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Non-Localized Physical Processes Can Help Speed up Computations, Be It Hidden Variables in Quantum Physics or Non-Localized Energy in General Relativity

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Non-Localized Physical Processes Can Help Speed up Computations, Be It Hidden Variables in Quantum Physics or Non-Localized Energy in General Relativity

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Abstract While most physical processes are localized – in the sense that each event can only affect events in its close vicinity – many physicists believe that some processes are non-local. These beliefs range from more heretic – such as hidden variables in quantum physics – to more widely accepted, such as the non-local character of energy in General Relativity. In this paper, we attract attention to the fact that non-local processes bring in the possibility of drastically speeding up computations.

1 Localized Character of Physical Processes Limits Computation Speed

Most physicists believe that all processes are localized. According to modern physics, all speeds are limited by the speed of light c. This means, in particular, that all physical processes are *localized* – if some event is happening at a spatial location x at moment t, then at a next moment of time $t + \Delta t$, the only objects that can be affected by this event are located at distance $\leq c \cdot \Delta t$ from the location x; see, e.g., [3, 8].

Localized character of physical processes limit computation speed. How does the localized character of physical processes affect computations? At any level of

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technological advancement, there are natural limitations on how faster a single processor can compute. To perform computations faster, a natural idea is to have several processors working in parallel. This is exactly how modern high-performance computers work: they consist of thousands of processors working in parallel.

At first glance, it may seem that the more processors we use, the faster the resulting computations. However, this first impression is wrong: limits on communication speed affects the resulting computation speed; see, e.g., [7].

Indeed, suppose that we ask a parallel computer to perform some computations. This computer performs the corresponding computations, and at some time t seconds after the task was given, delivers the result of this computation to us.

This computer may be huge, it may go all the way to the Moon, but, because of the limitations on the communication speed, the only processors that could affect the computation results are the ones which are located at a distance not exceeding $r = c \cdot t$ from our location. Processors located further away from our location may be trying their best, but cannot affect the computation result – since during the time t, any communication can only reach the distance $c \cdot t$.

So, all processors affecting the computation result are located inside the sphere of radius $r = c \cdot t$, with the center at our location. The volume of this inside of the sphere is

$$V = \frac{4}{3} \cdot \pi \cdot r^3 = \frac{4}{3} \cdot \pi \cdot c^3 \cdot t^3. \tag{1}$$

How many processors can fit into this volume? Let ΔV be the smallest possible volume of a single processor that can be attained at a current technological level. This means that the volume occupied by each processor is larger than or equal to ΔV. If N is the overall number of processors inside this area, this means that the overall volume of all the processors in this area is larger than or equal to $N \cdot \Delta V$. This volume cannot exceed the overall volume (1) of this area: $N \cdot \Delta V \le V$. Thus, we get an upper bound on the number of processors:

$$N \le \frac{V}{\Delta V} = \frac{4}{3} \cdot \frac{\pi \cdot c^3}{\Delta V} \cdot t^3, \tag{3}$$

i.e.,

$$N \le C \cdot t^3, \tag{4}$$

where we denoted

$$C \stackrel{\text{def}}{=} \frac{4}{3} \cdot \frac{\pi \cdot c^3}{\Delta V}.$$

In principle, anything that can be computed in parallel on N computers can also be computed sequentially, on a single processor:

- First, we simulate, on the single processor, the first computation steps on all N processors – first we simulate the first step of the first processor, then the first step of the second processor, etc. This simulation of a single step requires N computation steps of the single processor.

- Then, we simulate, on the single processor, the second computation steps on all N processors – first we simulate the second step of the first processor, then the second step of the second processor, etc. This simulation of a single step also requires N computation steps of the single processor, etc.

To perform each computational step of the parallel computer, we need N steps of the single processor. Thus, such simulation-based sequential computation requires time $N \cdot t$.

Let us denote by T the smallest amount of computation time needed to perform this computation on a sequential computer. Since a sequential simulation of a parallel computer is one of the ways to perform the corresponding computations on a sequential computer, we conclude that $T \le N \cdot t$. So, using the inequality (4), we can conclude that

$$T \le C \cdot t^3 \cdot t = C \cdot t^4. \tag{5}$$

This inequality, in its turn, implies that $t^4 \ge C^{-1} \cdot T$, i.e., that

$$t \le C^{-1/4} \cdot T^{1/4} = \text{const} \cdot c^{-3/4} \cdot T^{1/4}. \tag{6}$$

This lower bound on the computation time of parallel computation does not depend on the number of processors – it is an absolute lower bound preventing us from having an unlimited computation speedup.

2 But Are All Physical Processes Localized?

Hidden variables in quantum physics: a brief historical overview. Quantum physics describes micro-processes. For many of these processes, at present, we can only make probabilistic predictions. For example, for radioactive decay:

- we cannot predict at what moment the radioactive atom will decay,
- but we can predict – with high accuracy – the corresponding probabilities, so that we can accurately predict which proportion of the atoms will decay by time t.

Such probabilistic character of predictions did not start with quantum physics: similar probabilistic character is exhibited in statistical physics. For example:

- we cannot predict in what direction a small particle will move in a liquid due to Brownian motion,
- but we can predict, for a large number of such particles, how many of them will be in a certain area after a given amount of time.

