Wigner’s friend, Feynman’s paths and material records

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The place and role of an Observer in quantum mechanics has been a subject of an ongoing debate since the theory’s inception. Wigner brought this question to the fore in a celebrated scenario in which a super-Observer observes a Friend making a measurement. Here we briefly review why this “Wigner Friend scenario” has been taken to require the introduction of the Observer’s consciousness, or alternatively to show the inconsistency of quantum measurement theory. We will argue that quantum theory can consistently leave observers outside its narrative, by making only minimal assumptions about how the information about the observed results is stored in material records.

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And I come to the fields and spacious palaces of my memory, where are the treasures of innumerable images, brought into it from things of all sorts perceived by the senses. ...What then we have utterly forgotten, though lost, we cannot even seek after.

St. Augustine of Hippo

Are the rules of quantum mechanics internally consistent? To be consistent, the theory must give non-controversial prescriptions for any hypothetical situation, however difficult to realise in practice. An important question in this discussion is the extent to which quantum theory is able to deal with the role of a conscious Observer when a measurement takes place.

Some authors have considered consciousness to be instrumental in accounting for the observation of a measurement outcome. In their classic treatise, London and Bauer \cite{1} described the state of an Observer’s consciousness by a vector in a Hilbert space, that gets entangled with the system and the pointer in the pointer state basis. This cuts the von Neumann chain \cite{2}, since consciousness gives an Observer the faculty to know his own state. Influenced by London and Bauer’s work, Wigner \cite{3} described a scenario in which an agent needs to ascribe a state to another Observer undertaking a spin measurement. From the point of view of this agent, a “super-Observer”, unitary evolution would bring the Observer to absurd state of ”suspended animation” \cite{3}. Consciousness is therefore assumed to be needed in modifying the linear laws of quantum evolution. Recently, several authors \cite{4}-\cite{7} used an extended Wigner’s Friend scenario to question whether quantum mechanics rules have the necessary internal consistency.

In his Lectures, Feynman laid out the basis rules for evaluating probabilities with the help of probability amplitudes defined for a sum over virtual paths \cite{8}. The approach of \cite{8} is an agreement with Bohr \cite{9} and von Neumann \cite{2} and leaves Observer’s consciousness and sensations outside the theory’s scope. This implies that the usual unitary evolution must be replaced by another type of evolution - state projection or “collapse” - when a measurement takes place. Otherwise the system simply gets entangled with the different components of the pointer, the environment etc., in a growing von Neumann chain \cite{2}.

The purpose of this paper is to review the original Wigner’s Friend problem \cite{3} and, if possible, open up a new perspective on more complex situations, such as those considered in \cite{4}-\cite{7}.

The paper is organised as follows. In Sect. A we revisit standard quantum rules, as described in Feynman’s text book \cite{8}. Section B describes a setup in which a Friend(F) and Wigner (W) make their observations on a simple two-level systems, using their respective probes. In Sects. C to F we discuss possible choices open to F and W. Section G briefly revisits Wigner’s original analysis \cite{3}, and relates it to our own treatment of the problem. Sections H and I contain the conclusions of our review, and discuss some of their general implications.

A. CLASSICAL VS. QUANTUM RULES

Classical mechanics predicts correlations between initial and final positions of the system, $q(t_0)$ and $q(t_1)$, as seen by an Observer \cite{10}. In its Hamilton’s version, one represent the system by a point, tracing a unique path in the phase space, the latter treated as a mathematical abstraction, though reference to the physical world is secured by the equivalent Newtonian space-time formulation \cite{11}. A system property is defined in terms of the phase-space variables and the property value depends on the given path irrespective of whether the property is observed or not. The theory does not need, and hence makes no provision to account for the Observer’s consciousness.

