On the Origin of Space
Part 15: Composite Quantum Systems – Understanding the Many-Realities Idea

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Abstract

A clarification of Everett's interpretation of quantum theory is provided here to enable the extension of the theory to composite quantum systems. Such systems have been envisioned in the past but no theory of their evolution was developed as it was thought that they could only be a view of the mind with no practical way to effect them. It is shown here that, if we could physically build composite quantum systems, for example as computational devices, their capabilities would be more diversified than the probabilistic quantum computers presently addressed, as the present theory only envisions interfering realities in the evolution of the system, while the devices considered here would be able to use non-interfering realities as well.

Introduction

Deutsch (1985) provided an analysis of the physical reality underlying Turing machines, and defined a "quantum generalization" of such machines that he predicted could be more efficient than classical computers. He stated that the most intuitive explanation for the abilities of quantum computers would require Everett's interpretation of quantum theory (Everett, 1957). This interpretation was in answer to the quantum theory foundational question in Einstein et al. (1935). (This question was designed to show that quantum theory, as developed since the 1920's, was in fact an incomplete theory for fully representing the physical world by using a statistical approach instead of a deterministic one.) Everett's interpretation was presented under the name of "many-worlds" by DeWitt (1970a, 1970b).

Deutsch also identified a limitation of quantum computers for processing information *in parallel*. In order to prove this fact he utilized the present quantum theory viewpoint of a "measurement;" that is, he applied a program ζ which makes a "perfect measurement" of the state of the computer from a "macroscopic" level of observation. Seen from Everett's viewpoint, as I shall discuss below, Deutsch then tried to obtain a computation output directly from a quantum subsystem that simultaneously exists in several realities. As a classical observer of the system he could interact with only one of the states from all the possible ones, and thus could obtain only one of the values of his parallelizable function *G(f)* at a time. Therefore he had no choice but to rerun the computation in the hope next time another possible (different) reality would be observed. On the strength of this demonstration Deutsch advanced that quantum theory is "a theory of parallel interfering universes."

However, the limitation he identified is *only based upon the limitations of the present quantum theory formalism, not inherent limitations of the physical system*. While he took the viewpoint of a *classical* observer as the current quantum theory formalism requires, he could have taken the alternate approach by Everett where the "observer" is instead a *quantum* system interacting with an "object system," thereby defining a *composite quantum system* with it. Such a system may be able to perform a computation also, but Deutsch did not consider it, as no known formalism is available for it in the present quantum theory.

I am going to show that Everett's interpretation identifies the quantum to be in fact more than a set of "interfering universes," and Deutsch's conclusion was rather pointing to the well-known fundamental incompleteness of quantum theory about composite quantum systems (D'Espagnat, 1989). Everett's interpretation then gives, if not a formalism, at least a qualitative *understanding* of such systems evolution when they are restricted to "observer" and "object" subsystems, an understanding *which is not part of the limited view allowed by the present quantum* *formalism*. Such "simple" arrangements of observer and object subsystems could be in turn used as a base for much more complex composite systems.

A clarification

According to Everett's interpretation of quantum mechanics, there is physically no such thing as a "collapse of the (Schroedinger) wave function" as formally defined by von Neumann (1932). "Observations" in the physical world are merely a subset of physical interactions between subsystems of a *coherent* composite quantum system, *the Universe*. Everett did not know about the process of decoherence discovered in the 1990s (Zurek, 1991), which reduces all the quantum realities to a single one. Yet his interpretation is still applicable to ***a composite quantum system that remains coherent throughout its evolution***. The Universe is just not such a system.

"Observers" are then quantum subsystems part of a *composite system* in which their "states," as defined through the Schroedinger equation, are relative to, and *locally and physically interact* with an "object" subsystem states. Everett's interpretation sees a *deterministic* physical world, being a composite quantum system that realizes fully all the possibilities available when choices are to be made within an evolving system, and these realizations occur in as many "universe branches" (or quantum system realities), *some interfering and some not*, as there are choices.

