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Article

Quantum Parallelism Thesis, Many World Interpretation and Physical Information Thesis

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Abstract: The aim of this paper is to address a particular interpretation of quantum computational processes, namely, the so called Many World Interpretation (MWI). I will show that if such an interpretation is supported by the Quantum Parallelism Thesis (QPT) and the Physical Information Thesis (PIT) at the same time, then it falls under circularity. I will suggest, in fact, that as long as this variation states both PIT and QPT cannot furnish a physical explanation of the latter unless it is already stating the truth of MWI. This specific case suggests the more general conclusion that MWI and other accounts of quantum computational processes instill very different concepts of information. I will show that the concept instilled by MWI advocates is too abstract in order to be a reliable source for a physical interpretation of quantum computational processes. I will nevertheless then suggest that MWI is not completely useless for our understanding of quantum computation.

Keywords: quantum computation; quantum information theory; many world interpretation

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1. Introduction

Quantum information theory is a recent field or research which combines the efforts produced in the fields of information processing and computation by studying the effects that result from exploiting the "weird" effects of quantum mechanics. This specific field of research is located in-between many different disciplines: it involves in fact mathematics and computer science, but it is also matter of interest for physics and philosophy. The rise of this discipline is due to a suggestion of Richard Feynman [1]: he has shown that any simulation of quantum behavior by classical means, *i.e.*, by classical systems of computation, would require an exponential growth in terms of physical resources necessary to complete the simulation task. It has turned out—following Feynman's suggestion—that due to the bigger complexity of quantum systems, it is possible to complete some hard computational tasks (by hard task I mean a computational task which is theoretically solvable, but it is also such that the resources required for its solution grow exponentially with respect to a polynomial growth of the input.) in polynomial time by using quantum physical systems as "computational environment" and quantum information unit (qubits) as target object [2–4]. Nowadays, the design of quantum computers, and quantum information protocols is a very active field of research. The central question with respect to the theoretical role of quantum information theory is the which physicists have been struggling since the rise of quantum mechanics, and it comes down to this: "How and in which respect does the quantum world differ from the classical world?". As observed in Timpson [5] this question is addressed, in the field of quantum information theory, from a task-oriented point of view, so that the previous question may be rephrased as follows: "What kind of results can I achieve with physical quantum systems compared to their classical counterparts?"

When it comes to the theoretical relevance of quantum information theory—namely to the answer to the following question "where the quantum world differs from the classical one, in the light of the fact that different computational tasks are accomplished by means of quantum systems?"—there are many difficulties in providing a unified account for the interpretation of the fact that quantum computers show a different behavior with respect to classical ones, and these difficulties are related to the interpretation of quantum formalism. This paper aims at addressing one of those interpretations, namely the Many World Interpretation of quantum computation processes (MWI). MWI advocates would probably answer to the previous question in this way:

> The outperforming characteristics of quantum computers depend on the fact that those devices can evaluate functions in a massive parallel way [in the following I will call this QPT, Quantum Parallelism Thesis]. Quantum computation theory tells us that in the so-called "quantum environment", we have simultaneous access to many computational worlds.

The scope of this paper is to show that this answer is not satisfactory as long as our scope is to describe or represent the way the world works, which is one of the main reason for providing an interpretation for quantum formalism, and quantum information theory [6]. I will show that by developing an argument suggested in Cuffaro [7]; Cuffaro writes:

> [MWI] promises to explain quantum computation in terms of many worlds but on this response it appears that we need to appeal to the computation in order to explain these many worlds in the first place. This seems circular . . . [7] (p. 39) (Square brackets and their content refer to my abbreviation).

I will show that this suggested circularity stands as long as we need to furnish a physical explanation of the computational process. A need which justified by the idea that information is strongly tied to its physical representation, and hence, its modification and transitions should be justified as physical processes too [8]—through the paper we are going to call this thesis PIT (Physical Information Thesis).

The paper is structured as follows. In the next section I will provide a thorough description of the main concepts and thesis involved in the discussion of the argument, namely MWI QPT and PIT. In Section 3

I will develop the argument showing why MWI can not be supported by QPT and PIT at the same time. I will also suggest a criterion which helps to choose between the clashing elements highlighting that PIT is a far better element to rely on. In Section 4 I will then consider the idea that MWI instils a very different concept of information with respect to other interpretations of quantum information theory, and in which sense MWI is a useful tool in the comprehension of quantum information processes. In the last section I draw some concluding remarks.