Quantum mechanics also predicts correlations between two or more observations made on a quantum system. Its basic rules were given in \cite{8}, and we briefly review them here in a slightly tailored version (for more detail see \cite{12}). If $L$ quantities $Q^\ell$, $\ell = 1, 2, ..., L$ are measured at different times $t = t_1$, one looks for a probabilities
\[ P(Q_{i_L}^L \leftarrow Q_{i_{L-1}}^{L-1} \cdots \leftarrow Q_{i_1}^1) \] to obtains a series of outcomes \( Q_{i_L}^L \). Each quantity is represented by a Hermitian operator \( \hat{Q}^L = \sum_{i=1}^N |q_{i_L}^L \rangle \langle q_{i_L}^L| \), where \( N \) is dimension of the system’s Hilbert space. A virtual (Feynman) path \( \{ q_{i_L}^L \leftarrow q_{i_{L-1}}^L \leftarrow \cdots \leftarrow q_{i_1}^1 \} \), connecting the eigenstates \( |q_{i_L}^L \rangle \), is endowed with a probability amplitude

\[ A(q_{i_L}^L \leftarrow q_{i_{L-1}}^L \cdots \leftarrow q_{i_1}^1) = \sum_{n_2,n_3,\ldots,n_{L-1}=1}^N \prod_{\ell=2}^{L-1} (q_{n_\ell}^\ell |q_{n_{\ell-1}}^{\ell-1}\rangle |q_{n_{\ell-2}}^{\ell-2}\rangle \cdots |q_{n_1}^1\rangle), \] (2)

where \( \hat{U}(t', t) \) is the system’s evolution operator. Initial measurement (preparation) must define the initial state \( |q_{i_L}^L \rangle \) unambiguously, \( Q_{i_1}^1 \) \( \leftarrow |q_{i_1}^1 \rangle \). An amplitude for the observed sequence (real path) \( Q_{i_L}^L \leftarrow Q_{i_{L-1}}^{L-1} \cdots \leftarrow Q_{i_1}^1 \) is obtained by adding the amplitudes (1) according to the degeneracies of the eigenvalues \( Q_{i_\ell}^\ell \), \( \ell = 1, 2, \ldots, L-1 \) (virtual paths ending in different final states do not interfere [3]). This yields a “sum over paths” type equation

\[ A(q_{i_L}^L \leftarrow q_{i_{L-1}}^L \cdots \leftarrow q_{i_1}^1) = \sum_{n_2,n_3,\ldots,n_{L-1}=1}^N \prod_{\ell=2}^{L-1} \langle q_{n_\ell}^\ell |q_{n_{\ell-1}}^{\ell-1}\rangle |q_{n_{\ell-2}}^{\ell-2}\rangle \cdots |q_{n_1}^1\rangle, \] (3)

where \( \Delta(x-y) = 1 \) if \( x = y \), and 0 otherwise, account for the observed outcomes. The desired probability is found by taking the absolute square of the amplitudes,

\[ P(Q_{i_L}^L \leftarrow Q_{i_{L-1}}^{L-1} \cdots \leftarrow Q_{i_1}^1) = \sum_{n_2,n_3,\ldots,n_{L-1}=1}^N \prod_{\ell=2}^{L-1} \Delta(q_{n_\ell}^\ell \cdots q_{n_1}^1)^2, \] (4)

Note that the eigenstates \( |q_{i_\ell}^\ell \rangle \) are determined by the measurements the Observer is planning to make, and not by the actual state of the evolving system. The probability in Eq. (4) refers to the entire series of the planned observations [3], and does not refer explicitly to the collapse of the wave function.

Unlike the classical theory, quantum mechanics makes only statistical predictions for a real path \( Q_{i_L}^L \leftarrow Q_{i_{L-1}}^{L-1} \cdots \leftarrow Q_{i_1}^1 \). (One exception is the choice \( \hat{Q}^L = \hat{U}(t_{L}, t_{L-1}) \hat{Q}^L \hat{U}^{-1}(t_{L}, t_{L-1}) \), in which case an outcome, corresponding to the eigenvalue \( Q_{i_L}^L \) may be obtained with certainty [13].) Also, adding intermediate observations may destroy the interference between the Feynman paths in Eq. (2), and different choices of measurements lead to essentially different statistical ensembles [13].

Classical mechanics usually makes no claims about living matter [10]. In the original Wigner’s Friend scenario [3], Observer’s consciousness is itself a subject of quantum mechanical description [14]. Making it such a subject, however, is likely to lead to contradictions as we now discuss.