This picture of "states" has been used by statistical quantum mechanics for composite systems. Unfortunately, the corresponding formalism cannot apply for composite systems with internal fixed ways to "self-observe" as Everett in effect describes. Indeed Everett's viewpoint may be seen as describing a *coherent composite quantum system in which the parts interact ("observe each other") discretely (discontinuously) via quanta exchanges*.

Using the Schroedinger equation formalism (next section will discuss the validity of such a choice) for these parts or subsystems *taken as wholes*, Everett then proceeded to demonstrate the following propositions (certain words have been underlined here for their importance):

> "A 'good' observation [... is such that (1)] the [object-] system state, if it is an eigenstate, shall be unchanged, and (2) that the observer state shall change so as to describe an observer that is 'aware' of which eigenfunction it is." [Quote A]
>
> "With each succeeding observation (or interaction), the observer state 'branches' into a number of different states. Each branch represents a different outcome of the measurement and the *corresponding* eigenstate for the object-system state. All branches exist simultaneously in the superposition after any given sequence of observations." [Quote B]

The following will be inferred from the above propositions and Everett's related analysis contained in his referenced paper (a later section will give a formal backup):

1. Everett's definition of "observers" includes the case when the interaction does not result in a choice of outcome for the object system state, and the observer state may change, but a new reality is not generated (since then only one outcome is possible from the interaction, a direct negative formulation of Everett's Quote A above, when qualified by Quote B).
2. In other words, a given observation by an observer will split the original reality into a new set of realities for the observer *only* when it can have *different* possible outcomes (as a direct negative formulation of Quote B).
3. The realities of the composite quantum system that correspond to the states of the object subsystem *expand upon interaction to include the observing quantum subsystem* (per Quote B above, "the observer state branches," *nothing else*; also an obvious meaning from the superposition equations in the original paper by Everett).

Another key proposition from Everett is as follows:

> "Any observation of a quantity B between two successive observations of quantity A (all on the same object-system [<u>and not commuting with B</u>]) will <u>destroy the one-to-one correspondence</u> between the earlier and later <u>memory states</u> [of the observer] for the result of A." [Quote C]

The inferences here are:

1. Two successive observations of, or interactions with *commuting* (or identical) quantities will keep the one-to-one correspondence between the observations/ interactions while the observer subsystems branch in separate realities per the earlier quotes (as the negative formulation of Quote C above).
2. The realities created through observing commuting quantities can *merge back* through a later observation, resulting in the phenomenon of "interference" by subsequently observing the object-system in the merged reality (as a consequence of the realities one-to-one correspondence maintained during the evolution of the system from Quote C and the inference above).
3. When created from observations of *non-commuting* quantities the composite quantum system realities never "come back together" (from the word "destroy" in Quote C). Quote C then describes the origin of *irreversibility* for the evolution of the system, i. e. its "arrow of time."
4. Since observations are but a subset of physical interactions, the two kinds of reality branching effected by observers in a composite quantum system

as described in inferences 2 and 3 above can occur within such a system without the "macroscopic" (decohered) observations considered in the usual quantum theory.

Quote C permits one to infer Heisenberg's uncertainty principle (Heisenberg, 1930) as Everett's paper did. This axiom of conventional quantum theory could be seen in turn as reflecting the necessity for non-interfering realities within a composite quantum system, as identified in inference 3 above.

Finally, I will infer from Everett's views (the "observer that is 'aware' of" part in Quote A) that

- The quantum subsystems within a composite system *perceive* their own evolution within a given reality branching path as a continuous evolutionary process, while they remain "unaware" of the other realities, except (1) in the event "interfering" realities merge back, which then allows what quantum theory considers an "interference," i. e. a complex number sum of the hitherto separate realities, or (2) through an observation, one at a time, of a "non-interfering" reality from another reality.

