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Quantum One Go Computation and the Physical Computation Level of Biological Information Processing

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Abstract By extending the representation of quantum algorithms to problem-solution interdependence, the unitary evolution part of the algorithm entangles the register containing the problem with the register containing the solution. Entanglement becomes correlation, or mutual causality, between the two measurement outcomes: the string of bits encoding the problem and that encoding the solution. In former work, we showed that this is equivalent to the algorithm knowing in advance 50% of the bits of the solution it will find in the future, which explains the quantum speed up.

Mutual causality between bits of information is also equivalent to seeing quantum measurement as a many body interaction between the parts of a perfect classical machine whose normalized coordinates represent the qubit populations. This "hidden machine" represents the problem to be solved. The many body interaction (measurement) satisfies all the constraints of a nonlinear Boolean network "together and at the same time"—in one go—thus producing the solution.

Quantum one go computation can formalize the physical computation level of the theories that place consciousness in quantum measurement. In fact, in visual perception, we see, thus recognize, thus process, a significant amount of information "together and at the same time". Identifying the fundamental mechanism of consciousness with that of the quantum speed up gives quantum consciousness, with respect to classical consciousness, a potentially enormous evolutionary advantage.

Keywords Quantum information · Quantum algorithms · Quantum speed up · Quantum measurement · Many body problem · Quantum consciousness

1 Introduction

Quantum algorithms require a lower number of operations than the corresponding classical algorithms. This "quantum speed up" is puzzling since, in some instances, the number of

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operations (oracle's queries) required by the classical algorithm is demonstratedly the minimum possible with a classical computer (a Turing machine). It should be said that quantum algorithms have been found heuristically (starting with Deutsch's algorithm [9], which is the archetype of all others) and that the reason of the quantum speed up was poorly understood until recently. The reason we have provided is peculiar [3, 4]. Quantum algorithms require a lower number of operations because they know in advance 50% of the solution they will find in the future.

We briefly explain this. By extending the representation of quantum algorithms to problem-solution interdependence, the unitary evolution part of the algorithm entangles the register containing the problem chosen by the oracle with the register containing the solution provided by the algorithm. Entanglement becomes correlation, or "mutual causality" or "mutual knowledge" between the two outcomes of the final measurement of the computer registers: the string of bits encoding the problem and the string of bits encoding the solution. In former work [3, 4], we showed that this is equivalent to the algorithm knowing in advance 50% of the bits of the solution it will find in the future. Correspondingly, the quantum algorithm is the sum of all the possible histories of a classical algorithm that, knowing in advance 50% of the bits of the solution, performs the operations still required to identify the missing bits—each history is a possible way of getting the advanced information and a possible result of computing the missing information. Besides explaining the speed up, this finding has an important practical consequence. The speed up, in terms of number of oracle's queries, comes from comparing two classical algorithms, with and without advanced information.

Mutual causality between bits of information (measurement outcomes) is also equivalent to seeing quantum measurement as a many body interaction between the parts of a perfect classical machine whose normalized coordinates represent the qubit populations. This hidden machine represents the constraints of the problem to be solved, which in the present context can always be seen as the problem of satisfying a nonlinear Boolean network. The many body interaction satisfies all the constraints together and at the same time, "in one go", thus producing the solution. As we will see, the unitary evolution part of the quantum algorithm "assembles" the machine, measurement "operates" it.

One go computation can formalize the physical computation level of the theories that place consciousness in quantum measurement. It provides a solution, at the physical level, to Chalmers' "hard problem", namely explaining how the informations coming from disparate sensorial channels can come together in the unity and present of subjective experience.

Let us consider visual perception. In this moment I see the audience, the meeting room, the chairs, the entrance, a lot of things "all together and at the same time". This is a natural language expression, but one we cannot easily do without. I cannot say that I see the chairs and the audience at different times. Our consciousness concerns the present time. I certainly see the chairs and the audience "together and at the same time". "Seeing" implies recognizing, thus processing. As long as consciousness entails information processing, we should translate into the precise language of information theory the expression "processing a lot of information together and at the same time". With reference to visual perception, the amount of information we are dealing with is at least that of a digital picture of the scene before us.