**B. A WIGNER, HIS FRIEND AND A SPIN**

Anticipating on Wigner’s Friend scenario, to be introduced below, let us consider a system consisting of a spin-1/2, and two probes, one for the “Friend” (F), and one for the other observer (W). The probes are two-level systems, which W and F can access directly, while the spin itself remains invisible to the naked eye. As described in the previous Section, their observations amount to measuring projectors

\[ \hat{Q}_{FW} = |1_F, W\rangle \langle 1_F, W| \] (4)

with the eigenvalues \( Q_{FW}^{1_F, W} \) 0 and 1. That is to say that W and F may “obtain outcomes” from their respective probes, and see “yes” \( (Q_{FW}^{1_F, W} = 1) \) or “no” \( (Q_{FW}^{1_F, W} = 0) \) answers.

W and F are free to couple their probes to the spin, and to each other, if desired. The outcome of an initial preparation ascertains that, at \( t = t_0 \), the probes and the spin can be described by a product state

\[ |\Phi_0\rangle = |0W\rangle |0F\rangle |s_0\rangle. \] (5)

We recall that the probabilities in Eq. (4) must refer to the sequences of the outcomes experienced, or registered by the Observers [2]. Thus, one may ask about the odds on F seeing a “yes”, and W seeing his “yes” later. Moreover, F can decide not to register his result. Then, by the strict rules imposed in the previous Section, one may only ask about the likelihood of W seeing a “yes”. The question is whether the rules of Sect. A allow a mere act of “registering a result” on the part of F can alter W’s future experiences.

**C. BOTH F AND W COUPLE THEIR PROBES TO THE SPIN**

For simplicity, we assume that neither the probes, nor the spin have their own dynamics, and remain in the same condition, unless F or W does something to them. Let F briefly (practically instantaneously) couple his probe a \( \tau_F > t_0 \), and then look, or not look, at his result at \( t_1 > \tau_F \). The interaction (e.g., application of a CNOT gate) entangles the spin in an arbitrary given state \( |s\rangle \) with F’s probe according to

\[ |0F\rangle |s\rangle \rightarrow (|s_F^F\rangle |s_F^F\rangle |s_F^F\rangle + |s_F^F\rangle |0F\rangle |s_F^F\rangle). \] (6)

At \( \tau_W > t_1 \) Wigner couples his probe to the spin, using a different spin basis \( |s_1^W\rangle \),

\[ |0W\rangle |s\rangle \rightarrow (|s_W^W\rangle |1W\rangle |s_W^W\rangle + |s_W^W\rangle |0W\rangle |s_W^W\rangle). \] (7)

The experiment is completed when W looks at his probe at \( t = t_2 > \tau_W \).

The probability of W seeing a “yes” outcome (eigenvalue 1, the probe state \( |1W\rangle \)) is \( P(yes^W) \). Would \( P(yes^W) \) depend on whether F actually registered his result, or
just turned on the coupling between his probe and the the spin? In principle it could, since F’s experience belongs to the past and, according to the rule of Sect.A, could destroy interference between virtual paths, leading to W’s outcome \( |i'\rangle \). In practice, it doesn’t since there is no interference to destroy. The situation is sketched in Fig.1. There are only four virtual paths with non-vanishing amplitudes, \( \langle m \rangle \), \( m = 1, 2, 3, 4 \),

\[
A_1 \equiv A(1' \leftarrow 1 \leftarrow \Phi_0) = (1') \langle \bar{U}(\tau^W)|1\rangle \langle 1|\bar{U}(\tau^F)|\Phi_0\rangle \tag{8}
\]
\[
A_2 \equiv A(2' \leftarrow 1 \leftarrow \Phi_0) = (2') \langle \bar{U}(\tau^W)|1\rangle \langle 1|\bar{U}(\tau^F)|\Phi_0\rangle \tag{8}
\]
\[
A_3 \equiv A(3' \leftarrow 2 \leftarrow \Phi_0) = (3') \langle \bar{U}(\tau^W)|2\rangle \langle 2|\bar{U}(\tau^F)|\Phi_0\rangle \tag{8}
\]
\[
A_4 \equiv A(4' \leftarrow 2 \leftarrow \Phi_0) = (4') \langle \bar{U}(\tau^W)|2\rangle \langle 2|\bar{U}(\tau^F)|\Phi_0\rangle \tag{8}
\]