This last inference is inspired in part from comments by Bohm (Bohm and Hiley, 1993, Ch. 13). It is referred to as the "branch communication inference" in a later section, where it receives its support.

DeWitt's interpretation

DeWitt (1970) interpreted Everett's approach as seeing a clone for each term of the superposition of states in a Schroedinger equation results, regardless whether an interaction was involved or not with the agent affecting the state of the object considered. For example, in the Schroedinger Cat set-up (Schroedinger, 1935), per DeWitt, the cat would be cloned in two realities, one in which it would live and one where it would die depending on the state of the poison vial. (This is the picture brought out by Schroedinger himself in the referenced paper.) In the understanding described earlier, the cat and the vial are two subsystems of a composite quantum system, and the cat can only "get into" the reality where the deadly poison is released, as the cat physically interacts with it then. There is not another parallel reality where it lives, as there would not be any interaction of the cat with the state of the vial then (*no "measurement" of its state*). If the cat is found alive, it is because there were no realities where the vial observed an alpha particle from the atomic nucleus; not that alphas were not emitted in all realities of nuclear evolution, but in all cases the vial missed the observation. DeWitt simply failed to identify the concept of *composite quantum systems* in Everett's approach, and takes cat, vial and nucleus as one system. The universe is not one whole system, it is a composite quantum system with internal *discontinuous* physical interactions between its subsystems.

DeWitt's understanding has received an extensive review along the years (e.g. D'Espagnat, 1989; Bohm and Hiley, 1993; Penrose, 1994), that has pointed out the inability of that understanding to explain certain experiments as a result of its lack of definition relating to the physical behavior of the postulated universe branches. The analysis below confirms DeWitt's understanding as inappropriate.

Feynman's postulates and Many-Worlds (many-realities)

Everett's interpretation took as its starting point the Schroedinger equation for the system under study (which was referred as "process 2" in Everett's 1957 paper). However, as we have seen earlier, such a differential equation cannot be postulated in general for *subsystems* of composite systems. Since in the many-realities view observers are considered part of the quantum system under study, it assumes a composite system, and relying entirely on the Schroedinger equation to describe the evolution of observers as such subsystems would therefore be *mathematically inconsistent* (see below for more on this). I need to start from a postulate inherently valid for composite systems, which contains the Schroedinger equation as a particular case. Feynman's space-time path integral approach permits such a generalized formulation (Feynman, 1948; Feynman and Hibbs, 1965). It will allow me to deduce the main principles of the many-realities approach and to mathematically support the inferences presented in the earlier section. The discussion will be limited to such principles, and to those inferences that are not obvious.

1. Feynman's postulates

The definition of the *action* of a mechanical system between times t_a and t_b is given as:

$$S = \int_{t_a}^{t_b} L(q, \dot{q}, t)dt \tag{1}$$

where L is the system Lagrangian and q is a set of *generalized variables* (Menzel, 1953, Part II, Sect. 39).

A space-time path $q(t)$ is then mathematically defined as a *measure* over the compact $[t_a, t_b]$, physically meaning a trajectory of the system going from point a at time t_a to point b at time t_b within the *generalized configuration space* of the variables q. Equ. (1) could be interpreted as an action over the path $q(t)$ between a and b, $S[b, a] = S[q(t)]$, since L does not depend on derivatives higher than the velocity.

Each path is then postulated by Feynman as having a *probability amplitude*

$$\Phi\,[q(t)] = Constant\ .\ exp(\frac{i}{\hbar} S\,[q(t)]) \tag{2}$$

with $\Phi[q(t)]$ and $S[q(t)]$ understood as *functionals* (Schwartz, 1966, Ch. I, §1) of the measure $q(t)$.

