Simulating Time

Michael Nicolaidis
TIMA Laboratory

Abstract. In a famous article entitled "Simulating Physics with Computers", Richard Newman discusses the possibility of simulating quantum systems. The question of simulating time is also addressed. It is stated that, in simulations performed by cellular automata, time is not simulated but is rather imitated by being hidden behind the state to state transition. Simulating time and in particular simulating relativistic space-time can be important for enhancing our understanding of modern physics. In the present paper we introduce the notion of the observer that is part of the simulated physical system. For this kind of observers we show that time and relativistic space-time (in the sense of special relativity) can emerge if the computation rules used to compute the state to state transition obey certain conditions. Thus, by taking into account the point of view of such observers, we can simulate the emergence of time, including relativistic space-time. This kind of simulation could help us enhancing our interpretation of certain "paradoxes" of modern physics.

Keywords: simulating physics, simulating time, emergence of time in a simulated universe, emergence of relativistic space-time in a simulated universe

1. INTRODUCTION

In the present paper we treat the question of simulating physics and more particularly simulating time. This question was addressed in Richard Feynman's famous article "Simulating Physics with Computers" [1]. The article proposes the idea of a computer that could act as a *quantum mechanical simulator* [2]. This idea was one in a series of key events leading to the idea of a general quantum computing device [2]. Beyond its principal aim, related to the simulation of quantum systems, it also addresses some other issues concerning the simulation of physical systems, including time simulation. The following quote from [2], is a concentrate of most of the questions we are treating in the present paper. Some parts are underlined and numbered by us as they are specifically concern these questions:

"In order to simulate time, the first assumption that Feynman makes is that the time is discrete[1]. According to him, in cellular automata, time is not simulated, but is rather imitated by being hidden behind the state to state transition[2]. He explores ways to simulate time in cellular automata rather than imitating it. In particular, he shows an example in spacetime domain[3]. In his example, the state s_i at the space-time point i is a given function $F_i(s_j , s_k, . . .)$ of the state at the points j, k in some neighborhood of i:

$S_i = Fi(s_j, s_k, . . .)$. If F_i is such that it only contain the points previous in time, we can perform the computation in a classical way. However, if F_i is a function of both future and the past, would there be an organized algorithm by which a solution could be computed? Even if the function F_i is known, this task may not be possible."

Some other quotes from [2] "*Local probabilities cannot explain what is obtained in practice*. The two photons are in an entangled state, and measuring one determines the result of measuring the other "[4]. "Two or more objects in an entangled state have to be described with reference to one another, even if they are physically separated. …, it is this fact that is used by Feynman in an example to show how a local probabilistic classical computer cannot simulate quantum mechanics " [5], and also from Feynman's article itself [1] "I would like to have the elements of this computer *locally interconnected,* and therefore sort of think about cellular automata as an example (but I don't want to force it). But I do want something involved with the locality of interaction. I would not like to think of a very enormous computer with arbitrary interconnections throughout the entire thing"[6], are also useful for introducing the questions treated in the present article.

The questions/assumptions/claims stated above in the underlined text (quotes [1,2,3,4,5,6]) are fundamental for physics simulation and may also help enhancing our understanding of physics. The hope that simulation could help enhancing this understanding is actually the principal reason for which Feynman is interested in simulating physics as expressed in [1]: "There are interesting philosophical questions about reasoning, and relationship, observation, and measurement and so on, which computers have stimulated us to think about anew, with new types of thinking. And all I was doing was hoping that the computer-type of thinking would give us some new ideas, if any are really needed."

The aim of this paper is to revisit these questions by paying particular attention to the role of the observer, as her/his careful choice may bring new light on some of the "paradoxes of modern physics. To give a first example about the importance of the choice of the observer, let us consider the claim "time is not simulated, but is rather imitated by being hidden behind the state to state transition" (quote [2]). This claim is valid if we consider that the simulated system is observed by an observer external to it (e.g. the persons that created the simulation). For instance, in synchronous cellular automata, where the computations of all the cells are paced by a clock signal, the state-transitions of the cells are paced by this clock signal. As this clock signal corresponds to the flow of the time own to the external observer, this observer will perceive the state transitions to follow the flow of his/her own time. Thus, we can not talk about time simulation. However, if the goal of the simulation is to try to understand our own world, the observer of the simulated system should be in the same position as we are when we observe our world. That is, the observer must be internal to the simulated system, meaning that she/he is constituted by the same elementary entities (e.g. particles) as the ones forming any other object of the simulated system, and is using observation/measurement means constituted by such elementary entities.

Then, by considering the point of view of the observers that are part of the simulated system (referred also hereafter as simulated universe), we find that the term "time simulation" is fully justified, as under certain necessary and sufficient conditions time emerges for these observers. *This time, internal to the simulation, is governed by three principles:*

- *the principle of its independence from our time(or external time),*
- *the principle of its qualitative emergence (determined by the invariance of the rules that govern the computation of the states of the system, e.g. the simulated laws of physics),*

and

- *the principle of its quantitative expression (determined by the particular form of the laws that govern the computation of the states of the simulated system)*.

These conclusions are important because they suggest that we should be able to simulate the emergence of time by simulating the laws governing a physical system. This also applies to space-time (mentioned in quote[3]). We indeed find that, emergence of relativistic (Lorentzian) space-time or Galilean space-time will be observed by the observers being part of the simulated universe, if the computation laws obey certain conditions.

