Weak Decoherence and Quantum Trajectory Graphs

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Griffiths' "quantum trajectories" formalism is extended to describe weak decoherence. The decoherence conditions are shown to severely limit the complexity of histories composed of fine-grained events.

In response to the increasingly popular opinion that the Copenhagen interpretation of quantum mechanics raises more questions than it answers ( Omnès, 1992) and a desire to treat the entire universe quantum mechanically, Gell-Mann and Hartle (1990, 1993; Hartle, 1993) have worked to create an alternative interpretation of quantum theory, expanding upon earlier work by Griffiths (1984) and Omnès (1988). Their scheme emphasizes not individual events, but Griffiths' notion of a history, a sequence of events at a succession of times, and they assert that the histories to which one assigns probabilities are distinguished not by measurements made by an external classical "observer," but by the extent to which they satisfy certain "consistency" or "decoherence" conditions guaranteeing compliance with the classical rules of probability.

Basic questions about this formalism remain largely unanswered: How restrictive are the decoherence conditions? What kinds of histories decohere? Do they occur in sufficient variety to describe the physical world?

These questions have led us to investigate several aspects of decoherence. We have extended Griffiths' "quantum trajectories" formalism (Griffiths,

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1993) to describe weakly decohering sets of histories. We have found severe limits on the structure of fine-grained decohering histories.

Following Gell-Mann and Hartle, we let an event be described by a projection operator $P_\alpha$. If $P_\alpha$ is one dimensional, we say the event is fine grained; otherwise the event is coarse grained. A complete set of events $\{P_\alpha\}$ forms a resolution of the identity:

$$\sum_{\alpha} P_\alpha = I \quad \text{and} \quad P_\alpha P_\beta = \delta_{\alpha\beta} P_\beta$$  \hfill (1)

Let $\{P_\alpha(t_k)\}$ be the complete set of events (in the Heisenberg picture) at time $t_k$. The probability that event $P_\alpha(t_1)$ will occur at time $t_1$, $P_\alpha(t_2)$ at time $t_2$, ..., and $P_\alpha(t_n)$ at time $t_n$ is (Hartle, 1993)

$$p(\alpha_1, \alpha_2, \ldots, \alpha_n) = \text{Tr}(P_\alpha(t_n) \cdots P_\alpha(t_2)P_{\alpha_1}(t_1)pP_{\alpha_1}(t_1)P_{\alpha_2}(t_2) \cdots P_{\alpha_n}(t_n))$$  \hfill (2)

for an initial state described by a density operator $\rho$. With this sequence of events we associate the history $C_\alpha$ defined by

$$C_\alpha = P_{\alpha_1}(t_n) \cdots P_{\alpha_2}(t_2)P_{\alpha_1}(t_1)$$  \hfill (3)

in terms of which equation (2) becomes

$$p(\alpha) = \text{Tr}(C_\alpha\rho C_\alpha^\dagger)$$  \hfill (4)

With this expression in mind, we define the decoherence functional between histories $C_\alpha$ and $C_\beta$ for an initial state $\rho$ by

$$D(\alpha, \beta) = \text{Tr}(C_\alpha\rho C_\beta^\dagger)$$  \hfill (5)

and we say $\{C_\alpha\}$ forms a weakly decohering set of histories iff

$$\text{Re } D(\alpha, \beta) = 0 \quad \text{for all } \alpha \neq \beta$$  \hfill (6)

This condition guarantees that the probabilities associated with the histories in $\{C_\alpha\}$ obey the classical rules of probability (Hartle, 1993). For such a set of histories, the decoherence condition (6) and the probability formula (4) may be combined in the equation

$$\text{Re } D(\alpha, \beta) = p(\alpha)\delta_{\alpha\beta}$$  \hfill (7)

A set of histories which satisfies the stronger condition

$$D(\alpha, \beta) = p(\alpha)\delta_{\alpha\beta}$$  \hfill (8)

is said to exhibit medium decoherence. This condition is sufficient but not necessary to ensure compliance with the classical rules of probability. We
will consider both kinds of decoherence. Finally, we will speak of individual histories \( C_\alpha \) and \( C_\beta \) decohering if they satisfy equation (7) or (8).

From equations (4) and (5) and the cyclic property of the trace it follows that (i) histories with different final events always decohere and (ii) any history which occurs with zero probability decoheres with all other histories. Further, any decohering set of histories can be extended by inserting between any two times a set of events identical (in the Heisenberg picture) to those at the earlier or later time; the set of histories that results still decoheres. This corresponds to inserting a set of events in the Schrödinger picture which matches the earlier or later set aside from unitary evolution to the new time. We call this a congruent extension, since the new events are congruent with the old ones. In light of this, we will look for sets of histories with more than one nonzero-probability history but without congruent extensions.