where \( \bar{U}(\tau^W) \) and \( \bar{U}(\tau^F) \) are the evolution operators, corresponding to the evolutions \( (6) \) and \( (7) \) respectively, and we used a shorthand

\[
|1\rangle \equiv |0^W\rangle |1^F\rangle |s_1^F\rangle, \quad |2\rangle \equiv |0^W\rangle |0^F\rangle |s_2^F\rangle, \quad \tag{9}
\]
\[
|1'\rangle \equiv |1^W\rangle |1^F\rangle |s_1^W\rangle, \quad |2'\rangle \equiv |0^W\rangle |1^F\rangle |s_2^W\rangle, \quad \tag{9}
\]
\[
|3'\rangle \equiv |1^W\rangle |0^F\rangle |s_1^W\rangle, \quad |4'\rangle \equiv |0^W\rangle |0^F\rangle |s_2^W\rangle. \quad \tag{9}
\]

The amplitudes in Eq.(8) can be expressed via the amplitudes, defined for the spin, uncoupled to the probes,

\[
A_1 = \langle s_1^W \rangle \langle s_1^F \rangle \langle s_0 \rangle, \quad A_2 = \langle s_2^W \rangle \langle s_1^F \rangle \langle s_0 \rangle, \quad \tag{10}
\]
\[
A_3 = \langle s_1^W \rangle \langle s_2^F \rangle \langle s_0 \rangle, \quad A_4 = \langle s_2^W \rangle \langle s_2^F \rangle \langle s_0 \rangle. \quad \tag{10}
\]

The paths are shown in Fig.1a and, with both F and W looking at their results (see Fig.1b), we have

\[
P(yes^W, yes^F) = |A_1|^2, \quad P(no^W, yes^F) = |A_2|^2 \tag{11}
\]
\[
P(yes^W, no^F) = |A_3|^2, \quad P(no^W, no^F) = |A_4|^2. \tag{11}
\]

To evaluate W’s probabilities in the case F was not registering his outcome, we must add amplitudes of all virtual paths, leading to the same final state \( |i'\rangle \). However, there is only one virtual path connecting \( |\Phi_0\rangle \) with each of the W’s final states, so there is nothing to add. (Note that Fig.1a sketches an uninteresting double-slit problem, where four final positions on the screen, \( |1'\rangle, \ldots, |4'\rangle \), can be reached through one of the slits, \( |1 \rangle \) or \( |2 \rangle \), only.) Therefore, from \( (3) \) we have

\[
P(yes^W, F \text{ not registering}) = |A_1|^2 + |A_2|^2 \tag{12}
\]
\[
P(yes^W, yes^F) + P(yes^W, no^F) = P(yes^W, F \text{ registering}), \quad \tag{12}
\]

It does not matter whether F has registered his result or not, provided the probe was coupled to the spin. This is an expected result, to which we will return to it after considering first another example.

**D. W Measures F’s Probe Instead**

Suppose that at \( t = \tau^W \) Wigner decides to couple his probe not the spin, as before, but to his Friend’s probe instead. For this purpose, he uses a different basis \( (i = 1, 2) \)

\[
|\phi_i^F\rangle = u_{i1}|1^F\rangle + u_{i0}|0^F\rangle, \quad \langle \phi_i^F|\phi_j^F\rangle = \delta_{ij}, \quad \tag{13}
\]

and with F’s probe initially in some \( |\psi^F\rangle \) the coupling produces an entangled state

\[
|0^W\rangle |\psi^F\rangle \rightarrow \langle \phi_i^F|\psi^F\rangle |1^W\rangle |\phi_i^F\rangle + \langle \phi_i^F|\psi^F\rangle |0^W\rangle |\phi_i^F\rangle \tag{14}
\]

The situation is still described by the diagram in Fig.1a, but with only those amplitudes that now

\[
|1'\rangle \equiv |1^W\rangle |\phi_i^F\rangle |s_1^F\rangle, \quad |2'\rangle \equiv |0^W\rangle |\phi_i^F\rangle |s_1^F\rangle, \quad \tag{15}
\]
\[
|3'\rangle \equiv |1^W\rangle |\phi_i^F\rangle |s_2^F\rangle, \quad |4'\rangle \equiv |0^W\rangle |\phi_i^F\rangle |s_2^F\rangle. \tag{15}
\]

The four possible outcomes are still as shown in Fig.1b, the probabilities are given by Eq.(12) and, as before, F’s decision to register or not to register his outcome does not change the statistics of the results experienced by W. Next we discuss the reason for that.