Feynman further postulated that *all* paths from point a to point b contribute to (i.e. "interfere" to give) a *total probability amplitude*, through an integral over the paths:

$$K(b, a) = \int_a^b exp \left(\frac{i}{\hbar} S[q(t)] \right) \mathcal{D}q(t) \tag{3}$$

This *complex number* $K(b, a)$, called a "kernel" in integral equations theory (Byron and Fuller, 1992, Vol. 2), is in Physics a "*propagator*" for the system (Cohen-Tannoudji *et al.*, 1977, Vol. 1, Sect. J_{III}). It represents the system probability amplitude at point b when it is known at point a.

A *wave function* is separately defined by Feynman as

$$\psi(q_2, t_2) = \int_{-\infty}^{+\infty} K(q_2, t_2; q_1, t_1)\psi(q_1, t_1)dq_1 \tag{4}$$

where *the total probability amplitude to arrive at a particular place is independent of the path followed to reach it*. This definition however presupposes that

$$S[b, a] = S[b, c] + S[c, a] \tag{5}$$

as this *allows separating the future from the past* and obtain a differential equation for the path integral where ψ is a solution independent of the past history of the system.

2. Composite systems postulate

Now I postulate a system made out of two parts, one I shall call the "system" and the other the "observer," which could be a "measuring instrument," and with interactions present only at specific moments in the evolution of the total system. I shall call this postulate the *postulate of complexity,* as an analog to DeWitt's postulate (DeWitt, 1970a, 1970b) where "the universe is sufficiently complex so it can be divided into systems and apparatuses." The Lagrangian will be then the sum of three components L_S, L_M , and L_{int} , L_{int} being the interaction Lagrangian between the two parts. The propagator for such a system can be expressed as

$$K(b, a) = \int_a^b \int_a^b exp \frac{i}{\hbar}(S_S[q_s(t)] + S_M[q_M(t)] + S_{int}) \mathcal{D}q_S(t) \mathcal{D}q_M(t) \tag{6}$$

Here relation (5) does not hold for each subsystem as I cannot separate the future from the past throughout its evolution. I will say that they are *non-separable*. *They cannot have a wave function defined*, or have one which remains valid across their entire evolution (see Feynman's discussion). So the wave function concept cannot be used in a composite system formalism throughout its evolution, only the propagator can be. This is where Feynman's approach is more general than Schroedinger's.

Now, from Equ. (6), I identify separately the integral over the paths available for system M (the observer):

$$K(b,a) = \int_a^b exp\,(\frac{i}{\hbar} S_S)\; T[q_S(t), q_M(t)] \quad \mathcal{D} q_S(t) \tag{7}$$

with

$$T[q_S(t), q_M(t)] = \int_a^b exp\{\frac{i}{\hbar}\int_{t_a}^{t_b} (L_M + L_{int})dt\} \quad \mathcal{D} q_M(t) \tag{8}$$

The total amplitude of system M is thus the sum of the amplitudes over all the paths it follows corresponding to a given path of system S (the observed system).

Since the total amplitude given by Equ. (7) is an integral over *definite* paths, the probability amplitude meaning as given by Feynman can readily be replaced with an equivalent *deterministic* meaning under which *each path is in fact taken by the system*, branching at *a* in as many realities of its initial reality, following then a specific path between *a* and *b*, with ultimately all the realities merging ("interfering") back at point *b* such that there is a *definite phase* for the system at *b* represented by $K(b, a)$. With this reinterpretation, Feynman's postulate on "interference" between all possible paths matches the many-realities viewpoint [This supports Quote C, inference 2 of the earlier section].

So Equ. (8) then represents *an observer system for each of the observed system paths*. The action of the interaction S_{int} can only be associated with system M because it is an observation of system S by M. Mathematically, the measure $q_M(t)$ of the interaction is associated with the system M path integral, not with the system S integral.