We will use Griffiths' graphical representation (Griffiths, 1993) of "consistent histories," in which he represents the set of possible events at each time with an orthonormal basis of the system's state space. (In this formalism, every event is fine grained.) He represents the set of histories produced by this choice of events with a trajectory graph, in which each event at time \( t_j \) corresponds to a node in the \( j \)th column of the graph and a line is drawn between nodes in adjacent columns iff the transition amplitude between the corresponding events is nonzero. Figure 1 presents two examples of such graphs. Each path (unbroken line through two or more nodes) through a trajectory graph represents a nonzero-probability history with initial state given by the first node in the path. (Griffiths of course refers to our paths as "trajectories.") The set of histories described by the graph satisfies Griffiths' noninterference condition if any two nodes are connected by at most one path. We will show immediately below that the noninterference condition is equivalent to medium decoherence of the set of histories with any node in

\[
\begin{align*}
&\circ \quad \circ \\
&\circ \quad \circ \\
&\circ \quad \circ \\
&\circ \quad \circ \\
&t_j \quad t_{j+1} \quad t_j \quad t_{j+1}
\end{align*}
\]

(a) \hspace{1cm} (b)

Fig. 1. Griffiths trajectory graphs. (a) A candidate for a nontrivial transition in which the number of connected events does not increase. This graph is forbidden by the orthogonality of different events at \( t_j \). (b) Another candidate for the same transition. The orthogonality of different events at \( t_j \) demands that at least two events at \( t_{j+1} \) be doubly connected.
the graph as the initial state. However, we wish to follow in the spirit of Gell-Mann and Hartle, in which decoherence is a function of the initial state as well as the histories themselves. Further, since medium decoherence is a more stringent requirement than is actually necessary, we would like to have a condition for weak decoherence in terms of these graphs. As we will also prove below, the required condition is that at most two distinct paths connect any two events, and if there are two paths, the phases of the corresponding amplitudes differ by $\pi/2$. Thus, we will use a modified form of Griffiths’ quantum trajectory formalism in which (i) we specify the initial state (producing what Griffiths would call an elementary family of trajectories) and (ii) we impose the requirement of weak, not medium, decoherence. Figures 2 and 3 provide examples of such graphs.

Both decoherence conditions mentioned above are special cases of the following theorem.

**Theorem 1.** Suppose \( \{ C_\alpha \} \) is a decohering set of histories with initial state $\rho$ and suppose that two possible events $|j\rangle\langle j|$ at time $t_j$ and $|k\rangle\langle k|$ at a later time $t_k$ are fine grained. If at least one history leading to event $|j\rangle\langle j|$ occurs with nonzero probability, then of all histories which lead from $|j\rangle\langle j|$ to $|k\rangle\langle k|$, at most two occur with nonzero probability. If two occur, then the phases of the corresponding amplitudes differ by $\pi/2$. If the set \( \{ C_\alpha \} \) exhibits
medium decoherence, at most one history leading from $|j\rangle \langle j|$ to $|k\rangle \langle k|$ occurs with nonzero probability.

**Proof.** Any history leading from $|j\rangle \langle j|$ to $|k\rangle \langle k|$ can be written as

$$C_\alpha = |k\rangle \langle k| D_\alpha |j\rangle \langle j|$$

(9)

and the decoherence condition (6) applied to any two histories which include $C_\alpha$ and $C_\beta$ where $\alpha \neq \beta$ can be reduced to

$$\text{Re}(k|D_\alpha |j\rangle \langle k|D_\beta |j\rangle^*) = 0$$

(10)

If both amplitudes are nonvanishing, then

$$\text{arg}(k|D_\alpha |j\rangle) - \text{arg}(k|D_\beta |j\rangle) = \pm \pi/2$$

(11)

Thus, any two numbers in the set $\{k|D_\alpha |j\rangle\}$ are orthogonal in the complex plane. Since the complex plane is two dimensional, at most two of the $\{k|D_\alpha |j\rangle\}$ are nonzero. If there are two, they have the promised phase difference of $\pi/2$. Had we assumed that the histories exhibited medium decoherence, we would have used the decoherence condition (8) and in (10) we would not have taken the real part; then at most one member of the set $\{k|D_\alpha |j\rangle\}$ would be nonvanishing.