**E. THE “IN PRINCIPLE” PRINCIPLE. VON NEUMANN CHAINS**

In his lectures [2] Feynman stressed that scenarios which can be distinguished in principle cannot interfere. Thus, it should not matter whether a conscious Observer has actually experienced a particular outcome, as long as any Observer could experience it, perhaps at a later time.

In the example of Sect. C, F’s observation finds the spin in one of its states \( |s_i^F\rangle \). The spin’s condition changes when W applies his coupling. However, W’s manipulation does not affect F’s probe, which continues to carry the record of spin’s condition, as it was just after \( t_1 \).
Wigner’s Friend may decide to observe his probe later, or not to register his result at all (see Sect. 2-2 of [3]), and this is enough to preclude interference. With F’s machine switched off, the paths \( \{1W0F_s1W \leftarrow 0W0F_s1F \to 0F_{\Phi_0}\} \) and \( \{1W0F_s1W \leftarrow 0W0F_s2F \to 0F_{\Phi_0}\} \) would interfere, but with the machine on, the paths \( \{1W0F_s1W \leftarrow 0W1F_s1F \to 0F_{\Phi_0}\} \) and \( \{1W0F_s1W \leftarrow 0W0F_s2F \to 0F_{\Phi_0}\} \) lead to different final states, and become exclusive alternatives [3].

Similarly in Sect.D W destroys the state of F’s probe, but leaves alone the spin itself. Therefore, F can repeat his measurement using a different probe at a \( t_1 > t_2 \), and obtain the same result he would have seen if he had bothered to look at some \( t_1 < t_2 \). This information is now encoded in the spin’s, rather than in the probe’s condition.

In practice, Friend’s states \( |1F\rangle \) and \( |0F\rangle \) (and similarly \( |1W\rangle \) and \( |0W\rangle \)) may describe not a single degree of freedom, but a sequence of \( K \) objects and devices, starting with a simple pointer, coupled to the spin, passing through an amplifier to Friend’s retina and neurons, and ending at the elusive boundary, where information about physical world enters the Observer’s “extra observational inner life” [2]. With all elements of the chain in agreement, we can write

\[
|0^F\rangle = \prod_{k=1}^{K} |0_k^F\rangle, \quad |0^F\rangle|s_1^F\rangle = \prod_{k=1}^{K} |0_k^F\rangle|s_1^F\rangle.
\]

and then group the terms in an arbitrary manner. For example it is possible to redefine \( |0^F\rangle \to \prod_{k=n}^{K} |0_k^F\rangle \) and \( |s_1^F\rangle \to \prod_{k=1}^{m} |0_k^F\rangle|s_1^F\rangle \), or even \( |0^F\rangle \to \prod_{k=m}^{K} |0_k^F\rangle \) and \( |s_1^F\rangle \to \prod_{k=1}^{m} |0_k^F\rangle \). Wigner is free to couple his probe to the newly defined \( |0^F\rangle \) or \( |s_1^F\rangle \) as before, and with the same result. For as long as a single \( |0_k^F\rangle \) or \( |s_1^F\rangle \) remains to carry the evidence of what F would have seen at \( t = t_1 \), actually seeing it has no effect on W’s experience. We haven’t however yet discussed the original Wigner’s argument, and will do it next.

