The Wheeler-Feynman Interpretation of the Delayed-Choice Experiment and its Consequences for Quantum Computation

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In this paper, we shall describe the delayed-choice experiment first proposed by Wheeler[?] and then analyze the experiment based on both our interpretation of what is happening and the Wheeler/Feynman interpretation. Our interpretation includes wave-function collapse due to a measurement, while the Wheeler/Feynman interpretation attempts to avoid wave-function collapse in a measurement, as part of their explanation, to preserve consistent *unitarity* in quantum processes. We will also show that there are severe consequences for quantum computing if there is no wave function collapse due to a measurement.

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INTRODUCTION

John A. Wheeler, in his essay "Delayed Choice Experiments and the Bohr-Einstein Dialogue" envisions two experimental setups, indicated by Figures 1 and 2 below.

Figure 1

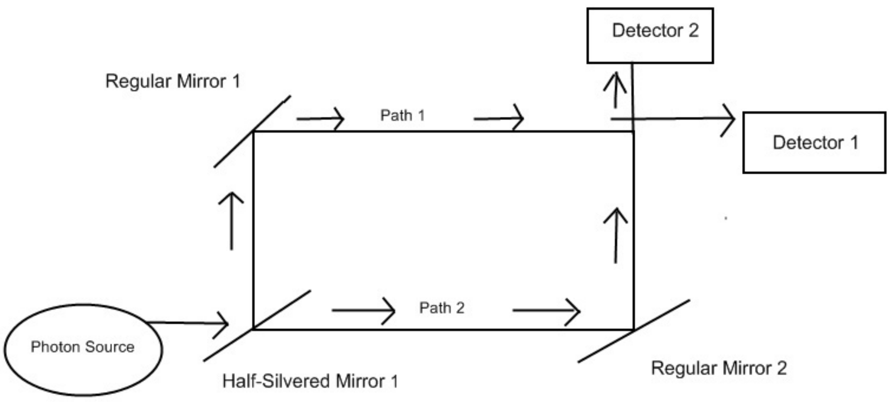
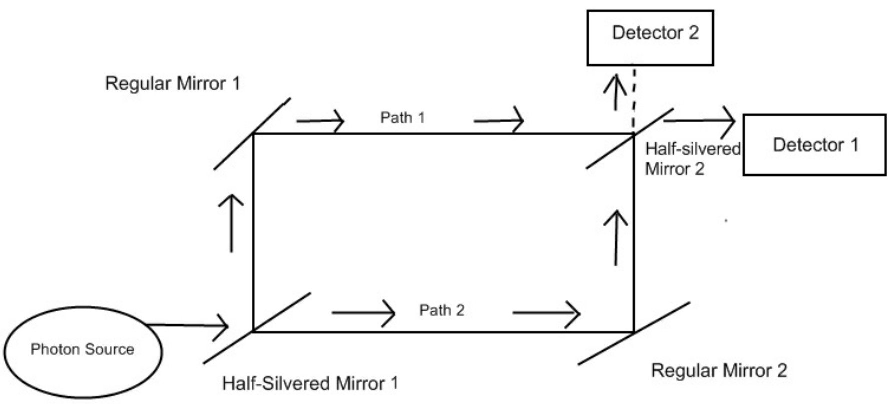


Figure 2



Let t_0 = the time a single photon is emitted from the source.

Let t_1 = the time the photon reaches the half-silvered mirror 1.

Let t_2 = the time the photon reaches the half-silvered mirror 2.

Let t_D = the time the photon reaches a detector.

Path 0 is the path from the source to the half-silvered mirror 1.

Path 1 is the path from the half-silvered mirror 1 to detector 1.

Path 2 is the path from the half-silvered mirror 1 to detector 2.

Define various position functions:

$\psi_0(x,t)$ $\quad$ $t_0 \leq t \leq t_1$,

$\psi_1(x,t)$ $\quad$ $t_1 \leq t \leq t_D$,

$\psi_2(x,t)$ $\quad$ $t_1 \leq t \leq \mathrm{t}_D$.

For $\mathrm{t}_0 \leq t \leq t_1$, $\quad \psi_0(x,t) = 1$ $\quad$ *if* x is the position along path 0 such that $x = ct$, and
$\psi_0(x,t) = 0$, otherwise.

For $\mathrm{t}_1 \leq t \leq t_D$, $\quad \psi_1(x,t) = 1$ $\quad$ *if* x is the position along path 1 such that $x = ct$, and
$\psi_1(x,t) = 0$, otherwise.