The question of non-locality exhibited by entangled particles (quotes[4,5,6]) is also related to the question of time, as measuring one of the entangled particles determines instantaneously (i.e. in nil time) the result of measuring the other particle. Another issue concerns the communication problem between distant entangled particles. The exclusion of arbitrary interconnections throughout the entire thing (quote [6]), imposes local probabilistic computer. But such a computer can not treat entanglement (quote[5].). In section 3, we propose to treat entanglement by changing some of the assumptions considered in [1]. On the one hand, the point of view of the observers that are part of the simulated universe can allow eliminating the contradiction between the instantaneous "communication" between entangled particles and the finite time of communication between the elements of classical computing systems (e.g. between the cells of cellular automaton). On the other hand, considering Hertzian communications based on tiny radios built on a single CNTB [3] could provide a solution to the interconnections strangle. Then, on the basis of these ideas, we discuss a practical approach for simulating entanglement.

Finally, the assumption of discrete time (quote[1]) is necessary if we consider digital computers. However, if the time in our world is not discrete, then, in theory, truly analogue computers could be built and used for simulating physics (or at least some parts of modern physics). Thus, the question of discrete or continuous time should not be considered as a fundamental limitation in simulating physics, thought in some situations, digital computers operating with discrete time may simplify the analysis. In particular, our treatment of relativistic time is done in a manner that is valid for both discrete and continuous time.

2. SIMULATION MODEL

To illustrate the discussion concerning the emergence of space and time in a simulated universe, let us consider a simple simulation model. First, as relativity is a deterministic theory related with the macroscopic world, deterministic models can be used for studying the emergence of space-time structure described by Lorentz or Galileo transformations. The simulation is performed over a cellular network composed of a plurality of computing cells. The state of each cell is stored in a set of state variables that include among others a position variable. Each cell computes the state of an elementary entity ("particle"). The cell determines the next values of the state variables of its associated "particle" as a function of the current values of these variables and of the current values of the state variables of the "particles" with which it interacts (e.g. those whose positions are close to the position of its associated "particle"), according to certain rules corresponding to the laws of physics that we wish to simulate. With this model, the distance between "particles" does not correspond to the distance of the corresponding cells in the cellular network, but to a numerical distance, determined by the values of the position variables of the "particles". Thus, in figure 1, two cells a and b are close in the cellular network, but their position variables have very different values. In this case, in the "universe" engendered by the cellular network, the corresponding "particles" a' and b' will have very distant positions. On the other hand, the cells b and c are very distant in the network but their position variables have very close values. Then, the positions of the "particles" b' and c' in the engendered universe will be very close. Because of the close values of positions, the particles b' and c' can interact. This interaction is performed by using the communication means of the cellular network to exchange information concerning the current state of the particles. Thus, the computation of the next values of the state variables of the particle b' will take into account the present values of the state variables of the particle c'. In a similar way, the computation of the state variables of the particle c' will take into account the state of particle b'. Eventually, according to the types of cells a' and b' and their current states, this interaction could lead to computations that maintain close values for the position variables of the two particles, which could bind in this way and participate in the creation of a stable structure forming a multi-particle object in the simulated universe.

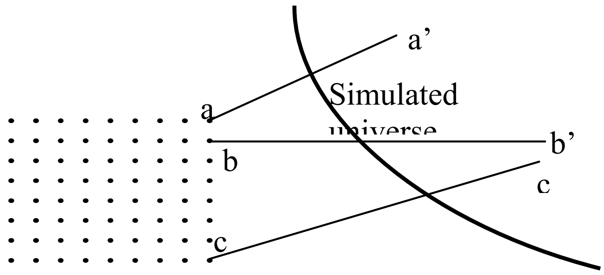

Figure 1. Cellular network and simulated universe

This way, remote cells in the network (e.g. b and c) can be projected on neighbour particles (b' and c') tied to form stable structures. To introduce the idea of observers that are part of the simulated universe (internal observers), let us neglect computational complexity issues as well as the question of adequate computation rules ("laws of physics") able to engender intelligent observers. Making this assumption will be ok, as far as the concept of these observers is used only for facilitating the discussion and in particular for introducing measurements that are consistent with the state of internal observers. Also, to illustrate the discussion, we will use some familiar objects of our universe. Figure 2 shows two stable structures (the eye of an observer and a flower) formed as discussed earlier, as well as a photon (particle a'). To simplify the illustration, instead of representing an instantaneous image of these objects figure 2 presents the evolution in time of a photon a' (trajectory represented by a dashed line). The computation of the state of the photon (carried out by the cellular network) has produced values for its position variable which correspond to this trajectory. When the value of this variable becomes very close to the values of the position variables of some of the particles forming the flower, cell a takes into account the values of the state variables of the cells corresponding to these particles, to compute the state of photon a'. Thus, this computation produces the new trajectory of the photon which moves towards the eye.

When the value of the position variable of cell a is close to the values of the position variables of some cells corresponding to the particles forming the eye, the computations performed by these cells in order to determine their next states take into account the state of cell a. The new states of these cells initiate a sequence of interactions with other cells forming the eye and then the brain of the observer, and create in this brain states corresponding to image of the flower. These figures illustrate the way in which cells having fixed positions in the cellular network, can create, via a computation, the structures and the processes which take place in a "universe" engendered by this kind of computation.