3. A composite system analysis set-up

To be able to represent an observer/observed system relationship while complying with the postulate of complexity, I must assume that *the observer does not continuously observe the system*, as a continuous observation makes the subsystems unseparable, and thus can only evolve together, so the observer would not see ever a change in the observed system. L_{int} needs to reflect this physical situation. To pursue the analysis in details I will assume (1) a sequence of observations at times α, β, γ, τ, (2) the observations occur on different variables of system S such that

$$L_{\text{int}} = f[q_{S_1}(t)]\delta(t-\alpha) + f[q_{S_2}(t)]\delta(t-\beta) + f[q_{S_1}(t)]\delta(t-\tau)) + g[p_{S_1}(t)]\delta(t-\gamma) \tag{9}$$

with $\alpha<\beta<\gamma<\tau$, and (3) system S has 4 variables $q_{S_1}, q_{S_2}, p_{S_1}, p_{S_2}$, with the *q*'s and *p*'s being conjugated variables, i.e. satisfying the commutation relations

$$[p_i\,,\,p_j\,] = 0 \qquad [q_i\,,\,q_j\,] = 0 \qquad [p_i\,,\,q_j] = i\hbar\delta_{ij} \tag{10}$$

The observations are thus represented by δ measures (measures of mass 1 concentrated at one point, i.e. "Dirac functions" - Schwartz, 1966) with α, β, τ observations being done on variables q while γ is done on variables p. Such a representation is justified as interactions between subsystems may be *discontinuous* in time, e. g. when the subsystems are spatially localized and when interactions occur via exchange of quanta at specific moments of the subsystems evolutions. A certain non-zero amount of action then corresponds to that instantaneous exchange.

I will use the rule described by Feynman stating that "amplitudes for events occurring in succession in time multiply." It is expressed by:

$$K(b, a) = \int_{q_d} \int_{q_c} K(b, d)K(d, c)K(c, a)dq_d dq_c \tag{11}$$

where the paths go from a to c, then to d and finally to b in time. To simplify the notation I will replace the integral signs by sums and separate the variables:

$$K(b, a) = \sum_c K_c(c, a) \sum_d K_d(d, c) K_d(b, d) \tag{12}$$

4. Observation α

Before observation α the two subsystems are evolving separately, and therefore each have a defined Schroedinger equation to represent their evolutions. Upon observation α, expressions (8) and (9) give:

$$T_{\alpha_i}[q_M(t)] = \int_a^b exp\,\frac{i}{\hbar}(S_M + S_{int}).\,exp(\frac{i}{\hbar}\,f[q^i_{S_1}(\alpha)]) \quad \mathcal{D}q_M(t) \tag{13}$$

Functional T then is replaced by a set of functionals, one for each path the system S was following at time α. Equ. (7) in the notation (12) gives for the overall system:

$$K(b, a) = \sum_i K_i(\alpha, a) \int_\alpha^b exp(\frac{i}{\hbar} S_{S_{\alpha_i}}) \quad T_{\alpha_i}[q_M(t)] \quad \mathcal{D}q_S(t) \tag{14}$$

$S_{S_{\alpha_i}}$ in the above formula is the action of a path $q_i(t)$ of system S as observed at time α by system M. The overall system evolution will be represented by :

$$K(b, a) = \sum_i K_i(\alpha, a) K_i(b, \alpha) \tag{15}$$

with, from Equ. (14):

$$K_i(b, \alpha) = \int_\alpha^b exp(\frac{i}{\hbar} S_{S_{\alpha_i}}) \quad T_{\alpha_i}[q_M(t)] \quad \mathcal{D}q_S(t) \tag{16}$$

After observation α a separate Schroedinger evolution occurs (no interaction between subsystems) corresponding to each of the functionals of expression (13) spawned by the observation [supporting Quote B in the earlier section identifying separate evolution branches]. The wave function of the system for each functional i is:

$$\psi_i(q,t) = \int_{-\infty}^{+\infty} K(q,t\ ;q_{\alpha_i},\alpha)\psi(q_{\alpha_i},\alpha)dq_{\alpha_i} \tag{17}$$