In statistical physics, the probabilistic character of predictions is caused by the fact when we do not know the initial positions and velocities of all the particles: the more accurately we measured these values, the more accurate our predictions. These initial positions and velocities can be called *hidden variables* – these variables have perfect physical sense, but they are "hidden" from us in the sense that usually, we do not know their values, since measuring them would be too complicated.

Naturally, when quantum physics appeared, many physicists – including Einstein himself – believed that the probabilistic character of quantum physics can also be explained by the existence of appropriate hidden variables; see, e.g., [2]. The corresponding theories did not became mainstream since they violated the localization ideas: in these theories, during time t, an event can affect other events located at distances larger than $c \cdot t$.

This non-localness was usually viewed as a limitation of the then proposed hidden-variable theories. The situation changed with the appearance of so-called Bell's inequalities paper [1], according to which if probabilities described by quantum physics are correct, then certain inequalities between these probabilities should be observed, inequalities that are not satisfied if hidden variables are localized. After the paper [1] appeared, two choices remained:

- either quantum physics is correct, then Bell's inequalities are satisfied, and only non-local hidden variables are possible,
- or quantum physics is only an approximation to reality, then Bell's inequalities are not satisfied, and local hidden variables are possible.

Later experiments confirmed that Bell's inequalities are true – for these results the 2022 Nobel Prize in Physics was awarded. Thus, we can definitely conclude that even if hidden variables exist, they should be non-localized.

While still not mainstream, non-localized hidden variable theories are being considered even now; see, for example, [9, 10], where a neural network-type model based on such hidden variables leads to a natural explanation of many physical equations and phenomena.

Another example of a non-local phenomenon: energy of the gravitational field. Gravitational forces can perform useful work – e.g., they are the main course of energy in hydroelectric power plants. So naturally, the gravitational field has energy. In Newton's physics, this energy is easy to describe – it can be described the same way as the energy of any other physical field.

In general, a physical theory is described by the so-called *Lagrangian* L, an expression whose value at a given space-time point x depends on values of the physical fields $\varphi(x,t)$ and their derivatives at this 4-point (x,t). The equations of this described theory come from the assumption that the so-called *action* $S \stackrel{\text{def}}{=} \int L(x,t)\, d^3x\, dt$ attains the smallest possible value.

The problem of a finding a function (or functions) that minimizes a functional is known as a *variational optimization* problem; see, e.g., [3, 4]. Such problems are generalizations of the usual calculus-related optimization problems in which we want to find the values of the variables $x_1, \ldots, x_n$ for which a given objective function $f(x_1, \ldots, x_n)$ attains its smallest possible value. According to calculus, at each such point $(x_1, \ldots, x_n)$, all the partial derivatives of the function f are equal to 0:

$$\frac{\partial f}{\partial x_i} = 0.$$

Similarly, to find the function(s) $\varphi(x,t)$ that minimize action, we need to equate the so-called *variational derivatives* to 0:

$$\frac{\delta L}{\delta \varphi} = 0.$$

There is a general expression for energy of any such field; see, e.g., [5]. To be more precise, what is described is the so-called energy-momentum tensor T_{ij} that described the energy density. The overall energy of the field can then be determined by integrating this energy density over the whole space – just like the overall mass of a body can be obtained by integrating its density.

The formulas from [5] describe T_{ij} when the space-time is flat. It is known that in reality, the space-time is curved; see, e.g., [3, 6, 8]. In the curved space-time, there also exist formulas that describe the energy-moment tensor of each physical theory. Namely, it turns out that the energy-momentum tensor is described in terms of the variational derivatives – namely, variational derivative with respect to the metric tensor g_{ij} that describes the space-time:

$$T_{ij} = \frac{\delta L}{\delta g_{ij}}. \tag{7}$$

This formula works well for almost all physical fields, with one notable exception – it does not work for the gravitational field. Namely, if we take, as L, the Lagrangian that describes the gravitational field, then the corresponding variational equations lead to

$$\frac{\delta L}{\delta g_{ij}} = 0. \tag{8}$$

So, in view of the formula (7), we conclude that $T_{ij} = 0$ – i.e., that the gravitational field carries no energy.

Of course, from the physical viewpoint, this conclusion makes no sense: as we have mentioned, the gravitational field has energy. What this conclusion actually shows is that the energy *density* T_{ij} is equal to 0. For all other fields, the overall energy can be determined as an integral of all the energy density values – in this sense, the energy is localized. In contrast, for the gravitational field, the energy cannot be described as such an integral:

- for this field, density is 0, so its integral is also 0,
- while the overall energy is non-zero.

Thus, for the gravitational field, the energy is *not* localized [6, 8].

Comment. It should be mentioned that this non-local character of gravitational energy does not depend on the theory: the same conclusion can be made if more accurate experiments will force us to replace General Relativity with some more accurate theory.

3 How Non-Localness Helps to Speed up Computations?

In the previous section, we showed that, according to some serious physicists, some physical processes are not localized. How can this non-localness help to speed up computations?

When all the processes are bounded by the speed of light c, the smallest parallel computation time is described by the right-hand side of the formula (6).

By definition, non-local processes means that some communications can spread with velocities v larger than the speed of light: $v > c$. In this case, similarly, we can derive a formula

$$t \geq \text{const} \cdot v^{-3/4} \cdot T^{1/4}. \tag{9}$$

Since $v > c$, the corresponding smallest parallel computation time – as described by the right-hand side of the formula (8) – is smaller that in the localized case. Thus, the use of non-localized physical processes can indeed speed up computations.

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