The requirement that perception processes a lot of information together and at the same time seems to be evident. Likely, it has remained unobserved because it did not match with any known form of computation. Quantum one go computation, because of its unique capability of satisfying a nonlinear Boolean network in one go, satisfies the requirement.

Identifying one go computation—i.e. the mechanism of the quantum speed up—with the physical computation level of consciousness, gives quantum consciousness a potentially enormous evolutionary advantage with respect to classical consciousness.

By generalization, it can be argued that one go computation is the physical computation level of biological information processing.

In the following sections, we review the explanation of the quantum speed up in a simple instance of data base search, gear it up with the many body analogy, and show that the resulting one go computation model interplays with a variety of information technology, biological, and philosophical issues

2 Reviewing the Explanation of the Quantum Speed Up

This section is an extract of former work. We review Gorver's algorithm [14] and our explanation of the quantum speed up [3, 4]. This is in view of the next section, where we describe the mechanism of the speed up by means of the perfect classical machine hidden in the quantum algorithm.

We consider the problem of data base search, visualized as the problem of finding a ball in a chest of drawers. Say that there are 4 drawers, numbered 00, 01, 10, 11. The problem can be seen as a game between two players. The first player, the oracle, hides the ball in drawer number $\mathbf{k} \equiv k_0 k_1$ (a two bit string) and gives to the second player the chest of drawers. In mathematical terms, he gives to the second player a black box, that, given the input $\mathbf{x} \equiv x_0 x_1$, computes the Kroneker function $\delta(\mathbf{k}, \mathbf{x})$, which is 1 if $\mathbf{k} = \mathbf{x}$ and 0 otherwise. The second player—the algorithm—should find the drawer number the ball is in—the value of $\mathbf{k}$—by computing $\delta(\mathbf{k}, \mathbf{x})$ for different values of $\mathbf{x}$—namely by opening different drawers.

In the classical case, on average the algorithm has to compute $\delta(\mathbf{k}, \mathbf{x})$ 2.25 times. Instead the quantum algorithm has to compute $\delta(\mathbf{k}, \mathbf{x})$ only once. More generally, given N drawers, a classical algorithm requires $O(N)$ computations of $\delta(\mathbf{k}, \mathbf{x})$, a quantum algorithm $O(\sqrt{N})$.

The quantum computer usually has two registers, X and V. X contains the value of $\mathbf{x}$ to query the black box with and V the output of the computation of $\delta(\mathbf{k}, \mathbf{x})$ (module 2 added to the former content of V for logical reversibility). We ideally add a third register K, just a conceptual reference, containing the oracle's choice—of the drawer number to hide the ball in. Extending the representation of the algorithm to the problem solved by the algorithm is a key step to explain the quantum speed up. In the initial state, all registers host even weighted superpositions—of oracle's choices, of arguments to query the black box with, of initial contents of register V:

$$\Psi_{in} = \frac{1}{4\sqrt{2}}(|00\rangle_K + |01\rangle_K + |10\rangle_K + |11\rangle_K)(|00\rangle_X + |01\rangle_X + |10\rangle_X + |11\rangle_X)(|0\rangle_V - |1\rangle_V). \tag{1}$$

One computation of $\delta(\mathbf{k}, \mathbf{x})$, followed by a suitable rotation of the measurement basis of register X, yields:

$$\Psi_{out} = \frac{1}{2\sqrt{2}}(|00\rangle_K|00\rangle_X + |01\rangle_K|01\rangle_X + |10\rangle_K|10\rangle_X + |11\rangle_K|11\rangle_X)(|0\rangle_V - |1\rangle_V). \tag{2}$$

The output of the quantum algorithm is in register X. Equation (2) simply says that, if the oracle's choice (of the number of the drawer to hide the ball in) is 00, then the algorithm—with just one computation of $\delta(\mathbf{k}, \mathbf{x})$—outputs 00, namely the solution for that choice of the oracle. If it is 01 then it outputs 01, and so on. The oracle's choice, of the drawer number to hide the ball in, has not been performed as yet. This choice is performed by measuring the content of register K—which we denote by $[K]$—in state (2) or, indifferently, (1). Measurement of $[K]$ selects a single value of $\mathbf{k}$, say $\mathbf{k} = 01$—i.e. oracle's choice 01. Correspondingly state Ψ_{out} reduces into:

$$\Psi_{out}^{a.m.} = \frac{1}{\sqrt{2}} |01\rangle_K |01\rangle_X (|0\rangle_V - |1\rangle_V). \tag{3}$$