2. Background Terminology

This section aims at introducing the necessary vocabulary for the discussion which is going to follow.

Many World Interpretation (MWI). By MWI (of quantum computation) I mean a precise theoretical account that builds a parallel between Everettian Interpretation of quantum states (For a survey on this topic see [9].) and the physical behavior of quantum computers. The main idea is that when quantum computers are performing a transition taking as input a superposition of states, like for example the following n qubit register $|X\rangle = \frac{1}{\sqrt{2^n}} \sum_{x=0}^{2^n-1} |x\rangle$ they gain access to many computational worlds—each associated to every possible value of $|X\rangle$—and they are actually performing many simultaneous transitions on each and every one of those states that are part of the superposition. The transition is real in the sense that it is performed in all the different worlds, to which the computation process gain access.

Quantum Parallelism Thesis (QPT). QPT is the thesis that gives an account for quantum computational speed up—namely the ability of quantum computers to outperform their classical counterpart—in terms of the fact that computational quantum devices can perform multiple simultaneous evaluations of functions in a single time step. It is formally represented by the so called Quantum Parallelism Process [10]:

$$\sum_{x=0}^{2^n-1} |x\rangle\,|y\rangle \longrightarrow \sum_{x=0}^{2^n-1} |x\rangle\,|f(x) \oplus y\rangle \tag{1}$$

As we will see PIT is strongly connected to MWI.

Physical Information Thesis (PIT). The difference between what can in principle be computed by a machine, and what can efficiently—*i.e.*, practically, without any exponential growth of the required resources—be computed by the same device raises some interesting question about the nature of information. If, as it seems to be, quantum computer can practically solve some "classical hard tasks" then it seems reasonable to tie the handling of information to the physical system which we use to encode data [8]. This statement is the core of PIT, a thesis which consists in keeping track of the strong relationship between computer science and physics by stating that information is not some abstract concept, but is rather tied to the restriction of the physical world and its laws. Quantum computational processes constitute a strong evidence with respect to this thesis (See references in the first section.).

Physical Explanation. By physical explanation I mean an account which shows that the specific formal representation of a process has empirical counterparts. Without that sort of explanation there is no ground in stating that some sort of mathematical formalism represents effects which happen in reality. The necessity of a physical explanation in the context of quantum computation and its interpretation is mostly forced by the fact that I am accepting PIT. By neglecting PIT one could be no longer forced in giving an account for the formal representation of computational processes.

3. A Joint Assumption for PIT and QPT?

The present aim is to show that the assumption of both PIT and QPT supporting MWI generates conflict. The form of conflict generated is a form of circularity which was also suggested by [7], in the sense that MWI is justified by QPT, but at the same time one of MWI's claim is necessary to justify QPT itself . As a conclusion we will be forced to drop one of those theses. I will then suggest a criterion for choosing between PIT on one side, and QPT on the other.

The first step into the argument consists in the explanation of the fact that MWI is justified by means of QPT. In order to show that it is necessary to see which is the relationship between those two theses. it is easy to see that QPT stands as a necessary condition for MWI: in fact QPT is the description of the behavior of a quantum computer that an advocate of MWI would provide, see e.g., [11]. It is in fact sufficient to take a look at the two definitions provided in the previous section to see how strong that relationship is, in the sense that neglecting QPT means that an advocate of MWI would have no chance to state its interpretation in terms of the physical behavior of a computational device. It seems then reasonable to conclude that the truth of QPT is an argument—perhaps the strongest—for supporting MWI, and that claims such as "at the crudest level quantum computation is just quantum parallelism" [11] show how closely related those ideas are.

Consider now a unitary U_f map that acts precisely like the process described in Equation (1): $|x\rangle$ and $|y\rangle$ are respectively input and output register, and hence it is possible to state that U_f is associated to the evaluation of a function f. As I showed in the previous section Equation (1) represents QPP and in order to provide a justification for QPT it is necessary to furnish a physical explanation for it.