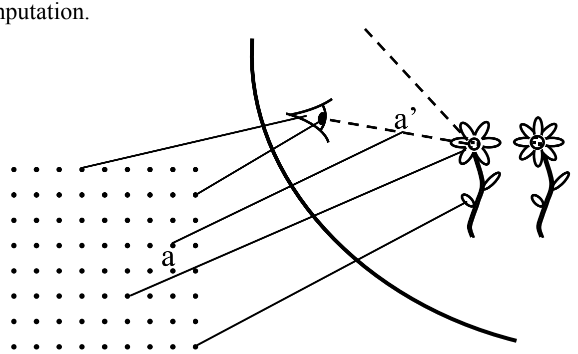

Figure 2. Formation of structures in a simulated universe.

In order to observe the evolution of the simulated "universe", we can visualize it on a two dimensional screen, provided that the particles use position variables with two co-ordinates, or in a 3D film, if they use position variables having three co-ordinates. We could of course use position variables of four co-ordinates, or even more, but we will have difficulties in visualizing such a universe, because we have neither visualization means nor senses allowing us to represent more than three dimensions. On the computer screen or in the 3D film, we will observe the evolution of a "universe" engendered by "particles" whose states evolve according to the evolution of state variables computed by a cellular network.

2.1 The form of space

The principal goal of this article is to discuss the emergence of time in a simulated universe. However, as space and time are imbricated in relativity, we will shortly talk in informal terms about the form of space before discussing the emergence of time. The cells of the cellular network calculate the values of the position variables of the particles. By visualizing these positions in a computer screen, or in a hologram, we can observe at any time the form of space occupied by the virtual particles, which could be for instance, a torus in the three-dimensional space of the 3D film. In more abstract terms, we can consider that the values of the position variables represent positions in a multi-dimensional system of Cartesian co-ordinates (e.g. in a four-dimensional system) corresponding to a virtual multi-dimensional space with Euclidian structure. The values of the position variables determined by all the cells will lie in a subspace of this virtual space. This subspace will have a certain form, for instance the surface of a curve of three dimensions in a four-dimensional space, illustrated in figure 3 by the surface of a sphere of two dimensions). Thus, the form of the space and its evolution are determined by the values that take along the simulation the position variables of the virtual particles. Because these values are determined by the rules ("laws of physics") used to compute them, the form of the space and its evolution will also be determined by these "laws".

The images projected on a computer screen, in a 3D film or in a Cartesian system of coordinates, will evolve according to a unique time (i.e. our own time), which is not imbricated with the position of the particles on the screen, in the 3D film or in the Cartesian system of coordinates. Also, as we have a unique and thus fundamental time, time dilatation could not be observed. Similarly, as particle positions are visualized in a unique and thus fundamental referential (the screen, the Cartesian system of coordinates), object dimensions and distances between objects will have a unique value (the one seen in the visualisation). Thus, the modification of lengths (e.g. length contraction) observed in special relativity when we observe an object from different inertial referentials, could not be experienced. All this suggests that the space-time of the simulated universe could not be relativistic. However, we will see that a relativistic-space time can indeed emerge if we consider the point of view of observers that are part of the simulated universe.

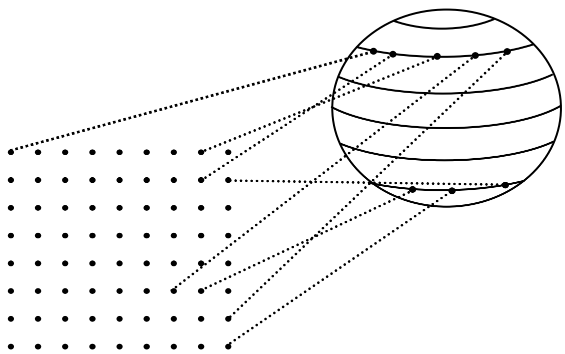

Figure 3. Emergence of space in a simulated universe

2.2 Emergence of time

Let us consider the point of view of the observers that are part of the simulated universe. Apart the information carried by the computations (e.g. the values of the variables of the virtual particles), no other information can reach these observers. Thus, the computing system which engenders their universe is a meta-system, in which the computations are paced by a temporal dimension (a meta-time). In the following, we will consider this point of view and we will use the term time, for the time emerged in the simulated universe and the term meta-time (to be referred also as external time) for our proper time. We will also call universe the simulated universe, meta-universe our universe. As there is no possible confusion As for the system performing the simulations, we will call it indifferently computing system or computing meta-system.