For $\mathrm{t}_1 \leq t \leq t_D$, $\quad \psi_2(x,t) = 1$ $\quad$ *if* x is the position along path 2 such that $x = ct$, and
$\psi_2(x,t) = 0$, otherwise,

where c is the speed of light.

ANALYSIS

Our analysis of experimental set-up 1 is:

For $\mathrm{t}_0 \leq t \leq t_1$, the photon is in the state: $\mid \psi_0(x,t) = 1\rangle$.

For $\mathrm{t}_1 < t < t_D$, the photon is in the state:

$\frac{1}{\sqrt{2}} \mid \psi_1(x,t) = 1\rangle + \frac{1}{\sqrt{2}} \mid \psi_2(x,t) = 1\rangle$.

At t_D, since detector 1 clicks or detector 2 clicks but not both, a measurement is made. So, by the projection postulate of quantum mechanics, the prior state of the photon collapses at $t = t_D$ to $\mid \psi_1(x,t) = 1\rangle$ with a probability of $\frac{1}{2}$ or to $\mid \psi_0(x,t) = 1\rangle$ with a probability of $\frac{1}{2}$.

Our prediction based on this analysis is that for a large number of runs of set-up 1, about half the time detector 1 will click and about half the time detector 2 will click.

Wheeler's analysis of experimental set-up 1 is the following:

For $t_0 \leq t \leq t_1$, the photon is in state $\mid \psi_0(x,t) = 1\rangle$.

For $t_1 < t \leq t_D$, the photon is either in the state $\mid \psi_1(x,t) = 1\rangle$ or in the state $\mid \psi_2(x,t) = 1\rangle$. There is a $\frac{1}{2}$ probability that the photon will be in the state $\mid \psi_1(x,t) = 1\rangle$ and a $\frac{1}{2}$ probability that the photon will be in the state $\mid \psi_2(x,t) = 1\rangle$.

The prediction based on Wheeler's analysis is the same as on our analysis. In a large number of runs of set-up 1, about half the time detector 1 will click and about half the time detector 2 will click. On Wheeler's analysis, there is no *wave-function collapse* due to a measurement. In Wheeler's words: "...one will find that the one counter goes off, or the other. Thus the photon has traveled only <u>one</u> route."[?]

Wheeler's and our analysis of experimental set-up 2 is the same:

For $t_0 \leq t \leq t_1$, the photon is in the state

$\mid \psi_0(x,t) = 1\rangle$.

For $t_1 < t \leq t_2$, the photon is in the state

$\frac{1}{\sqrt{2}} \mid \psi_1(x,t) = 1\rangle + \frac{1}{\sqrt{2}} \mid \psi_2(x,t) = 1\rangle$.

For $t_2 \leq t \leq t_D$, the photon is in state

$\mid \psi_1(x,t) = 1\rangle$.

So, the action of half-silvered mirror 2 is to collapse the wave function of the photon. But this is not wave-function collapse due to a measurement.

The prediction based on Wheeler's and our analysis of experimental set-up 2 is:

In every run of experimental set-up 2, detector 1 will click.

On Wheeler's analyses, the action of half-silvered mirror 1 on the photon depends on the experimental set-up, and there is no wave-function collapse due to a measurement. On our analyses, the action of half-silvered mirror 1 on the photon does not depend on the experimental set-up, and there is wave-function collapse due to a measurement in set-up 1.

In a "delayed-choice" experiment, which experimental set-up 1 has is not determined until after t_1 and before t_2. (After t_1 and before t_2, a decision is made whether or not half-silvered mirror 2 will be in place.) Wheeler's analysis and our analysis of the "delayed choice" experiment will make the same predictions. So, no running of the delayed choice experiment can decide between the two analyses. The crucial difference between Wheeler's analysis and ours of the experiment is that on Wheeler's analysis, the action at t_1 of the half-silvered mirror 1 on the photon depends on the decision made after t_1. On our analysis, the action at t_1 of the half-silvered mirror 1 on the photon does *not* depend on the decision made after t_1. On Wheeler's analysis the past can be changed, On our analysis, it can't.

