Decomposing the Universe

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1 Introduction

In his case for "Why we live in the Computational Universe," Giorgio Fontana argues that it is possible for our Universe to show evidence that the observable reality exists within a larger context [1]. He applies concepts from computer science within the framework of a computational model for cosmology. While at first this approach seems forced, he eventually shows that the new Quantum Computational Universe model developed by Seth Lloyd has great potential.

He begins by defining what he terms the First Level Universe (FLU) as follows: "The First Level Universe is a system that is not optimized for efficiency and has no error." He then compares this with the Computational Universe, distinguishable by evidence of the characteristic "effects, consequences, and limitations" of the computation, and in particular signs of optimization, which he sees as "unavoidable" in such a model. For purposes of acronym allocation, I will refer to this second model as the Computationally Perfected Universe (CPU).

Next Fontana sets out to support the possiblity that we in fact live in the CPU. He illustrates this first in terms of a classical model based on his own work in general relativity, and then moves on to a quantum model drawn from the recent work of Seth Lloyd. Before examining these models in depth, let us begin with his distinction between the FLU and the CPU in terms of optimization.

2 Optimization

A first step towards interpreting Fontana's separation of the FLU and CPU is to understand what is meant by optimization. Tommaso Toffoli expressed it in simple terms in a paper on "Physics and Computation [2]. He states, "Here, instead of a direct problem (What will happen in this situation?) we have what is called an 'inverse problem' (In what situations will such a thing happen?), which is usually much harder to solve since it may involve an exhaustive search." Fortuanatly, new search techniques are developing [3], particularly those based on quantum computing, so it seems natural to connect a quantum computation with optimization.

David Wolpert has recently shown that there are limits to what we should expect from physical computation [4]. However, his "results hold for any single computer not so powerful as to preclude the possible existence anywhere else in the universe of another computer as powerful as it is." Once we introduce *two* computers, we could not call such a computation universal. Wolpert notes that his results imply, "In a certain sense, the universe is more powerful than any information-processing system constructed within it could be." This leaves the possibility of the universe itself as the information-processing system.

Detecting such a computation in the cosmology of our universe at first seems highly unlikely. Toffoli points out that, "The physics of it doesn't make any difference to the logic of a computation; it just affects certain material aspects, such as speed, volume, and energy dissipation." Then a *universal* computation could affect these on the cosmological scale. Fontana's argument is basically that we should then be able to recognize optimization, a characteristic that is not allowed in the FLU, in these physical properties.

3 The Computational Universe

In Fontana's opinion, "The most compelling evidence for the Computational Universe is the fact that physical laws and physical constants are the same everywhere in the Universe." From this he has supposes that the laws of physics exist outside of the four-space in which we live. For example, having associated particles with datasets, he then compares quantum tunneling to the deletion of a particle, followed by the appearance of another particle replacing it according to the rules of physics, a sort of re-allocation of "local variables" in the CPU. He cites action at a distance as an indication of optimization since "a process is applied to a particle only when required." Here he seems to be comparing entanglement to memory addressing. In a word, this is just "spooky."

Fontana's other assertions of the features of the CPU are rather farfetched. For example, his discussion of the implications of the CPU for human beings rests on tests involving memory that hardly seem appropriate for scientific discussion. However, he seems to reach more solid ground in his analysis of Seth Lloyd's recent contributions from quantum computation, which will be discussed in the next section. A notable difference between their papers is that Lloyd makes no mention of a *programmer* in applying the computational principles. Fortunately, Lloyd's model offers more compelling evidence than Fontana's classical one in terms of specific, observable predictions.

It is not entirely surprising that Fontana's classical discussion of the CPU falls somewhat short of being convincing. Feynman put it plainly: "Nature isn't classical, dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look easy" [5].

4 The *Quantum* Computational Universe

As Fontana notes, most dynamical laws derived from the Quantum Computational Universe model are automatically covariant, so Einstein's equations naturally follow. In describing this model, Seth Lloyd goes further in developing the connection to general relativity, showing that since a quantum computation includes a superposition of states, the quantum computational universe is a superposition of spacetimes [8]. Each quantum state is in fact a computational history of scattering events, the logical operations of this generalized computer.

Lloyd models quantum computations with graphs, each consisting of an input state, a series of quantum wires and logic gates, and if the computation halts, a final state. The logic gates correspond to unitary operations on the states. He shows how this can simulate the behavior of dynamical systems. In particular, he relates the model to lattice gauge theory. Lattice models work particularly well if the underlying theory is quantized.

Associating the wires and gates of the Quantum Computational Universe with paths and events, respectively, Lloyd connects this model with general relativity so that the computation itself produces quantum gravity. He then generalizes the computational graphs to manifolds in spacetime. By his analogy, "the information that moves through the computation effectively 'measures' distances in spacetime in the same way that the signals passed between members of a set of GPS satellites measure spacetime." Thus information flow replaces the more familiar concept of the propagation of elecromagnetic waves.