Within a given complete set of orthogonal solutions φ_k of the Schroedinger equation corresponding to the integral equation above, the *complex sum of paths* among all the paths that can be observed (within a specific history) having a given eigenstate is fixed [supporting the superposition principle of quantum theory and the probabilistic meaning of the coefficients therein]. For each of the φ_k of the observed system there will be then an observer system evolution. The original observer system will be then in multiple realities, one for each subset i of paths as described above existing at time α. Each *observer system reality* then follows its own evolution according to the functional T in expression (16) in "parallel" with the corresponding *observed system paths* [This supports Quote B and its inference 3 in the earlier section. Quote A is supported by expressions (13) and (16) where the path observed is *recorded* by the observer system reality in the corresponding propagator expression segment]. I shall also note that a propagator segment (16) may very well have a zero value, thus the corresponding subset of paths has no corresponding observer system reality. (There is no such thing as a "non-observer" as DeWitt envisioned in the previous section.)

5. Observation β

Now I reach the time β for the second observation, which is done on another q_S variable. According to Equ. (13):

$$T_{\alpha_i\beta_j}[q_M(t)] = \int_a^b exp\,\frac{i}{\hbar}(S_M + S_{int}).\,exp(\frac{i}{\hbar}\,f[q^i_{S_1}(\alpha)]).\,exp(\frac{i}{\hbar}\,f[q^j_{S_2}(\beta)])\,\mathcal{D}q_M(t) \tag{18}$$

Equ. (14) becomes:

$$K(b,a) = \sum_i K_i(\alpha,a)\int_\alpha^\beta \exp(\frac{i}{\hbar}S_{S_{\alpha_i}})T_{\alpha_i}[q_M(t)]\mathcal{D}q_S(t)\sum_j \int_\beta^b \exp(\frac{i}{\hbar}S_{S_{\beta_j}})T_{\beta_j}[q_M(t)]\mathcal{D}q_S(t) \tag{19}$$

or, in my notation:

$$K(b,a) = \sum_i K_i(\alpha,a)\sum_j K_i(\beta,\alpha)K_j(b,\beta) \tag{20}$$

The new variable being independent from the previous, each observer system reality has branched into j observer realities (represented by the various components of the sum in Equ. (20)). Within a given history ij (one of the terms of $K(b,a)$), each observer reality i becomes one of the j observer realities, thus perceiving an apparent random sequence of definite values for the variables q_S. [This supports Everett's relation of Many-Worlds determinism to conventional quantum theory non-determinism.]

I could have put Equ. (20) as

$$K(b,\,a) \;=\; \sum_i \sum_j K_i(\alpha,\,a)K_i(\beta,\,\alpha)K_j(b,\,\beta) \tag{21}$$

Since the individual propagator segments *add up,* the various reality branches of the system then continue to "interfere" [This supports Quote C and its inferences 1 and 2]. Each term of the sum contains data from the previous evolution segment, thus the "memory" on which branch it went through is maintained [This supports the branch communication inference of the earlier section]. Since variations on the paths observed at α and β commute (are exchangeable) per relations (10) the evolution of each propagator branching across its two segments is reversible in time [This supports in part Quote C].

If the observation β is done on the same variable as in observation α, the same eigenstate will be observed and the observer realities are not branched. The overall system propagator is then:

$$K(b,\,a) \;=\; \sum_i K_i(\alpha,\,a)K_i(\beta,\,\alpha)K_i(b,\,\beta) \tag{22}$$

The observer system realities effectively "follow" the observed system evolution each "from a different angle." The observed system reality has a state *relative* to the reality which observed it [as Everett identified in his paper].