Measuring $[X]$ in (3) yields the solution 01. Summarizing: the oracle hides the ball in drawer 01 and the algorithm, after computing $\delta(\mathbf{k}, \mathbf{x})$ only once, outputs 01. We could say that the oracle's choice of the drawer number 01 causes the algorithm to output 01. However, in (2), there is a complete symmetry between the content of register K and that of register X. Instead of measuring $[K]$ we could have measured $[X]$. This time we should say that reading the output of the algorithm and finding 01, causes the oracle to choose 01.

$[K]$ causes $[X]$ or $[X]$ causes $[K]$? We see the nondeterministic production of the contents of the two registers, due to measuring either $[K]$ or $[X]$ in (2), as *mutual determination* between such contents (mutual determination, or *mutual causality*, or *mutual knowledge* is between bits of information). The precise meaning of "mutual" is specified by the following use of the term.

We cannot say that reading the content of register K at the end of the algorithm (or indifferently at the beginning) causes the content of register X, namely that choosing the drawer number (a value of $\mathbf{k}$) to hide the ball in on the part of the oracle determines the drawer number the ball is found in by the algorithm: this is the classical perspective with no mutual determination.

For the same reason we cannot say that reading the content of X at the end of the algorithm causes the content of K, namely that reading the solution provided by the algorithm determines the drawer number chosen by the oracle, namely creates the ball in the drawer with that number.

Mutual causality is symmetrical [5]. We should say that the content of the two registers is determined by reading the first (second) bit of register K and the second (first) bit of register X. For example, finding that the first bit of K is 0 and the second bit of X is 1 changes (2) into (3). In this perspective, one bit of the data base location is created by the oracle (by the action of measuring either bit of K), the other bit by the action of reading, at the end of the algorithm and on the part of the second player, the other bit of the data base location in register X (i.e. by the action of measuring the other bit of X). It is important to notice that this other bit is the ball created in that bit. This explains why the quantum algorithm has to search only the bit created by the oracle, which requires just one computation of $\delta(\mathbf{k}, \mathbf{x})$.

Mutual causality or mutual knowledge is, in a different perspective, *advanced knowledge*. We should think of backdating, to before running the algorithm, the state reduction induced by measuring $[K]$ (as well known, reduction can be positioned any time). To the second player (to the algorithm), this is indistinguishable from having a $[K]$ measured before running the algorithm—thus to having a predetermined value of $\mathbf{k}$. In this perspective, the second player, by measuring $[X]$ at the end of the algorithm, does not "create" any bit of information, he just "finds" the two bits created by the oracle. Having to search only one bit becomes the second player knowing in advance, before running the algorithm, either one of the two bits that he will read at the end of the run. In other words, the algorithm knows in advance, before running, 50% of the information about the solution it will produce at the end of the run.

Either form of mutual causality explains the structure of the quantum algorithm. The computation stage of the quantum algorithm can be represented as the sum of all the possible histories of a classical algorithm that, knowing in advance 50% of the information about the solution of the problem (here the value of either k_0 or k_1), performs the oracle's queries still required to identify the solution (here one computation of $\delta(\mathbf{k}, \mathbf{x})$). Each history corresponds to a possible way of getting the advanced information and a possible result of computing the missing information still required to identify the solution.

For example, if we know in advance that $k_0 = 0$, to determine the data base location we can compute $\delta(01, 00)$, or $\delta(01, 01)$, or $\delta(00, 00)$, or $\delta(00, 01)$. Let us assume that we compute $\delta(01, 00)$ and obtain $\delta(01, 00) = 0$. We are pinpointing one among all the possible histories. This means $k_1 = 1$: the data base location is identified. Assuming that the initial content of V was 1, the result of the computation is $(1 + 0) \bmod 2 = 1$. We represent this history in quantum notation as a sequence of sharp states. The history initial state is thus $\frac{1}{\sqrt{2}}|01\rangle_K|00\rangle_X|1\rangle_V$ and the state after the computation of $\delta(\mathbf{k}, \mathbf{x})$ is the same.