If the initial state of the system is pure, then the theorem is still valid if we replace $|j\rangle \langle j|$ with $\rho$. Thus, if the initial state is pure and the set $\{C_\alpha\}$ exhibits weak (medium) decoherence, then at most two histories connect (one history connects) the initial state to any fine-grained event with nonzero probability.

An immediate consequence of this theorem is interesting enough to be a theorem of its own.

**Theorem 2.** If $t_j < t_k < t_i$ and a nonzero-probability history leads to a fine-grained event at $t_i$ which does not occur at $t_k$ but occurs again at $t_j$, then no set of histories containing these events can decohere.

**Proof.** At least two nonzero-probability histories must connect the event at $t_j$ to its twin at $t_i$. Further, the product of the amplitude for one history and the complex conjugate of that for the other is real (and positive), because the factors linking $t_j$ to $t_k$ are the complex conjugates of those linking $t_k$ to $t_i$. Thus condition (10) of Theorem 1 cannot be satisfied.

With Theorem 1 in hand we can immediately describe all possible decohering sets of histories of a two-level system (spin 1/2) with a pure initial state. All sets of histories with one event after the initial state exhibit (medium) decoherence automatically; thus we begin by considering two-event sets. We assume the system is initially polarized in the direction $i,$
polarized parallel or antiparallel to \( n \) at \( t_1 \), and parallel or antiparallel to \( f \) at \( t_2 \). Writing the corresponding projection operators in the standard way using Pauli matrices, one discovers that the weak decoherence condition (6) becomes

\[
(\mathbf{i} \times \mathbf{n}) \cdot (\mathbf{n} \times \mathbf{f}) = 0
\]

(12)

(This result is known (Omnès, 1992.) Only these sets of two-event histories weakly decohere. Further, every decohering set of histories with three or more events is a congruent extension of a two-event set; if it were not, the number of nonzero-probability histories would be at least five, so at least three would lead from the initial state to one of the two final events, which Theorem 1 does not allow.

If we were to impose medium decoherence instead, the allowed sets of histories would simplify considerably. Theorem 1 allows at most one nonzero-probability history to lead from the initial to each of the final states; thus the total number of nonzero-probability histories would be at most two. Any set of histories which is not a congruent extension of a one-event set will have at least three nonzero-probability histories; thus it would not decohere. Therefore, the only sets of fine-grained histories of a two-level system which exhibit medium decoherence are one-event sets and their congruent extensions. In Griffiths’ language, we have shown that weakly decohering sets of histories corresponding to the graph in Fig. 2a exist, but the only sets exhibiting medium decoherence are represented by graphs like the one in Fig. 2b, a congruent extension of a one-event set.

We call an event in a trajectory graph connected if its node leads back to the initial state through at least one path (if at least one history leading to the event from the initial state occurs with nonzero probability). We call it singly connected if exactly one path leads back to the initial state, doubly connected if two paths lead back to the initial state. In these terms, Theorem 1 demands that every fine-grained event in a decohering set of histories be at most doubly connected (or singly connected if the set exhibits medium decoherence). An event is unconnected if it has no overlap with the connected events at the previous time; thus the unconnected events at any time lie in the span of the unconnected events at the previous time. Therefore the number of connected events is a nondecreasing function of time.

Theorem 3. In every transition between times in a decohering set of histories represented by a trajectory graph, either:

1. the connected events before and after the transition are identical;
2. the number of connected events increases by at least one;
3. the number of doubly connected events increases by at least two; or
4. both 2 and 3 occur.
Proof. All we need to prove is that if 1 and 2 do not occur, then 3 must occur. Thus, suppose the connected events before and after the transition from time $t_i$ to time $t_{i+1}$ are not identical, yet the number of connected events does not increase. Then at least one event at $t_{i+1}$ must be connected to two events at $t_i$, as shown in Fig. 1a. However, that one event at $t_{i+1}$ cannot be the only one linked to two events at $t_i$; since the first event at $t_i$ is connected to only the first event at $t_{i+1}$, the two differ at most by a phase, and because the first and second events at $t_i$ are orthogonal, the first event at $t_{i+1}$ and the second event at $t_i$ must also be orthogonal. Thus at least two events at $t_{i+1}$ must be connected to two events (each) at $t_i$, as shown in Fig. 1b. None of the doubly connected events from $t_i$ can be involved in this part of the transition (since that would make one of the events at $t_{i+1}$ at least triply connected); therefore, the number of doubly connected events increases by at least two.