6. Observation γ

This time conjugated variables p_S are observed. The measure of the interaction is then associated with the conjugated variable representation of each propagator segment K_j $(b,\,\gamma)$ starting at γ . I will add a prime to the sum symbol to signify the sum is defined on a different path representation of the *overall* system. Expression (21) becomes

$$K(b,\,a) \;=\; \sum_i \sum_j K_i(\alpha,\,a)K_i(\beta,\,\alpha)K_j(\gamma,\,\beta){\sum_k}' \int_\gamma^b \exp(\frac{i}{\hbar}S_{S_{\gamma_k}}) \quad T_{\gamma_k}[p_M(t)]\mathcal{D}p_S(t) \tag{23}$$

or:

$$K(b,\,a) \;=\; \sum_i \sum_j K_i(\alpha,\,a)K_i(\beta,\,\alpha)K_j(\gamma,\,\beta){\sum_k}' K_k(b,\,\gamma) \tag{24}$$

with:

$$T_{\gamma_k}[p_M(t)] \;=\; \int_\gamma^b \exp\frac{i}{\hbar}(S_M \;+\; S_{\text{int}}).\,\exp(\frac{i}{\hbar}\;g[p_{S_1}^k(\gamma)]) \quad \mathcal{D}p_M(t) \tag{25}$$

T is now a set of functionals of a conjugated function, i. e. of a path in a new representation. A new branching of observer systems realities occurs as in observation α, but in their propagator segments there is no longer any *relationship data* for each observer reality to the previous collection of paths *i,* following now paths of conjugated variables. I could picture this feature through a given observer reality tied previously to an observed system variable. Since at time γ it observes rates of changes, it cannot observe the rate of change of the variable it was following. The commutation relations (10) express this fact mathematically. Therefore a given observer system reality has no choice but to observe one of the paths of system S *at random*. In formulae (23) and (24) there is no parameter available to tie each term of the last sum univocally to a term of the previous sum. Consequently, a given history cannot be "retraced" as the physical information is not there to do the backwards evolution in time. The propagator segments after time γ cannot be represented as one system since they do not contain the information to put them together univocally. The various realities are then no longer an interfering set of system realities [This supports Quote C and its inference 3].

The evolution of the observer system becomes tied to the set of orthogonal wave functions corresponding to conjugated variables p_S. Variables q_S are now free to evolve in the system S independently of the observer realities.

7. Observation τ

Now the observation is on the q_S variables. I have then a repeat of the observation γ functional T switch to a conjugated function, this time to the earlier one. The overall system propagator becomes:

$$K(b,a) = \sum_i \sum_j K_i(\alpha,a) K_i(\beta,\alpha) K_j(\gamma,\beta) \sum_k{}' K_k(\tau,\gamma) \sum_l K_l(b,\tau) \tag{26}$$

There is now a multiplicity of observer system realities corresponding to the same variables q_S, because each reality has experienced a different random *non-reversible* sequence of functionals T (a different history).

8. Addition of a second observer

Going back to expression (6), (7) and (8), I could have a second observing system N interacting with the system S at time $\theta > \tau$ through the q_S variables. The overall system evolution would be expressed by:

$$K(b,a) = \int_a^b \int_a^b \int_a^b \exp \frac{i}{\hbar}(S_S + S_M + S_N + S_{MS\,\mathrm{int}} + S_{NS\,\mathrm{int}}) \quad \mathcal{D}q_S(t)\mathcal{D}q_M(t)\mathcal{D}q_N(t) \tag{27}$$

$$K(b,a) = \int_a^b \exp(\frac{i}{\hbar}S_S)\; T_M[q_S(t), q_M(t)]\; T_N[q_S(t), q_N(t)]\; \mathcal{D}q_S(t) \tag{28}$$

$$T_N[q_S(t), q_N(t)] = \int_a^b \exp\{\frac{i}{\hbar}\int_{t_a}^{t_b} (L_N + L_{NS\,\mathrm{int}})dt\} \quad \mathcal{D}q_N(t) \tag{29}$$

Since L_{NSint} does not act until past time τ, systems N and S are independent from each other until that time. Expression (26) represents the evolution of system M as an observer of system S within composite system (S, M), even after the observation by system N because *observations inherently do not affect the evolution of system S*. Thus a new composite system (S, M) can be defined with the propagator:

$$K(b, a) = \sum_m K_m(\theta, a)K_m(b, \theta) \tag{30}$$

Then, after the observation by system N at time θ of a variable q_S in system S, observer N reality is branched by observing system S paths at time θ, as observer M reality was in observation α.