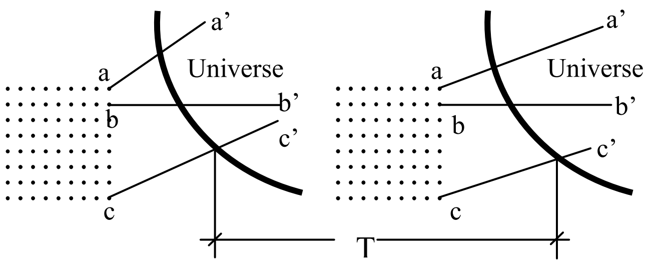

Figure 4. Universe engendered by a synchronous computation

To simplify the discussion, we will suppose, as in [1], that the computations are synchronous and are paced by a meta-clock of period T. That is, at each cycle of the meta-clock, the system computes new values for the state variables of the particles composing the universe, and through them a new state for the whole universe (see figure 4). Then, to each cycle of this clock will correspond a period of time t_h of the (simulated) universe that separates two consecutive states of this universe. Thus, t_h would be the shortest period of time in this universe. This seems to indicate that the shortest time period th will correspond to the meta-time period T, leading as in [1] to the conclusion that time is not simulated, but is rather imitated by being hidden behind the state to state transition (quote[2]). But we will see that this is not the case. In particular, we find that the time is independent of the meta-time. This is achieved by showing that:

- Time is not a translation of meta-time (the pace of its flow is not determined by the pace of the flow of meta-time).
- Time is determined by the laws which govern the evolution of the state of the particles:
    - The invariance of the laws is the sufficient and necessary condition for its emergence.
    - Quantitatively, time is determined by the ratios of paces of evolution of the processes that take place in the universe. These ratios are determined in their turn by the laws governing the evolution of the states of the particles (or of the universe).

To discuss the necessary and sufficient condition for the emergence of time, let us describe a well known invariance principle that seems to govern the evolution of our own universe. Consider a process H (for example the evolution of a clock) and k consecutive states $h_1, h_2, h_3, \ldots, h_k$ of this process. Consider a second process G (for example the fall of a water drop) and k successive states $g_1, g_2, g_3 \ldots g_k$ of G, which are synchronous to the states $h_1, h_2, h_3 \ldots h_k$ of H. Suppose that the processes H and G take again place under exactly the same conditions as the first time and that the state g_1, of G is synchronous to the state h_1, of H. Then, according to above mentioned invariance, the states $g_2, g_3 \ldots g_k$ of G will be synchronous to the states $h_2, h_3 \ldots h_k$ of H. Because of this invariance, each time the two processes H and G take place and their initial states h_1 and g_1 are synchronous, their states $h_2, h_3 \ldots h_k$ and $g_2, g_3 \ldots g_k$ will also be synchronous. Therefore, if we observe the two processes a first time, we will be able at any other time to anticipate the evolution of process G by observing the evolution of clock H.

The above discussion is not limited to our universe but determines the necessary and sufficient condition for the emergence of time for observers being part of any "universe", including simulated universes. Let us imagine a world in which there is always the same relationship between the paces of evolution of two processes, whenever these processes take place. In such a world we can speak about time, because:

- we can choose a process as time reference, and
- after having observed for a first time the correspondence between the events of this process and the events of another process we can:
    - use the reference process to predict the instant (event of the reference process) in which each event of the second process occurs.
    - measure the duration of a process, by observing the events of the reference process in which the process under measurement starts and finishes.

Thus, in a simulated universe, time will emerge if the rules that govern the computation of the states of the particles are invariant (i.e. are independent of the values of the position variables of the particles, and the direction of their velocity variables and remain unchanged throughout the evolution of this universe). Indeed, in this case, the correspondence between the events of two processes will remain the same each time these processes take place. This is illustrated in the right part of figure 5. In this figure, the fall of a water drop and the evolution of the needles of a clock observed a first time (case A) and a second time (case B), evolve identically in both cases, since the laws which govern their evolution remain unchanged. Thus, an observer belonging to this universe will be able to make the actions described above. Consequently, this symmetry (the invariance of the laws which governs the computation of the states of the particles, done by the cellular automaton shown in the left of the figure) constitutes a sufficient condition for the emergence of time in such a universe.

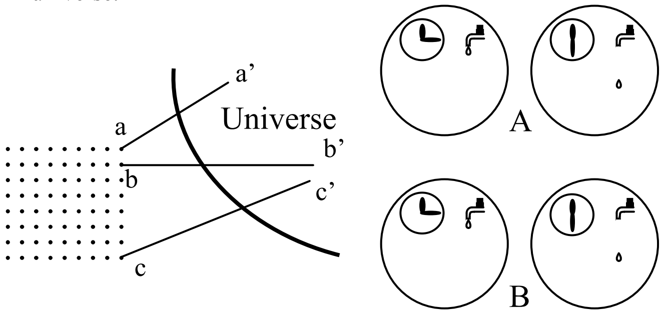

Figure 5. Emergence of time

Let us now imagine a world in which:

- certain times the zebras are incomparably faster than the lion and certain times the opposite,
- a car being at several kilometres of distance covers suddenly this distance in a fraction of a second and crushes us,
- the earth carries out hundreds of evolutions around the sun without your biological age being advanced, while several generations of people already passed, and suddenly you age of a hundred years in a fraction of a second,
- ......,

Let us imagine a world in which processes evolve arbitrarily the one with respect to the other, and thus, there is no invariant correlation between the paces of evolution of the different processes. In such a universe, the observation of the changes would not lead an intelligent observer to form the notion of time. Moreover, it would be improbable that such a universe will engender the intelligence. In fact, an intelligent being could not act by anticipation to protect itself from a natural phenomenon, because the speed of evolution of the phenomenon would be completely unpredictable; a herbivore could not escape a carnivore thanks to its speed, nor the carnivore to catch a herbivore thanks to its speed, its strategy and its power, because the relative speed of these animals would change in a unpredictable way. For the same reason, the intelligence could not be developed, and in any case its existence would not have any sense: what would be the utility of intelligence if it could not anticipate any event?