If we sum together all the possible histories, with phases that reconstruct the quantum algorithm (and maximize entanglement between registers K and X), we obtain the computation stage of the quantum algorithm. The final rotation of the basis of register X transforms entanglement into correlation between measurement outcomes—oracle's choice and solution. This holds for all quantum algorithms and is a tool to create new ones [4].

3 Analogy with Many Body Interaction

Interestingly, the quantum data base search algorithm can be represented by means of a perfect classical machine that computes $\delta(\mathbf{k}, \mathbf{x})$ only once (the 2.25 computations on average apply to realistic, imperfect, classical machines). This machine performs a hypothetical many body interaction that is actually a visualization of the behavior of the qubit populations throughout quantum measurement [1, 2]. This many body interaction representation shows that a precondition of the quantum speed up is processing all the information together and at the same time, which naturally implies a nondeterministic form of computation.

We start with a representation of classical computation that highlights its two body character. This is Fredkin&Toffoli's billiard ball model of reversible computation [12]. We have a billiard and a set of balls moving and, from time to time, hitting each other or the sides of the billiard, with no dissipation. We should prepare initial ball positions and speeds so that there will be no many body collisions. This is not a problem, it is just an essential feature of the machine: each individual collision is between two balls or a ball and a side. Many body collisions should be avoided because they yield undetermined outcomes—this is the many body problem of course.

Where and when in this situation can we say that any amount of information is processed together and at the same time, as assumedly required to explain perception? Outside collisions, the positions and speeds of different balls are processed independently of one another. In collisions, the positions and speeds of two balls are processed together and at the same time. However, this joint processing of information never scales up, it is always confined to ball pairs. The information processed together and at the same time is the three bits of the input of a universal Boolean gate—represented as a two body interaction by Fredkin's controlled swap gate or Toffoli's controlled-controlled not gate. Of course, parallel computation—several two ball collisions at the same time—does not count since the information is not processed together. Summing up, we should discard classical computation as a model of perception, because the amount of information processed together and at the same time is no more than three bits.

The many body problem arises when more than two balls collide "together and at the same time". The problem is that the outcome of the collision is undetermined. However, this is an idealization; in fact the slightest dispersion in the times of pairwise collisions restores deterministic two body behavior; a different way of ordering the successive two body collisions originates discretely different outcomes.

Now we describe the perfect classical machine (perfectly rigid, accurate, and reversible) hidden in the quantum algorithm—see also [1] and [2]. We represent $\delta(\mathbf{k},\mathbf{x})$, a function of the binary strings $\mathbf{k} \equiv k_0k_1$ and $\mathbf{x} \equiv x_0x_1$, by the system of Boolean equations

$$\begin{aligned} y_0 &= \sim XOR(k_0, x_0), \\ y_1 &= \sim XOR(k_1, x_1), \\ \delta(\mathbf{k},\mathbf{x}) &= AND(y_0, y_1), \end{aligned} \tag{4}$$

of truth tables

	k_0	x_0	y_0
C_{00}	0	0	1
C_{01}	0	1	0
C_{02}	1	0	0
C_{03}	1	1	1

	k_1	x_1	y_1
C_{10}	0	0	1
C_{11}	0	1	0
C_{12}	1	0	0
C_{13}	1	1	1

	y_0	y_1	δ
C_{20}	0	0	0
C_{21}	0	1	0
C_{22}	1	0	0
C_{23}	1	1	1

(5)

The C_{ij} labeling the rows of the truth tables are real non-negative variables. They are the coordinates of the machine parts—our hidden variables. We replace the system of Boolean equations (4) by the following system of equations, representing mechanical constraints between the coordinates of the machine parts,

$$\forall i : Q = \sum_j C_{ij}, \qquad Q^\chi = \sum_j C_{ij}^\chi, \tag{6}$$

$$C_{01} + C_{02} = C_{20} + C_{21}, \qquad C_{11} + C_{12} = C_{20} + C_{22}, \tag{7}$$

with $\chi > 1$. Q is an auxiliary coordinate. In (6), we can think that left equations are implemented by three differential gears, one for each truth table i. Each gear has one input Q and four outputs $C_{i0}, C_{i1}, C_{i2}, C_{i3}$; right equations are implemented by a similar arrangement with input Q^χ and outputs $C_{i0}^\chi, C_{i1}^\chi, C_{i2}^\chi, C_{i3}^\chi$, obtained from the former coordinates by means of nonlinear transmissions. Equations (7) are implemented by other two differential gears, each with two inputs and two outputs, and the coordinate C_{20} replicated in each gear.