In a set of histories represented by a trajectory graph, the system's behavior is specified at only a finite number of times. We might have hoped to better approximate continuous time evolution by inserting additional sets of events between those already in the graph. However, as the next theorem shows, the possibilities for this are very limited.

**Theorem 4.** Suppose that between times $t_i$ and $t_{i+1}$ in a decohering set of histories represented by a trajectory graph, exactly one step of change occurs: either the number of connected events increases by exactly one or the number of doubly connected events increases by exactly two (but not both). Then if an additional set of events is inserted between $t_i$ and $t_{i+1}$ while maintaining decoherence, it must be identical to either the set at $t_i$ or the set at $t_{i+1}$.

**Proof:** Suppose that the new set is identical to neither the set before nor the set after. Then in the transition from $t_i$ to $t_{i+1}$ at least two steps of change must occur (one for the transition from $t_i$ to the intermediate time, one for the transition from the intermediate time to $t_{i+1}$).

The histories are restricted even more drastically if only finitely many events occur with nonzero probability (so only that many events are connected).

**Theorem 5.** Consider a trajectory graph representing a set of decohering histories with a finite number $n$ of connected events at a particular time. Excluding congruent extensions, the number of transitions prior to that time is at most $n + \lfloor n/2 \rfloor - 2$, where $\lfloor \cdot \rfloor$ denotes the greatest integer part.

**Proof:** Suppose that the given set of decohering histories contains no congruent extensions. The number of connected events at time $t_i$ is therefore
at least two, so the number of transitions that increase the number of connected
events is at most $n - 2$. The number of transitions that increase the number
of doubly connected events is at most $[n/2]$. Thus the total number of transi-
tions is at most $n + [n/2] - 2$. ■

This bound is the strongest possible, because for every $n$ there is a set
of decohering histories in an $n$-dimensional space with this maximum number
of noncongruent steps (the $n = 5$ case is illustrated in Fig. 3). The con-
sequences of this theorem are avoided only if the number of connected events
is infinite right at the start, so that infinitely many events occur with nonzero
probability at each time.

Comparison with Fig. 2 shows that in each of the last two transitions
in Fig. 3 the system can be decomposed into two subspaces, in one of which
the transition is to congruent events, while in the other the transition is that
of a two-level system. In fact, a large class of transitions is of this general
type, as we show with our final theorem.

Theorem 6. In every transition in which the number of connected events
is finite and does not increase, the matrix describing the transition between
the connected events is block-diagonal (to within rearrangement of the rows
and columns), and each block is either $2 \times 2$ or $1 \times 1$.

Proof. Let the transition from $t_j$ to $t_{j+1}$ leave the number of connected
events $n$ unchanged. Since the span of the connected events at $t_j$ lies in the
span of the connected events at $t_{j+1}$ and both have dimension $n$, the two
subspaces are the same; so they have the same orthogonal complement. Thus
each (un)connected event at $t_{j+1}$ overlaps only the (un)connected events at $t_j$.
Since each connected event at $t_{j+1}$ is at most doubly connected, each is linked
to either one or two connected events at $t_j$ and no others; thus the matrix
describing the entire transition has at most two nonzero entries in each column
representing a connected event at $t_{j+1}$. If a column has only one nonzero
entry, then unitarity guarantees that the entry is also the only nonzero entry
in its row; this yields all of the $1 \times 1$ blocks. If a column has two nonzero
entries, then the orthogonality of different rows and columns demands that
the entries in the same two rows of one and only one other column are also
nonzero. Those two columns together form a $2 \times 2$ block; all other entries
in their rows and columns are zero. ■

This theorem reduces the allowed transitions to an extremely simple
form; its restrictions are avoided only if the number of connected events (the
number of events that occur with nonzero probability) increases continually
over time.

These results suggest that the decoherence conditions strongly favor
histories dominated overwhelmingly by congruent extensions. It is not surpris-
ing that decoherence selects out the histories that conform with the system’s unitary evolution, but the extent to which they are preferred is remarkable. For example, only congruent events can occur between congruent events (Theorem 2), and if continuous classical evolution is to be approached by inserting events at more and more times, almost all insertions must be congruent extensions (Theorems 2, 4, and 5). Probabilities that are periodic in time and are for a finite number of events at some time must be for congruent events and are therefore constant in time. (The number of connected events can not decrease, so if it is periodic, it must be constant and Theorem 6 applies.)

REFERENCES