For similar reasons, this discussion shows that in a universe engendered by a computation, there will be emergence of time only if the laws which govern the computation of the states of the particles are invariant (i.e. are independent of the values of the positions variables of the particles and remain unchanged throughout the evolution of this universe). Indeed, in the contrary case the correspondence between the events of two processes will change arbitrarily, as illustrated in figure 6. In this figure, the variability of the computation rules which govern the evolution of the states of the particles that compose a clock and of the computation rules that govern the evolution of the states of the particles which compose a drop of water, has as consequence that the time duration of the fall of the water drop measured a first time (case A) is different from that measured a second time (case B). Thus, the invariance of the laws which govern the computation of the states of the particles constitutes a necessary condition for the emergence of time.

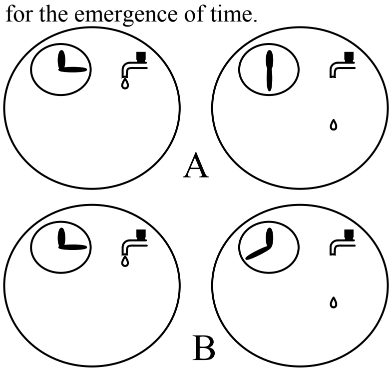

Figure 6. Destruction of time in the event of loss of invariance of the laws of physics

Consequently, from the discussions related to figures 5 and 6, *the invariance of the laws constitutes the necessary and sufficient condition for the emergence of time for the observers belonging to a universe, and this is true for a universe engendered by a computation as well as for a universe which has an existence per se.*

It is worth to note that this condition could be somehow relaxed without preventing the emergence of time in the mental structures of an observer belonging to a universe. Indeed, the variation of the laws which govern the evolution of a universe will not prevent this emergence as long as this variation remains sufficiently weak or sufficiently slow to allow the prediction of the events with a sufficiently small margin of error (for example, the position of an object or the instant of the occurrence of an event could slightly vary compared to the predicted position or instant). Variations on the synchronism between two processes could also be observed in case of non-deterministic laws. In particular, in our universe, the synchronism between the events of two processes H and G observed a first time may not be perfectly identical if H and G are observed a second time, due to the quantum indeterminism. However, this synchronism will be observed with low, generally unnoticed, variation each time two macroscopic processes are repeated.

So, the invariance of the computation rules (laws of physics) is the qualitative principle that underlies the emergence of time (it represents the necessary and sufficient condition for its emergence, as illustrated above in relation with figures 5 and 6). On the other hand, the internal observer will determine the quantitative properties of time, by comparing the pace of evolution of various processes. For instance she/he could compare the pace of evolution of a process G with the pace of evolution of another process H selected as a time referential. The comparison will be done by observing the correspondence (synchronism) between the states through which the two processes H and G evolve. This correspondence is determined by the form of the laws governing the evolution of the processes H and G and more generally by the form of the laws which govern the universe. For instance if process H is governed by an electromagnetic interaction having a given expression and process G is governed by a gravitational interaction having another expression, the particular expressions of these laws will determine how the states of process G will evolve in correspondence with the states of process H (e.g. how many times earth evolves around its axis during the travel of light from a distance galaxy to the earth). Therefore, the particular form of the computation rules or of the laws of physics will determine the quantitative manifestation of time (quantitative principle).

The above discussion shows that the time in the simulated universe has nothing to do with our time (the meta-time), since both the qualitative and the quantitative principles for the emergence of time are not related to the meta-time. Therefore, the quote "time is not simulated, but is rather imitated by being hidden behind the state to state transition"[2], is not valid if we consider the point of view of the observer that is part of the simulated universe, and we could conclude that time can indeed been simulated by simulating the laws governing the evolution of the states of physical processes.

Let us now illustrate the independence of time from meta-time with an additional argument. Consider the case where the meta-system which computes the states of a universe is paced by a meta-clock whose period corresponds to a duration T of meta-time (as in figure 4). This duration will correspond to the meta-time that the meta-system disposes for carrying out one step of computation (e.g. for exchanging information between meta-cells and computing the new state of the meta-cells). This step of computation will carry the minimal changes that can occur in the engendered universe. Therefore, it will correspond to a minimal duration of time t_h in this universe. Let us consider that the period T of the meta-clock that paces the meta-system is variable (i.e. has different durations T1, T2, … at different meta-clock cycles). Because in each meta-clock cycle the meta-system carries out one cycle of computation, corresponding to the minimal time duration t_h of the (simulated) universe, then, the same time duration of this universe (t_h) will correspond to different durations of meta-time (T_1, T_2, …), as illustrated in figure 7.