We discuss the behavior of this analog computer assembling it step by step:

1. We start with one of the left equations/gears (6), for some value of i. Initially all coordinates are zero. If we push (the part of coordinate) Q, the C_{ij} move to satisfy push and equation. We have a many body interaction between 4 machine parts of coordinates C_{ij}—we choose Q as the dependent variable. Collisions between bodies are replaced by pushing between parts. A push instantly changes the force (or couple) applied to a part from 0 to $\neq 0$. The outcome of this many body interaction is undetermined: for a given Q, there are infinitely many possible "machine movements". Since we have to match machine behavior with the transition from state (2) before measurement to one of four possible states after measurement, each occurring with probability $\frac{1}{4}$, we postulate that the probability distribution of machine movements is symmetrical for the exchange of any two C_{ij}.
2. We add the right equation/gear for the same value of i. Now pushing Q can move at most one C_{ij}—C_{ij} movements of are mutually exclusive with one another. Perfect coincidence

of the times of the push exchanged between pairs of parts implies perfect rigidity and accuracy of the machine. Flexibility and other imperfections restore deterministic two body behavior, likely with an ordering of pairwise pushes that frustrates the mechanical constraints, thus jamming the machine. For example, if two or more C_{ij} move initially, thanks to a slight deformation of the constraints, the further movement of Q increases the deformation until the machine jams. No deformation, i.e. machine perfection, implies no jams, namely postulating that one of the C_{ij} moves to satisfy push and equations. Symmetry of the probability distribution yields even probabilities of movement for the C_{ij}. The machine movement produces the Boolean values of the row (of the truth table i) labeled by the one $C_{ij} > 0$.

3. We add the remaining equations/gears. Equations (6) assure that only one C_{ij} moves for each i, (7) assure that the C_{ij} that move label the same values of the same Boolean variables, namely that the machine movement satisfies the system of Boolean equations (4).
4. If we push Q, there are 16 mutually exclusive machine movements, corresponding to the possible ways of satisfying the system of Boolean equations (4). We have a many body interaction between the 8 machine parts of coordinates C_{0j} and C_{1j}, the other coordinates being dependent variables.
5. If we push C_{23} instead of Q, the movement of C_{23} yields $\delta(\mathbf{k}, \mathbf{x}) = 1$. Now there are 4 mutually exclusive machine movements. Each movement produces an oracle's choice and the corresponding solution provided by the second player by means of a single computation of $\delta(\mathbf{k}, \mathbf{x})$, namely a single transition $C_{23} = 0 \rightarrow C_{23} > 0$.

This postulated many body interaction represents the behavior of the qubit populations in quantum measurement. In fact there is an invertible linear relation between the eight $\frac{C_{0j}}{Q}, \frac{C_{1j}}{Q}$ ($j = 0, 1, 2, 3$) and the eight qubit populations. For example, with reference to the reduced density operator of qubit k_0, let $p_{k_0}^{00}$ be the population of $|0\rangle_{k_0}\langle 0|_{k_0}$, and $p_{k_0}^{11}$ that of $|1\rangle_{k_0}\langle 1|_{k_0}$. By looking at the truth tables, one can see that their relation with the $\frac{C_{ij}}{Q}$ is:

$$p_{k_0}^{00} = \frac{C_{00} + C_{01}}{Q}, \qquad p_{k_0}^{11} = \frac{C_{02} + C_{03}}{Q}. \tag{8}$$

The relation for the other qubits, k_1, x_0, and x_1, is derived in a similar way. When all coordinates are 0, all ratios are $\frac{0}{0}$ and are thus compatible with any value of the populations in the state before measurement. Having postulated a symmetric probability distribution of machine movements sets to $\frac{1}{2}$ the values of the qubit populations before measurement (like in state 2). When $C_{23} > 0$, these ratios become determined and correspond to either 0's or 1's of the populations of the measured observables: the C_{ij} that do not move yield $\frac{C_{ij}}{Q} = 0$, those that move yield $\frac{C_{ij}}{Q} = 1$.