Let say that Equation (1) represents the evaluation of a function, taken just by itself: then the whole computational process is to be intended as a formal passage between input and output configurations with respect to the unitary operation U_f. This could be a very abstract characterization of the whole process, but it doesn't keep any track of PIT. The account just furnished is far too abstract and cannot explain in which sense it holds that if information is physical than its manipulation is of course to be considered a physical process. As suggested before, the truth of PIT commits us into furnishing a physical explanation of the formalism. What we need to account for in this case is the right side of Equation (1), namely $\sum_{x=0}^{2^n-1} |x\rangle\, |f(x) \oplus y\rangle$, since it represents formally the fact that the multiple evaluation of $f(x)$ happens.

In order to provide such an explanation we need to state that the process of transition formally represented in Equation (1) relies on two facts:

(a) The state described in the right side of Equation (1) is real;
(b) It is possible to identify a physical realization for it.

It is a fact of quantum theory that it is impossible to obtain more than one single value for $f(x)$ [12], so there is no direct observable effect of the multiple evaluation of $f(x)$. This raises the question of how can we account for (b)—and consequently for (a)—without having a direct observable effect of the multiple evaluation of $f(x)$. The only available path seems to be to conceive of the computation as running in parallel and in many different worlds, but this claim is misleading for two reasons:

(1) It relies on indirect observables effects, not direct ones. This might be considered a minor issue but we will consider that later;
(2) The claim that "the computation is running in parallel and in many different worlds" is precisely one of the main claims of MWI, namely the interpretation for which QPT is supposed to ground for. In this sense it is circular to state the truth of QPT on the basis of MWI, if, as suggested, QPT is to be considered the strongest thesis for supporting MWI itself.

As a partial conclusion for this paper I claim that MWI cannot be supported by both QPT and PIT. In fact if we try to do so we are forced to state the truth of MWI as a necessary condition for QPT.

The fact that the two theses cannot be stated together forces us to choose between PIT on the one side and QPT/MWI on the other. The criterion I will suggest is strongly related to the first reason for which I considered a physical explanation of QPT through many world evaluation of the function f misleading.

Both QPT and PIT have observable effects supporting them. Let me consider PIT first: the behavior of a quantum computer, and the possibility to solve classically intractable problems is a direct observable effect of the fact that information coded into different physical systems behave in a different fashion. This may raise the question whether information is different or whether its codification is so: but at a practical level this fact does not undermine the strong relationship between information and physical laws. This is a brute fact, and it stands as such.

Let me consider now what kind of observable effects support QPT: the fact that different measurements may give rise to different outcomes, coherently with the description provided by the formalism, is in some sense a supporting element for QPT. The main reason for considering this a weaker supporting element, with respect to the one suggested for PIT is the following. Computational processes like the one described in Equation (1) do not allow to identify a specific couple of input-output values, within the transition from input and output registers. This might be considered a minor problem, but it actually cause difficulties in satisfying one of the constraints for considering an effective procedure as evaluating a function [13], namely that one of reliability. More than that it is possible to highlight other descriptions of processes such as Equation (1) which do not support QPT and are perfectly coherent with both formalism and observation. As an example consider [14]: his account for such a process neglects completely the idea that a quantum computer is able to perform simultaneous computations, even though it is perfectly coherent with the rules of quantum mechanics for predicting outcomes of measurements.

Is this a strong reason for dropping QPT? My opinion is that the given argument for circularity plus the fact that evidences for stating PIT are stronger than for QPT, are enough elements for dropping QPT and keeping PIT. And even if one is not committed to dropping QPT, still the burden of proof relies on advocates of QPT and MWI (on this topic see especially [15]).

4. MWI and Information

Is MWI useless in the interpretation of quantum computational process? I guess that this is a too strong conclusion. In the previous sections I have shown something which is different from that claim. Summarizing, what I have highlighted is that:

- QPT and MWI are strongly related, the truth of QPT is a necessary condition for stating MWI;
- QPT and PIT cannot be stated together as "supporting cast" for MWI. Doing so means falling into circularity;
- There are strong reasons for keeping PIT and dropping QPT, namely the fact that empirical evidences for supporting PIT are more evident than for QPT.

Hence I conclude that MWI is not a reliable interpretation for the processes of quantum computation.