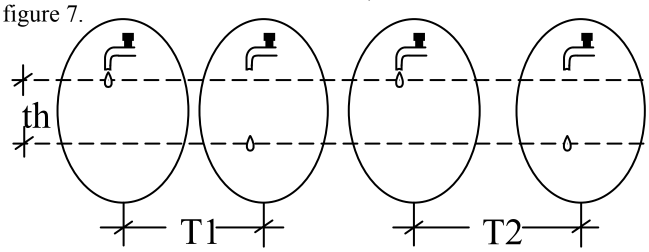

Figure 7. Independence between time and meta-time

In this figure, the period T of the clock of the computing meta-system takes two different values T_1 and T_2 in two different cycles of computation. Thus, the computation of the new state of the simulated universe takes in the one cycle a duration T_1 of meta-time and in the other cycle a different duration T_2. In this figure, the new state is represented by the change of position of a falling water drop. The same interval t_h of time will correspond in this case to two different intervals T_1 and T_2 of meta-time. We will observe the same if in the place of the water drop we use a process employed as time reference. Thus, stopping, decelerating, or accelerating the meta-clock will not have any influence on the time observed by the observers that are part of the (simulated) universe.

The above discussion shows that the *internal time of the (simulated) universe is governed by three principles:*

- *the principle of its independence from the "meta-time or "external time" (or "engine of change"),*
- *the principle of the qualitative emergence of internal time (determined by a symmetry or invariance of the laws that govern the change), and*
- *the principle of the quantitative expression of the internal time (determined by the particular form of the laws which govern the simulated universe)*.

3. SIMULATING RELATIVISTIC SPACE-TIME AND NON-LOCALITY

The previous section shows that if the laws governing the simulation of a physical system are invariant, an internal time will emerge in the simulated system (referred also as simulated universe). The quantitative expression of this time will be determined by the form of these laws (principle of the quantitative expression of the internal time). This suggests that we should be able to simulate time by simulating the laws of physics. However, this is simpler saying than doing as the laws of our universe are very complex and sometimes "strange".

The principal goal of this section concerns the simulation of relativistic time (more exactly of space-time described by Lorentz transformations, as time can not be treated independently of space in special relativity). Nevertheless, as the effect of non-locality plays a central role in [1], leading to the conclusion that quantum systems could not be simulated in local probabilistic computers (quotes[4,5,6]), we also shortly discuss this issue on the basis of the conclusions made in the previous section. Let us consider discrete time as stated in [2], quote[1], "In order to simulate time, the first assumption that Feynman makes is that the time is discrete".

Non-locality is related with time simulation as it requires simulating the instantaneous "communication" acting between entangled particles. This seems to be impossible with classical computers, where any computation and any communication require finite time. Fortunately, the independence of the internal time of the simulated universe from the external time (i.e. our time), could allow us simulating non-locality. Consider as an example two distant particles p1 and p2 having entangled their observable A. Suppose that the observable A of particle p1 is measured at instant ti of the internal time corresponding to the computation cycle i. During the computation cycle i+1, particle p1 will compute the value of its observable A (which at instant i+1 will become the result of the measurement), and will communicate this value to particle p2. During the same computation cycle, particle p2 will compute its new state by taking into account the value of observable A received from particle p1. Thus, observables A of the two particles will take their new, correlated values, at the same instant (ti+1). As a matter of fact, for the internal time of the simulated universe the "communication" between the entangled particles will take place instantaneously. A second issue for simulating the non-local behaviour of entangled particles in classical computers concerns the complexity of interconnections needed for performing the communications between any two cells of a cellular network that could be entangled during a simulation cycle, or, in Feynman's terms [1] from quote [5], "I would not like to think of a very enormous computer with arbitrary interconnections throughout the entire thing.". Indeed, the communication struggle is the most serious problem in parallel computers, and is exacerbated in a totally parallel computation where the state of each particle is simulated by a particular cell of a cellular network, as considered in [1]. Realizing material interconnection between any two cells of such a network will lead to an exponential hardware cost. Thus, creating the required communication at reasonable cost requires a different principle. Hertzian communication seems better adapted for this kind of communication. As an illustration, the communication means could comprise an identification number ID unique to each cell simulating a particle, an entanglement variable EV and a mechanism of emission/reception (more than one entanglement variables will be used if more than two particles are entangled). At the instant of entanglement, particle p1 allocates to its entanglement variable EV_1 the identification number ID_2 of particle p2 ($EV_1 = ID_2$) and particle 2 allocates to its entanglement variable EV_2 the identification number ID_1 of p1 ($EV_2 = ID_1$). Subsequently, p1 will emit the state of its observable A by using as modulation frequency for this emission its identification value ID_1. Particle 2 uses as demodulation frequency the value of its entanglement variable ($EV_2 = ID_1$). This way it permanently receives the state of the observable A of p1 and can instantaneously adapt its state to the eventual changes of the state of this observable. In a similar manner, p1 can adapt instantaneously its state to the eventual changes of observable A of particle 2. Thus, conceptually, Hertzian communication provides the means needed for simulating entangled particles. However, there are major technological issues that should be addressed for realizing it in practice, including a technology allowing implementing Hertzian emitters and receivers in each cell of the cellular network. A first step on this direction is the tiny receiver realized on a single carbon nanotube [3]. If such a technology, integrating large numbers of tiny emitters and receivers on a single chip, isolated from interferences external to the system performing the simulations, acting in tiny range (e.g. within the dimensions of a cellular nano-network), and operating at very low power, could be realized, it will allow developing a new kind of totally parallel computing able to simulate complex physical systems with high efficiency.