Wheeler and Feynman

What is the source of Wheeler's analyses? One can go back to Feynman in The Theory of Fundamental Processes[?] and his analysis there of the two-slit experiment (pp. 2 - 3). Feynman analyzes the case where there is no detector behind slits 1 and 2 (call this set-up 1), and the case where there is a detector behind slits 1 and 2 (call this set-up B). In set-up A, the photon is in a superposition of going through slit 1 and going through slit 2. (Feynman does not say "superposition"; he rather says "amplitudes are added".) In set-up B, the photon goes through slit 1 and is detected behind slit 1 with a certain probability, or goes through slit 2 and is detected behind slit 2 with a certain probability. (Feynman says "probabilities are added".) Per Feynman, there is no wave-function collapse due to a measurement by the detector in set-up B.

QUANTUM COMPUTATION AND DELAYED-CHOICE

What does any of this have to do with quantum computing? In interesting cases of quantum computing, the output is a superposition of different bit strings. In order to extract information from this superposition, the computation is run many times, yielding the same output each time, and a measurement of the output is made each time. The measurement results are individual bit strings in the superposition. If Feynman and Wheeler are correct, the output before measurement is a single bit string, and the measurement simply reveals what that bit string is. Hence on multiple runs of the computation, if different bit strings are obtained as measurement results, the output is not the same for those runs, in contradiction to what quantum computing states.

In particular, if the Wheeler-Feynman interpretation of the "delayed-choice" experiment were correct, one could not build a Hadamard gate, which is a very important component of one type of quantum computing architecture and a key feature of many of the important quantum algorithms available. In essence, the Wheeler-Feynman interpretation of the "delayed-choice" experiment says that a measurement at the crucial time means that there never was a superposition at the source of the experiment. The "quantum magic" is not that the wave-function randomly and irreversibly collapses, but that the superposition never happened, or that the past was, somehow, changed, by the measurement. Let us look at the HADAMARD and C-NOT gates in particular and the role they play in quantum computing to try to understand what is supposed to be happening under these interpretations.

C-NOT and HADAMARD Gates

The following is the logical characterization of C-NOT:

C-NOT$|0\ 0\rangle = |0\ 0\rangle$,

C-NOT$|0\ 1\rangle = |0\ 1\rangle$,

C-NOT$|1\ 0\rangle = |1\ 1\rangle$,

C-NOT$|1\ 1\rangle = |1\ 0\rangle$.

Why would a C-NOT gate be "easy to build"? A C-NOT is "inherently classical," in the sense that if it operates on a 2-bit string, it gives you back a 2-bit string.

The following is the logical characterization of the HADAMARD:

$H|\,0\,\rangle = \frac{1}{\sqrt{2}}\,|\,0\,\rangle + \frac{1}{\sqrt{2}}\,|\,1\,\rangle$,

$H|\,1\,\rangle = \frac{1}{\sqrt{2}}\,|\,0\,\rangle - \frac{1}{\sqrt{2}}\,|\,1\,\rangle$.

Why would a HADAMARD gate be "hard to build"? A HADAMARD gate is not inherently classical. If it operates on a 1-bit string, it does not give you back a 1-bit string; it gives you back a superposition of 1-bit strings (= a *qubit*). If you build one, you have to make sure it gives you a superposition that does not rapidly collapse to a bit.

Consider a simple quantum computational process:

Input: $|\,0\,\rangle$.

Apply Preparation H, i.e., send the input through a HADAMARD gate.

Output: $\frac{1}{\sqrt{2}}\,|\,0\,\rangle + \frac{1}{\sqrt{2}}\,|\,1\,\rangle$.

Measure the output: There is a 50% chance that $|\,0\,\rangle$ is measured and 50% chance that $|\,1\,\rangle$ is measured.

This is like set-up B (two slit, detector present) in Feynman. Per Feynman-Wheeler, if you measure the output and find $|\,0\,\rangle$, the output was $|\,0\,\rangle$ *prior* to the measurement. Also, if you measure the output and find $|\,1\,\rangle$, the output was $|\,0\,\rangle$ *prior* to the measurement. But, the output was not $|\,0\,\rangle$ prior to the measurement, and it was not $|\,1\,\rangle$ prior to the measurement. It was $\frac{1}{\sqrt{2}}\,|\,0\,\rangle + \frac{1}{\sqrt{2}}\,|\,1\,\rangle$ prior to the measurement.

The bottom line is: in quantum computing, there has to be wave-function collapse due to a measurement. In Feynman-Wheeler, there is no wave-function collapse due to a measurement. Since the results of a quantum computation implies a measurement, it is hard to see how quantum computing is possible under the Feynman-Wheeler interpretation.

REFERENCES

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