That infinite classical precision can be dispensed for (thus implemented, it can be argued) by quantization was already noted by Finkelstein [11].

This many body analogy helps to understand what goes on, computationally, in quantum measurement: satisfaction in one go—and with a single computation of $\delta(\mathbf{k}, \mathbf{x})$—of the nonlinear system of Boolean equations constituted by (4) and $\delta(\mathbf{k}, \mathbf{x}) = 1$ (satisfied by pushing C_{23}).

On the contrary, satisfying this system classically, by means of deterministic two body interactions, would require on average, 2.25 computations of $\delta(\mathbf{k}, \mathbf{x})$. More in general, a classical computation satisfies in one go (i.e. satisfying each gate at the first attempt) a linear Boolean network, in fact through the deterministic propagation of an input into the output. In the case of a nonlinear network, local deterministic satisfaction of gates can be done in several ways, and is likely done in a way that does not satisfy other gates. This leads to trial and error and repeated computations, which yields the relative zero of the quantum speed up.

In the initial state of the quantum algorithm (1), the hidden machine is disassembled and the coordinates of the machine parts are independent of one another. Correspondingly the quantum state is factorizable—quantum measurement of the register contents would yield uncorrelated outcomes.

The unitary evolution part of the quantum algorithm, yielding state (2), assembles the machine: all parts—in the configuration all coordinates zero—get geared together in a non-functional relation (established by (6), (7)). Correspondingly the quantum state is entangled. Measuring the register contents in this state corresponds to operating the machine—to pushing C_{23}. This generates the interaction that in one go produces the oracle's choice, runs the algorithm, and produces the solution.

Note that this interaction, corresponding to the transition $C_{23} = 0 \rightarrow C_{23} > 0$ changes the entire forward evolution, the unitary transformation of the preparation ending with the state before measurement, into the backward evolution, the same transformation but ending with the state after measurement. In the transition, all the information is processed together and at the same time, however, as a retaliation, we cannot say when this happens.

It is interesting to check the behavior of the hidden machine when the oracle's choice is fixed before running the algorithm, say to $k_0 = 0$, $k_1 = 1$. Correspondingly, the quantum algorithm becomes

$$\begin{aligned} \Psi_{in} &= \frac{1}{4\sqrt{2}} |01\rangle_K (|00\rangle_X + |01\rangle_X + |10\rangle_X + |11\rangle_X)(|0\rangle_V - |1\rangle_V), \\ \Psi_{out} &= \frac{1}{2\sqrt{2}} |01\rangle_K |01\rangle_X (|0\rangle_V - |1\rangle_V). \end{aligned} \tag{9}$$

Measuring $[X]$ in Ψ_{out} yields the solution in a deterministic way, with no state reduction.

The hidden machine for this choice of the oracle is obtained by adding the equations/gears representing it:

$$\begin{aligned} Q &= C_{00} + C_{01}, \\ Q &= C_{12} + C_{13}. \end{aligned} \tag{10}$$

Pushing C_{23} deterministically, with probability 1, yields $k_0 = 0$, $k_1 = 1$, $x_0 = 0$, $x_1 = 1$. It should be noted that there is still a many body interaction that satisfies a nonlinear Boolean network in one go—namely with a single computation of $\delta(01, \mathbf{x})$ against the 2.25 on average of classical computation. The outcome of the interaction is deterministic just because this time the nonlinear network admits a solution only. In other words, quantum measurement performs a nondeterministic computation with a deterministic outcome.

This many body analogy (with or without pre-fixed oracle's choice) can easily be generalized.