To discuss the emergence of relativistic space-time in a simulated universe, we consider a simulation where the cells of a cellular network compute the states of elementary entities (e.g. particles) composing the simulated universe. The cells calculate their states by using some computation rules corresponding to the laws of interaction between particles. Since special relativity is a deterministic theory concerning the macroscopic world, we will discuss the emergence of space-time in simulations using deterministic computation rules, corresponding to deterministic interaction laws. We will also consider that the cellular network is a synchronous system, paced by the external time (e.g. a single clock which synchronously activates the computation in all cells of the network, similarly to the clocks used in our synchronous computers). Several issues have to be addressed for simulating the emergence of a space-time obeying Lorentz transformations:

First, on the contrary of general relativity, which attributes the curvature of space-time described by Einstein's equation to the gravitational interaction, *special relativity does not attribute the structure of space-time* described by Lorentz transformations *to any interaction*. It rather considers that these transformations reflect a primary structure of space-time which exists in a manner independent of the form of the laws of interactions. Under this assumption, we can not expect simulating the emergence of relativistic space-time by simulating a system composed of a set of particles whose interactions obey certain laws. To cope with this shortcoming, we start by reversing the relation between the structure of space-time and the properties of objects and processes. That is, instead of considering, as in special relativity, that the structure of space-time imposes constraints to the objects and processes which result in the contraction of objects dimensions and the slow down of the pace of evolution of processes, we will consider that certain forms of interaction laws could imply the above properties on the objects and processes engendered by interacting particles. In their turn, these properties will imply that the measurements of spatial and temporal dimensions verify relationships corresponding to Lorentz transformations. More particularly, we determine the necessary and sufficient condition that the form of the rules used to compute the state of particles (interaction laws) have to conform in order to imply that the measurements of lengths and durations performed by the internal observers of the simulated universe obey the Lorentz transformations. This way, in the simulated universe, Lorentz transformations will emerge as a consequence of the effect that the form of the computation rules (interaction laws) has on the dimensions of objects, the distances between objects and the paces of evolution of processes, rather than being implied by a pre-established structure of space-time.

Second, *performing the simulation in a synchronous cellular network implies that all simulated processes obey a fundamental synchronism* determined by the unique clock that paces the computations of all cells of the cellular network *and introduces a fundamental time*. Furthermore, the computation of the position variables of the cells (calculating the positions of the simulated particle), should be done with respect to a given referential (as it is not possible to be done for all possible inertial referentials). Thus, the simulation seems to inherently produce **a fundamental inertial referential** referred hereafter as $\mathbf{S_0}$, and **a fundamental time**. This situation suggests that the simulation could not be compatible with special relativity. However, by considering the point of view of the observers that are part of the simulated universe, we can show that a space-time having the structure described by special relativity can emerge in this kind of simulation. We have validated this claim in terms of both simulation experiments and formal proof.

The simulation experiments will be presented in details in a further publication. They consist on: using computation rules (interaction laws) obeying the above mentioned necessary and sufficient condition; creating a length unit (an object composed of particles initialized in a manner that their mutual distances remain in equilibrium under the above laws); creating a clock (a set of particles initialized in a manner that under the above laws evolve over a cyclic sequence of states); creating various rigid objects (sets of particles initialized in a manner that their mutual distances remain in equilibrium under the above laws); creating various processes (various set of particles initialized randomly and evolving under the above laws); creating the above length unit, clock, objects and processes in various inertial frames (frames having constant speed with respect to S_0); synchronizing clocks placed in various positions in each of these frames; using in each inertial frame the length unit and the synchronized clocks to measure the length of the rigid objects and their distances and the duration of the different process; checking that the measurements comply Lorentz transformations.

Thought extensive simulation experiments, as the ones described above may give a good indication about the validity of our claim, a conclusive validity requires a formal proof. We present the formal proofs in [5].

4. LESSONS LEARNED

The principal reason for which Feynman was interested in simulating physics is the hope that ideas coming from the field of computer science may help enhancing our understanding of modern physics. This is expressed several times in [1]:

"There are interesting philosophical questions about reasoning, and relationship, observation, and measurement and so on, which computers have stimulated us to think about anew, with new types of thinking. And all I was doing was hoping that the computer-type of thinking would give us some new ideas, if any are really needed.",

"we always have had a great deal of difficulty in understanding the world view that quantum mechanics represents."

"I'm trying to do is to get you people who think about computer-simulation possibilities to pay a great deal of attention to this, to digest as well as possible the real answers of quantum mechanics, and see if you can't invent a different point of view than the physicists have had to invent to describe this."

In the present paper we consider the point of view of observers that are part of the simulated system and we analyze the impact of this point of view on simulated time and more precisely on the emergence of time in the simulated system. This section is discussing whether this point of view could bring new light on some "paradoxes" of modern physics.

From the previous sections we learned that the *internal time which emerges in the (simulated) universe is governed by three principles:*

i. *The principle of its independence from the time that paces the simulation (our time). This is the objective time for us, but it is a meta-time for the "observers" that are part of the simulated system, as they have no means for assessing its structure and its pace.*
ii. *The principle of the qualitative emergence of internal time (determined by the invariance of the laws that govern the simulation).*
iii. *The principle of its quantitative expression (determined by the particular form of the laws which govern the simulated universe).*

From principle ii, we can create a simulated universe in which it emerges an internal time, by using invariant simulation rules. This time will be independent from our time and its quantitative expression can be determined by selecting adequate simulation rules. For the “observers” that are part of the simulated universe these rules will correspond to their laws of physics.