**F. THE WIGNER’S FRIEND PROBLEM**

In a nutshell, the problem discussed in [3] concerns the case where W decides to engage the entire composite F’s probe + spin, so that no material record of what happened at \( t_1 \) is carried forward for future reference. In order to do so he may couple his probe at \( t = \tau W \) thus entangling it with a composite’s state \( |\varphi\rangle \)

\[
|0^W\rangle|\varphi\rangle \to (1^{FS}|\varphi\rangle|1^W\rangle|1^{FS}\rangle + \sum_{i=2}^{4} |i^{FS}|\varphi\rangle|0^W\rangle|i^{FS}\rangle,
\]

using, for example,

\[
|1^{FS}\rangle = \frac{|1^F\rangle|s_1^F\rangle + |0^F\rangle|s_2^F\rangle}{\sqrt{2}}, \quad |2^{FS}\rangle = \frac{|1^F\rangle|s_1^F\rangle - |0^F\rangle|s_2^F\rangle}{\sqrt{2}}.
\]

(Two remaining orthogonal basis states, \( |3^{FS}\rangle \) and \( |4^{FS}\rangle \), are not connected by the evolution operators in [1], and need not be specified.) Two possible final states of the composite W’s probe + F’s probe + spin, therefore, are

\[
|1'\rangle = |1^W\rangle|1^{FS}\rangle, \quad |2'\rangle = |0^W\rangle|2^{FS}\rangle.
\]

Now the four virtual paths, shown in Fig. 2a, correspond to a primitive double-slit problem with only two final positions, \( |1'\rangle \) and \( |2'\rangle \), each of which is accessible via both “slits” [1] and [2]. The corresponding amplitudes are given by

\[
A_1 = \langle 1'|U(\tau W)|1\rangle \langle 1|U(\tau F)|\Phi_0\rangle, \quad
A_2 = \langle 1'|U(\tau W)|2\rangle \langle 2|U(\tau F)|\Phi_0\rangle, \quad
A_3 = \langle 2'|U(\tau W)|1\rangle \langle 1|U(\tau F)|\Phi_0\rangle, \quad
A_4 = \langle 2'|U(\tau W)|2\rangle \langle 2|U(\tau F)|\Phi_0\rangle.
\]

Both interactions [6] and [17] are now in place. The question is whether F registering his outcome at \( t = t_1 \) would change the odds on W obtaining his “yes” outcome at \( t = t_2 \). Our rules of Sect.A say that it would. Indeed, with F registering, there are four real observable outcomes shown in Fig.2b, and

\[
P(yes^W|\text{F registering}) = |A_1|^2 + |A_2|^2 = |\text{P(yes}^W, \text{yes}^F) + |\text{P(yes}^W, \text{no}^F)|^2
\]

while with F not registering, we have a different result

\[
P(yes^W|\text{F not registering}) = |A_1 + A_2|^2 = |\text{P(yes}^W|\text{F registering}) + \text{Re}[A_1^* A_2]|^2
\]

This is the result we want to examine, but first we briefly revisit Wigner’s own argument.
G. WIGNER’S TREATMENT OF THE PROBLEM

Wigner’s formulation of the dilemma was slightly different. He asked (in our notations) whether just after $F$ registered his result at $t = t_1 + 0$, $W$ should ascribe to the composite $F$’s probe + spin a pure state
\[ |\phi\rangle = (s^F_1|s_0\rangle|1^F\rangle)|s^F_1\rangle + (s^F_2|s_0\rangle|0^F\rangle)|s^F_2\rangle, \] (23)
or a statistical mixture
\[ \hat{\rho} = |1^F\rangle|1^F\rangle^\dagger + |0^F\rangle|0^F\rangle^\dagger. \] (24)

This is not the language we used in Sect. A. Feynman’s rule does not refer directly to the state of the system at a given time, or to the “collapse of the wave function” following an observation.

Translated into the language of the previous Section, Wigner’s choice is between considering the paths \{1\} and \{2\} (as well as \{3\} and \{4\}) in Fig. 2a as interfering or as exclusive alternatives. Indeed, if \{2\} is true, the probability of $W$ seeing a “yes” is given by
\[ P(\text{yes}^W) = \text{tr} [\hat{\rho} |1^F\rangle|1^F\rangle^\dagger] = |A_1|^2 + |A_2|^2. \] (25)

If, on the other hand, \{24\} holds, the same probability should be
\[ P(\text{yes}^W) \equiv |\langle 1'|\phi\rangle|^2 = |A_1 + A_2|^2. \] (26)

Feynman’s prescription, however, is clear. With both $F$ and $W$ looking, interference must be destroyed, and Eq. \{24\}, rather than Eq. \{23\}, must be used. As far as we know, while discussing distinguishable scenarios \[8\], Feynman never specified how they can be distinguished and by who.