More than that it seems to me that the notion of information taken into account by MWI is far to abstract and does not build any link to the fact that quantum information theory is, in the first place, a physical theory of information. Consider for example [6] (p. 890): "in neo-Everett [MWI] there is no quantum/classical divide. Bits are not, in fact, a different sort of thing altogether with qubits". Statement like this certify an approach to the whole theory of communication and information, that draws no substantial link between a pure theoretical characterization of information (see, e.g., [16,17]) and its codification into physical systems. I think this notion of information is too *näive* for two main reasons.

In the first place it does not account for the different physical behavior of quantum computers. An advocate of MWI could answer for this specific case that the account for the different behavior in terms of the fact that the computation runs in many parallel worlds—and apparently he can do so, since the notion of information I am taking into consideration does not commit to furnishing physical explanations. Nevertheless, this answer is unsatisfactory: on the one hand, as I have shown before, there are strong reasons to keep a physical notion of information. On the other hand, even admitting that the previous reason is not enough, this account comes up with a very complex explanation of a physical behavior of a quantum computer. It does so just to save the idea that the formalism which describes quantum evolution is not just a powerful tool for predicting measurement outcomes but rather describes the whole computational process. A process which we cannot appreciate in terms of direct experience (see on this topic [15]). So, this notion of information may perhaps be stated in order to support the truth of QPT, but at the same time it seems to me too *näive*, by means of the fact that it cannot account for the different physical behavior of quantum computing devices with respect to classical counterparts (for a review of the fact that the difference between quantum and classical information is relevant within that topic see, e.g., [18] (chap. 14)).

The second reason for stating that this general conception of information is not accurate with respect to the study case of quantum information theory is strongly related to the fact that one of the most important philosophical contributions of quantum computational theory is to show that the strong version of the Physical Church-Turing Principle admits critical review [5] (p. 36):

> The efficiency of computation for any physical system is the same as that for a Turing machine (or perhaps, for a probabilistic Turing machine).

Quantum computational results achieved in the last thirty years show in fact that this thesis has to be, at least, modified. Is MWI able to justify a modification of this strong version of the Church-Turing thesis, without appealing to the fact that quantum computers are dealing with another kind of information? The answer to this question is a *desideratum*, but it seems to me that the only strategy is to rely once again on QPT, by stating that quantum computers can guarantee more computational efficiency by evaluating many values of the function in a single computational step.

In general it seems to me that a physical notion of information—and hence a physical divide between quantum and classical notions—is the simplest and more satisfactory strategy to explain the fact that the physical version of the Church-Turing thesis has to be modified. In fact this strategy appeals to the difference of physical behavior in physical terms—namely the different kinds of information which can be encoded into physical systems.

So, once again, is MWI useless? No, MWI is very helpful as a *näive* element for the comprehension of quantum information processes and also as an epistemological tool for the simulation of them. It really helps into getting an understandable, accurate reproduction of the quantum computational process. By the way it is not—up to my opinion and coherently with what I showed in this paper—an interpretation *tout court* of what is going on during quantum computational processes. The fact that the formalism of quantum mechanics may suggest that the computation is running on in many parallel worlds during transaction like the one described in Equation (1) is not a sufficient reason for committing to MWI.

5. Conclusions and Future Works

In this paper I showed that the Many World Interpretation of quantum computation (MWI) cannot be supported coherently by the Quantum Parallelism Thesis (QPT) and the Physical Information Thesis (PIT) at the same time. If does so, then he falls into circularity like suggested in [7]. Due to that fact I was forced to drop either one of PIT or QPT. I have shown that there are far the strongest empirical reasons for keeping PIT and dropping QPT and hence MWI, since this latter is strongly connected to the idea that the computation runs in parallel. I have discussed what kinds of notion of information can be stated in order to support QPT and MWI. I showed that this notion of information is weak. Finally, I analyzed in which sense MWI can be considered useful.

I am of course aware of the fact that what is missing in this paper—and this is a general feature of quantum information theory (see, e.g., [19])—is a proper, well defined notion of information. The previous discussion helped in outlining a so-called *pars destruens*, in the sense that I have outlined what a good notion of quantum information should not be, what kind of characteristics it should not have. However, of course, such a work draws a list of possible features that the notion of quantum information could have. A more precise investigation with respect to this topic is matter for further, future, investigations.

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Conflicts of Interest

The authors declare no conflict of interest.

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