We also learned that, when the interaction laws (i.e. the rules computing the evolution of the states of the elementary particles as a function of their own state and of the state of the particles with which they interact), satisfy a certain condition, it emerges a space-time obeying Lorentz transformations. In this emergence the point of view of the observer is fundamental. The point of view of the observers external to the simulated universe (e.g. the ones that created the simulation), could be considered as objective, since they have complete knowledge of the simulated universe, including the knowledge of the computational processes that engender it. It turns out for these observers that the time of the simulated universe does not obey the transformations of Lorentz. In particular, for these observers, there is a fundamental time and a fundamental inertial referential. In addition, time dilatation and length contraction operate in one direction (when processes taking place and objects being at rest in an ordinary inertial frame are observed from the fundamental one). These inconsistencies with special relativity disappear under the action of “subjective” measurements performed by the “observers” that are part of the simulated universe, and give place to a relativistic space-time. The resulting – subjective - structure of space-time becomes objective for these observers as it corresponds to the only means they dispose for making coherent measurements. These means include length and time units and principles for distant-clock synchronization that are compatible with the proper state of each of these observers. For this reason, they are unitary and produce clocks that are synchronized in objective manner for these observers, but in subjective for the external observers (which should be considered as the objective observers). Thus, the relativity emerges in the simulated universe thanks to this relative manner through which an observer perceives its universe, and gives an additional sense to the notion of relativity.

The difference between the external time that paces the evolution of the simulated universe (its engine of change) and the internal time perceived by the observers that are part of the (simulated) universe, could be used to provide an answer to a fundamental dilemma concerning the 4D world vision introduced by special relativity. This dilemma is expressed with clarity in the foundation text of the International Conference on the Nature and Ontology of Spacetime [4]:

“A 3D world requires not only a relativization of existence, but also a pre-relativistic division of events into past, present, and future. Therefore, it appears that such a world view may not be consistent with relativity. However, the alternative view – reality is a 4D world with time entirely given as the forth dimension – implies that there is (i) no objective time flow (since all events of spacetime are equally existent), (ii) absolute determinism (at the macro scale), and (iii) no free will. It is precisely these consequences of the 4D world view that make most physicists and philosophers agree that a world view leading to such implications must be undoubtedly wrong. But so far, after so many years of debate, no one has succeeded in formulating a view that avoids the above dilemma and is compatible with relativity.”

To resolve the above dilemma we observe that: the external time that paces the simulation (also corresponding to the fundamental synchronism and the related fundamental time of the simulated universe), determines an objective time flow and a division of the events of the simulated universe into past, present, and future. Nevertheless, the use by the internal observers of a synchronisation principle that is consistent with their own state introduces the time in the measurements of distances and the distance in the measurements of time, creating a 4D vision of space and time. Thus, this dual view of space-time avoids the above dilemma. On the one hand, the external (or objective time) corresponds to a 3D vision that eliminates the problems (i), (ii), and (iii) mentioned above. On the other hand the space and time perceived by the internal observers of the simulated universe, as a result of their way to perform measurements that are coherent with their proper state, correspond to a 4D space-time compatible with special relativity. This interpretation of special relativity is relevant to us, since we also acquire a 4D perception of our universe as observers which are part of it and we use measurement means that are coherent with our own state.

Yet another “paradox” of modern physics concerns the non-local behaviour of entangled particles. This “paradox” can be eliminated in the simulated universe by considering discrete time simulations together with the independence of the internal time from the external time. On this basis we found that we can implement a mechanism which engenders the non-local behaviour of entangled particles for the internal observers of the simulated universe, though this mechanism uses communications operating at finite time for the external observers.

An important question resolved in a previous communication [6] concerns the combination of the entanglement mechanism described in this paper with a stochastic computation based on deterministic functions that manipulate stochastic signals, to provide a simulation model for quantum systems that eliminates the “paradoxes” of superposition and entanglement.

An important question that we will treat in a subsequent communication concern the applicability in the real world of the ideas developed in this paper. This will be done by showing that some of the assumptions considered in this article are satisfied in our universe, while the validity of the remaining ones does not impact the perception of the universe for the observers that are part of it.

Important questions for further investigations concern the impact of physics simulation on our vision of general relativity, quantum field theory and unification theories.

REFERENCES

[1] Richard Feynman , “Simulating physics with computers”, In International Journal of Theoretical Physics, Vol 21, Nos. 6/7, pp. 467-488, 1982

[2] Michael Demmer, Rodrigo Fonseca, Farinaz Koushanfar, “Richard Feynman. Simulating physics with computers”, CS294: Reading the Classics

[3] Single nanotube makes world's smallest radio, http://www.berkeley.edu/news/media/releases/2007/10/31_NanoRadio.shtml

[4] http://alcor.concordia.ca/~scol/seminars/conference/minkowski.html

[5] M. Nicolaidis, “Emergence of relativistic space-time in a simulated universe: the formal proofs”, TIMA Laboratory, ISRN TIMA- RR--08/12--01-FR. Can be accessed at http://www-tima.imag.fr/publications/index.php, **Type of publications:** select reports**, Publ. Year(s):** select 2008

[6] M. Nicolaidis, “On the State of Superposition and the Parallel or not Parallel Nature of Quantum Computing: a controversy raising view point”, Presented at ECAP, June 2008, Montpellier, France