While he derives the Einstein-Regge equations for this model, he notes that they have not been solved. This will be a crucial step in further development of the model. Lloyd's work basically develops the specific connection of the model to cosmology only as far these approximations. The specifics of a full analytical extension of this model remain to be explored. However, even in the context of qualitative principles and the course-grained approximations done to date, the model explains many experimental observations and makes a few strong predictions.

5 Observable Evidence

5.1 Quantum Gravity

While Lloyd claims that this model "supports" gravity waves, they in fact emerge rather naturally. He almost seems to be joking when he remarks that, "if the computation contains LIGO, it will detect those gravity waves," since the Laser Interferometer Gravitational-Wave Observatory (LIGO) is certainly present in our universe, whether it is computational or not. However, the indications of the computational universe model for solving the back reaction problem are not to be taken lightly.

Back reaction concerns the connection between gravity and the metric. Essentially, gravity waves can effect the evolution of space-time. Mukhanov *et al.* have shown based on calculations of the associated 'effective' energy-momentum tensor that this should have a non-negligible effect on the evolution of the early universe during inflation [6].

In the quantum computational universe model, back reaction is explained since fluctuations in the metric are coupled to fluctuations in the matter distribution. Lloyd generally asserts that, "Any local quantum theory involving pairwise interactions allows the construction of a theory of quantum gravity;" although, he admits that the full details of this coupling for the quantum computational universe have not been investigated and may be nontrivial. Substantively, since matter performs the quantum computation, the metric arising from the resulting information must be affected by changes in its local behavior.

Based on this feature of the model, Lloyd makes a solid prediction concerning the possible future experiment described in Ref. [7] by W. Marshall *et al.* The authors propose to probe quantum interference by coupling a large mirror with a single photon. This could produce a quantum superposition of $10^1$4 atoms, which is a much more massive system than has previously been observed.

From the contraints of the computational model, Lloyd explicitly states that this experiment, "should reveal no intrinsic decoherence arising from the self-energy of the gravitational interaction." Up to periodic oscillations, Marshall *et al.* show this implies that the system should be found in the state

$$\frac{1}{\sqrt{2}}(|0\rangle_A|1\rangle_B + e^{i\kappa^2 2\pi}|1\rangle_A|0\rangle_B)|\beta\rangle$$

where the superposition of the photon in state A or B and the coherent state $|\beta\rangle$ of the mirror is disentangled. This can be observed by interference effects. Decoherence is described by the condition that "If the environment of the mirror 'remembers' that the mirror has moved, then, even after a full period, the photon will still be entangled with the mirror's environment, and thus the interference for the photon will be reduced." In Lloyd's model this represents information flow from the photon/mirror system to the surroundings. The results of this experiment will be an interesting check of the quantum computational universe model.

5.2 Inflation

Other predictions of the model concern its compatibility with the current theories of inflation in the early universe. Using a common specific example of a large-scale physical computation, Lloyd points out that "cellular automata may not be isotropic: particular directions may be picked out." However, he considers a model built up from lattice QCD, giving large scale isotropies for so-called coarse-grain dynamics. In Lloyd's course-grained approximation, the quantum computational universe is homogeneous and isotropic, and the Friedman-Robertson-Walker (FRW) equations apply. For now we can consider this approximation as a working model, for as Feynman remarked back in 1982 in reference to physical computation, "there might be very small anisotropies. Physical knowledge is of course always incomplete, and you can always say well try to design something which beats experiment at the the present time, but predicts anisotropies on some scale to be found later."

With this assumption, the model recovers all of the standard results of inflation. Writing the FRW equations as

$$\frac{-16\pi}{3}GK = \dot{H}$$

and

$$\frac{8\pi}{3}G(K+U) = H^2 - \frac{k}{a^2}$$

where K is the kinetic and U the potential energy density, leaves the freedom to choose the initial values of K and the scale factor a. By setting $a = 1$ and K = 0, Lloyd recovers conventional inflation at the Planck scale. However, as with most theories of inflation, the critical "magic" phase transition driving the creation of a radiation-dominated early universe remains largely unexplained.

6 Discussion

In discussing the implications of Lloyd's model, while not entirely rigorously, the main point that Fontana underscores is that this is currently an area of rapid theoretical development. While Lloyd's model needs a great deal of further work, particularly in the full solution of the Einstein-Regge equations, he has shown that it fits with current observations, at least for the so-called course-grain approximations done so far. It explains experimental observations and features of our reality quite well. As Feynman challenged, "That would be good physics if you could predict something consistent with all the known facts and suggest some new fact that we didn't explain." So far the Computational Universe models seem to have a good handle on the first part of this, as well as giving testable predictions of new physics.

References

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