \( F_1 \) measures \( t \) upon measuring \( \uparrow \).

e. \( F_1 \) about \( W \) (collapse) If \( F_1 \) assumes a collapse to happen after his measurement he can calculate the conditional probability over \( W \)’s result as follows.

\[
P_{\text{clps}}(w | f_1) = \frac{1}{N_{f_1}} \text{Tr} [V |f_1\rangle \langle f_1|V^\dagger \cdot I_{\text{rest}} \otimes |w\rangle \langle w|]
\]

where \( V = V_W \cdot V_A \cdot V_{F_2} \cdot V_{F_1} \). This yields the distribution

\[
\begin{array}{c|c|c}
w & P_{\text{clps}}(w | H) & P_{\text{clps}}(w | T) \\
\hline
F & 0.5 & 1.0 \\
O & 0.5 & 0.0
\end{array}
\]

So upon measuring \( T \), \( F_1 \) can conclude that \( W \) measured \( F \).

f. \( F_1 \) about \( W \) (no collapse) The distribution turns out to be

\[
P_{\text{ism}}(w | f_1) = \frac{1}{N_{f_1}} \text{Tr} [V |\phi_{C}\rangle \langle \phi_{C}|V^\dagger \cdot |f_1\rangle \langle f_1| \otimes |w\rangle \langle w| \otimes I_{\text{rest}}]
\]
In this note we critically review a recent result [7] by Frauchiger and Renner questioning the logical consistency of single-world interpretations of quantum theory. In fact, the authors of [7] prove an inconsistency of the Frauchiger/Renner protocol, however, two parties make opposing predictions for a setup containing encapsulated observers. The contradiction in the latter is based on the possibility of ad-di-tional measurement results, and can thus merely be tested in a statistical analysis of multiple runs. In the Frauchiger/Renner protocol, however, two parties make opposing predictions for a single measurement result (once the halting condition is met): Their protocol makes the conflict more striking and evident.

The contradiction cannot be resolved with the notion of “many worlds” established in [16] as illustrated in the original Wigner’s-friend experiment. The conflict becomes manifest only if encapsulated observers can communicate — i.e., if the friend and Wigner can test their predictions against actual observations. It has been questioned whether this is in principle possible.

The Wigner’s-friend experiment can (in principle) discriminate between two competing quantum formalisms describing a measurement — the unitary relative-state formalism and the non-unitary measurement update rule. A specific combination of these two formalisms, together with the assumption regarding possible communication, gives a contradiction. We do, however, not regard a formalism to necessarily imply a particular interpretation like “many worlds” or “collapse.” We believe that the contradiction above does, therefore, not disqualify a particular interpretation of quantum mechanics.
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