If several function evaluations are required, like in data base search with $N > 4$, just one computation of $\delta(\mathbf{k}, \mathbf{x})$ and one rotation of the X basis creates the superposition of a state of maximal entanglement between K and X (corresponding to the assembled machine) and the factorizable initial state back again [3, 4] (corresponding to the disassembled machine). Iterating these operations $O(\sqrt{N})$ times "pumps" the amplitude of the entangled state to about 1. Measurement should be performed—the machine operated—in this final state.

In the other quantum algorithms, the oracle chooses a function $f_{\mathbf{k}}(x)$ out of a known set of functions and gives to the second player the black box for its computation. The second player should find out a certain property of the function (e.g. its period) by means of one computation of $f_{\mathbf{k}}(x)$—against, classically, a number of computations exponential in the size of the argument. It is sufficient to: (i) represent the oracle's choice and the property of the function as a network of Boolean gates, with the rows of the truth tables labeled by the hidden variables, (ii) introduce the equivalent system of equations on the qubit populations, (iii) assemble the perfect machine through the unitary evolution part of the quantum algorithm, and (iv) operate it by measuring register contents. Quantum measurement satisfies in one go a nonlinear Boolean network.

4 Possible Interdisciplinary Implications

The notion that a quantum algorithm knows in advance 50% of the solution it will find in the future, and the equivalent notion of one go computation—satisfying in one go a nonlinear Boolean network, interplay with a variety of scientific and philosophical issues.

Among the scientific issues, we find:

- The character of visual perception implies the capability of processing "together and at the same time" a significant amount of information. One go computation can process in this way any amount of information, therefore it can be the physical computation basis of perception. Classical computation, capable of processing together and at the same time no more than three bits, could not.
- One go computation provides a formalization of the physical computation level of those neurophysiological and physical theories that place consciousness in quantum measurement, like Hameroff&Penrose's orchestrated objective reduction theory [16–18] and Stapp's theory [25].
- Let us adopt the strong artificial intelligence (AI) assumption that a state of consciousness is a computation process with an upper bound to the number of computation steps, thus representable as the process of satisfying a Boolean network. In the present perspective, the entire computation should be performed in one go, together and at the same time, by quantum measurement. To match subjective experience, the computation should represent the feeling of self, memories, emotion, thinking, sensorial information, etc. Most of the processing (e.g. the feeling of self) would be repeated at each successive measurement; part of the processing would be updated to track changes—in memories, emotions, etc. A frequency of 50 measurements per second (50 "frames per second"), could cope with our rates of change.
- One go computation solves—at the physical computation level—the "hard problem" pinpointed by Chalmers [7]: explaining how disparate informations can come together in the unity and present of subjective experience.
- A qualia is an atomic sensation—apparently without an internal logical structure—like that of "redness" [22]. Classical computation is phenomenological in character, feeling a qualia would correspond to an algorithm that behaves consistently with that feeling (talking of the red color, stopping at a red light). In the context of quantum one go computation, "seeing", or "feeling", are synonyms of "measuring". Feeling a qualia could correspond to measuring some fundamental observable (and, at the same time, the self—possibly comprising other qualia—and some relation between feeling of self and the feeling of a color).
- Identifying consciousness with one go computation—i.e. the mechanism enabling the quantum speed up—gives quantum consciousness a potential evolutionary advantage over

classical consciousness. The former could be immensely quicker and/or leaner in computational resources in tasks essential for survival. With respect to classical computation, quantum associative memory requires an exponentially lower number of artificial neurons [28], quantum pattern recognition can be traced back to quantum data base search, which yields a quadratic speed up [27, 30], quantum machine learning has recently been shown to be substantially faster [20].

- Teleological evolutions often explain organic behavior better than deterministic classical evolutions [13]. However, such explanations are generally considered to be phenomenological in character, because of the belief that, really, evolutions could not be driven by final conditions. Quantum algorithms, being partly driven by their future outcome, provide well formalized examples of teleological evolutions.
- Stapp's theory relies on the quantum Zeno effect and lives with decoherence [25]. The present model suffers decoherence exactly as quantum computation does, which means very much. This divergence could mean cross fertilization. It puts emphasis on the quantum information approach of driving the state of the computer registers by means of the Zeno effect [24].
- The notion that quantum algorithms are partly driven by their future outcome is consistent with Sheehan's retrocausation theory and critical revision of the notions of time and causality in physics [23].