Wigner, for his part, brought this question to the fore, and made three points. Firstly, a superposition \{23\} is allowed for inanimate objects (including macroscopic ones), but ought to be considered absurd if applied to a conscious $F$, thereby forced to remain in a state of “suspended animation” until $W$ asks him what he saw.

Secondly, and because of that, $F$’s consciousness should act onto material objects, so that the wave function of $F$’s probe + spin is turned into a statistical mixture.

Thirdly, in practice, telling the difference between a pure state and a mixture can be extremely difficult for sufficiently complex systems, such as $F$ and his macroscopic probe (laboratory).

Now much depends on how $F$’s consciousness and quantum theory are interrelated. According to London and Bauer \[1\], $F$’s consciousness should be described by a quantum state, which we could include in the Friend’s states denoted $|0^F\rangle$ or $|1^F\rangle$ in Eq. \{17\}. This would have to destroy the superposition \{17\} because, by introspection, consciousness knows that a single outcome has been observed. But standard linear quantum mechanics lacks the means for doing so. In \[3\] Wigner provides the necessary means postulating a non-linear evolution whenever human consciousness is involved. Indeed, if standard linear QM were to be applied, the composite $F$ consciousness + $F$’s probe would be in a superposition that Wigner asserts “is not credible” \[15\]. Next we turn to Ref. \[8\] for more insight.

H. FEYNMAN’S RULES AND MATERIAL RECORDS

In our attempt to follow the approach of \[8\] and Sect. A, we would need to observe at least the following four restrictions.

(i) The probabilities in Eq. \{3\} refer to the impressions, registered by conscious Observers, (see also \[2\]).

(ii) Quantum theory, has nothing to say about consciousness itself, or about its interaction with material (i.e., inanimate) world.

(iii) Quantum theory, [i.e., Eqs. \{1\}-\{3\}], applies to all material objects, regardless of their size and complexity.

(iv) (Uncertainty Principle) In the Young’s double-slit experiment it is impossible to know which slit was chosen by a particle, while maintaining the interference pattern on the screen \[8\].

The second assumption appears to be the most vulnerable, and we are forced at least to speculate about some properties of Observer’s consciousness and the existence of material records.

We begin with a contradiction. If a record of a registered outcome is kept inside $F$’s “inner world” (which we can say nothing about), and $W$ manages to entangle with his probe all objects holding the material records [but not $F$’s consciousness (see ii)], we contradict the Uncertainty Principle (iv). Indeed, $W$ detects the presence of the interference term in Eq. \{21\}, and yet $F$ knows that the system has passed through the “slit”, represented by, say, \{1\} in Fig. 2a.

An attempt to remedy this by including $F$’s inner world into a quantum mechanical calculation, as suggested by London and Bauer \[1\] returns us to the unsavoury notion of the “state of suspended animation” \[3\], experienced by $F$ prior to $W$’s query.

A possible way out requires making certain minimal assumptions about the existence of material records. The rules of Sect. A readily account for the discrepancies between probabilities in Eqs. \{21\} and \{22\}, if each act in which an Observer registers his/her result is accompanied by producing a record in the memory, or indeed on any other material object. Adding the record’s degree(s) of freedom would change the size of a Hilbert space and create new virtual and real paths. Thus, two calculations of Sect. F, one for $F$ registering his result, and the other for $F$ not doing so, would naturally be different.