If on the other hand the second observer interacts with the first instead of system S, through one of its variables, expressions (28), (29) and (30) become:

$$K(b, a) = \int_a^b \exp(\frac{i}{\hbar}S_S) \int_a^b \exp \frac{i}{\hbar}(S_M + S_{MS})T_N[q_M(t), q_N(t)]\, \mathcal{D}q_M(t)\, \mathcal{D}q_S(t) \tag{31}$$

$$T_N[q_M(t)q_N(t)] = \int_a^b \exp\{\frac{i}{\hbar}\int_{t_a}^{t_b}(L_N + L_{NM\,\mathrm{int}})dt\} \quad \mathcal{D}q_N(t) \tag{32}$$

$$K(b, a) = \sum_i \sum_j K_i(\alpha, a)K_i(\beta, \alpha)K_j(\gamma, \beta) \sum_k{}' K_k(\tau, \gamma)\sum_l \sum_m K_l(\theta, \tau)K_m(b, \theta) \tag{33}$$

Therefore the second observer reality is branched into all the existing branches of the first observer. I have now a composite system made of three parts. The reality branch of the first observer expands to include the second observer upon interaction (and obviously to include nothing else) [This supports Quote B inference 3].

If subsequently the second observer observes the first observer *a second time* on a variable *conjugated* with the previous one, its reality will be branched as the first observer reality was earlier in observation γ while erasing its propagator segment connection data. Within a given history *ijklmn* (*n* being the index of the next term that will appear in Equ. (33)) it will then “get into” any one of the first observer existing reality branches *at random* being now its own reality branches [This supports the “branch communication inference”].

9. Final remarks

(1) The above formalism does not attempt to differentiate the individual evolutions corresponding to each propagator reality branch segment, but a Lagrangian in a suitable form (measure-wise) could possibly handle such a differentiation.

(2) The instants of the observations have been identified as fixed while they ought to have been entered in the observation measures as themselves functions of the observer and/or observed systems variables.

(3) The case of a system S that would be affected through the observation process has not been covered. This relates to, for example, an atomic nucleus that is observed through its emitted decay particle. This case could be handled by explicitly formalizing the composite nature of S then as a set of observer subsystems, which definition would include the ability to observe and be observed ("reciprocal observers").

The departure of one of the observers at a given instant in a given propagator segment could be represented by a measure non-zero up to that instant, and the instant being necessarily a function of all the systems variables, the system composition *definition* being itself changed. Such an event in the affected propagator segment would then affect in turn all the contemporary observers propagators segments, coming from a common term in the Lagrangian of the system.

Conclusion

Present quantum theory, and probabilistic quantum computers, can only use a classical "observer" *non-deterministically* tracking the quantum system it observes performing a computation in interfering realities (as Deutsch pointed out), and thus can only obtain statistical results from the subjacent multiple realities.

But "interferences" among realities occur only with *observations of interfering realities, and such decohered "observations" are the only kind addressed by the quantum theory formalism*. Then, in order to obtain *separate* results of several computation reality branches in a computational run, "non-interfering" realities need to be created and collected at a coherent quantum level, not at the "macroscopic" level as the present quantum computer theory proposes, that is, before decoherence destroys the branched realities relationships. Each of these non-interfering realities could be then observed one at a time without rerunning the computation.

The characteristics of a "non-deterministic" computation in the sense of computer science would be thereby available. Such quantum set-ups could potentially display greater computational capabilities and/or more diversified behaviors than what can be obtained through the probabilistic definition of quantum computation. The concepts presented here will be applied to a specific theoretical set-up in a separate article (Gouin, 2004) to show how they can be used.

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