Among the philosophical issues, we find:

- Being entirely driven by past conditions excludes free will, as well as being entirely driven by future conditions. Being partly driven by either condition—like quantum algorithms—leaves room for freedom. In quantum algorithms, freedom from determinism is nondeterministic computation—capability of satisfying in one go a nonlinear Boolean network.
- A quantum algorithm, for the fact of knowing in advance 50% of the solution it will find in the future, "exists" in an extended present. This suggests that our existence is not confined to the instantaneous present we normally experience. With reference to e.g. Indian philosophy, the experience of an instantaneous present would be illusory, the timeless reality experienced in Moksa (in western language, in special "altered states of consciousness" [8]) objective.
- Insight—understanding an even immensely complex structure in one instant—seems to be a most evident experience of one go computation.
- One go computation has an upper bound to the number of computation steps, like quantum algorithms and AI. This is a limitation with respect to Lucas-Penrose's argument that consciousness—being able to "see" Gödel's theorems—is not confined to finitistic computation [19, 21]. As for the possibility of extending one go computation to denumerably infinite Boolean networks, see [6].
- Mind-body duality, or the duality between a perfect world of ideas and an imperfect material world, here becomes the duality between (i) perfect/nondeterministic classical machines (hidden in quantum measurement), yielding a speed up and capable of processing any amount of information together and at the same time, thus of hosting consciousness, and (ii) imperfect/deterministic classical machines, capable of processing no more than three bits together and at the same time, incapable of hosting consciousness. This also matches with Stapp's distinction between the mind and the rock aspect of matter [25]. If there is only quantum physics, this duality vanishes. The perfect/nondeterministic side would be objective, the other side phenomenological or illusory.

5 Conclusions

The advanced knowledge of the solution, which explains the quantum speed up, can be seen as a many body interaction between the parts of a perfect classical machine whose coordinates represent the qubit populations throughout quantum measurement. In one go, this interaction satisfies all the constraints of a nonlinear Boolean network together and at the same time.

This also holds when the oracle's choice is fixed before running the algorithm. In this case, the unitary evolution part of the quantum algorithms can produce an eigenstate of the observable to be measured. Thus quantum measurement produces the solution of the problem with probability 1. However, this does not mean that the algorithm produces the solution in a deterministic way. Quantum measurement still performs a nondeterministic computation, satisfying in one go a nonlinear Boolean network that admits just one solution. One should not mistake the nondeterministic production of a deterministic outcome with a deterministic production.

The main character of "one go computation" is processing any amount of information together and at the same time.

In contrast, the amount of information processed together and at the same time by classical computation is limited to the three bit input of a single universal Boolean gate—many such gates in parallel do not count since the information is not processed together. Correspondingly, classical computation cannot satisfy a nonlinear Boolean network in one go (but for a very lucky instance).

This way of seeing together the many body problem, classical computation, quantum measurement, and quantum computation could be interesting in both the physics of computation and the interpretation of quantum mechanics.

From another standpoint, one go computation answers our prerequisite for the physical computation level of perception—namely, being capable of processing any amount of information together and at the same time. With reference to the theories that place consciousness in quantum measurement, one go computation seems to take two pigeons with one stone:

1. it formalizes the physical computation level of these theories,
2. in such a way that the fundamental mechanism of consciousness is the same of the quantum speed up.

The overall result is giving quantum consciousness, with respect to classical consciousness, a potentially enormous evolutionary advantage.

More in general, one go computation could be the physical computation level of biological information processing. It provides a scientific ground to teleological explanations of organic behavior and a possible answer to long standing philosophical questions.

The assumption that biological computation is one go computation implies that the brain hosts a sufficient quantum coherence [10, 15, 25, 26, 29]. It can be argued that the problem of decoherence is common to quantum information, whose alleged advantage—possibility of working close to 0 Kelvin and without hydrophobic pressure—is frustrated by the fact that the size of the computation cannot scale up in any conceivable way. Our biased opinion is that the top level evidence that the mind is quantum, and cannot be classical, is strong enough to look for a common solution. Tackling the problem of decoherence from the two leads—quantum information and biological—might yield cross fertilization.

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