Now by (iii) we must assume that the record left in $F$’s memory or elsewhere is, in principle, accessible to $W$’s manipulations. There is, however, no contradiction. If all material records could be erased by $W$’s subsequent measurement, previous $F$’s experience would not count -it could be undone and would never be confirmed- and
W’s probabilities would be given by Eq. (22). If W’s measurement misses at least one material record left in F’s memory or in his laboratory, the presence of the corresponding orthogonal states will guarantee that Eq. (3) will yield the probabilities \(\text{[21]}\). Subsequent observations on the part of F cannot change this result, since the rules \(\text{[2]}\) and \(\text{[3]}\) are explicitly causal, and forbid the influence of future measurements on the results already obtained (see, for example, \[12\]). In effect, we are able to leave aside the very act of registering, and concentrate on its physical consequences. Quantum mechanics only briefly loose the narrative while the perceived outcome is being passed to the Observer’s memory, but quickly recovers it after a tangible material evidence is provided.

Finally, it is worth recalling, that quantum theory can be used (and is most often used) by a third person, say, W’s cousin (C), who is reasoning about the joint experiences of F and W, and is not taking part in the actual experiments herself. Her conclusion must be that the odds on W seeing a “yes” outcome are given by Eq. (21) if his measurement preserves some form of F’s record, and by Eq. (22) if W completely destroys it. Personalities do not matter, and in C’s mind particular F and W can be replaced by any pair of two human Observers, which may or may not communicate with each other during the course of the experiment.

I. DISCUSSION AND CONCLUSIONS

Quantum theory is ”invented” (in the words of Wigner \[3\]) by human consciousness for dealing with material physical phenomena and, from the start, we do not expect it to be a suitable judge of the consciousness itself \([16]\). For this to be true one needs to show that the theory remains internally consistent, if restricted to physical phenomena only. This idea arises already in classical physics \([10]\), and is exacerbated in the quantum case, where the theory predicts essentially different statistical ensembles, with and without the presence of an intermediate Observers. Wigner’s radical answer to this conundrum \[3\] was to bring the Observer’s consciousness into the theory’s remit in another way, by modifying the standard (linear) quantum mechanical evolution. One may reasonably wonder whether the problem can be treated without such a dramatic departure from conventional quantum theory.

With this in mind, we have argued that Feynman’s rules, as given in \[8\], allow one to leave conscious Observers outside the theory’s scope, on a condition that all information about the outcomes of the observations made be contained in material records, themselves subject to a quantum analysis. Certain, albeit minimal, assumptions about the Observer’s behaviour are, therefore, necessary. In particular, whenever asked about the outcome of an experiment, the Observer would need to consult the relevant record, and cannot simply be ”aware of it” at all times. Such a record can be kept as a note on a piece of paper, a file on a microchip, or in the Observer’s own memory.

The rules of Sect. A automatically account for the existence of such a record, by including the corresponding degree of freedom into a quantum mechanical calculation. Virtual paths, previously leading to the same final state, are thus modified to lead to distinguishable outcomes. This is sufficient for destroying the interference present if a Hilbert space of a smaller dimension is used, as happens, for example, in Fig.1. A record can be destroyed, e.g., by subsequent measurements, as happens in Fig.2. Although some records, e.g., macroscopic ones may be more robust, all information can be destroyed in this manner in principle, if not in practice. With all records destroyed, one must conclude that the information about the outcome of a particular experiment is irretrievably lost, in a stronger sense than in the classical case. It was argued by Feynman and Hibbs \[17\], by design a measurement apparatus yields a stable record in situations in which, through the statistical mechanics of amplification, the amplitudes play no more role. In \[8\] Feynman argues also that even if a photon, scattered each time an electron passes through the first slit of the Young’s experiment, is never observed, the interference pattern will be destroyed. In both cases we deal with records robust in the sense that in practice they will never be engaged by the participants of the experiment, which one would take into account while evaluating the probabilities of the outcomes.

Finally, allowing the Observer to keep information about his/her perceived outcomes in a domain beyond the reach of quantum theory would lead to a conflict with the Uncertainty Principle. Indeed, in Fig.2 the Principle demands that the outcome of F’s measurement remain indeterminate, since the paths \{1\} and \{3\} (\{2\} and \{4\}) interfere. Friend’s awareness of his result would, in this case, amount to knowing the slit, chosen by an electron in the Young’s double-slit experiment and maintaining the interference pattern on the screen. Given the Principle’s crucial role in ”protecting” quantum mechanics from a logical collapse, \[8\], avoiding such conflict should be a necessary requirement for any analysis of the Wigner’s Friend problem.

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