Reality is ultimately digital, and its program is still undebugged

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Abstract

Reality is ultimately digital, and all the complexity we observe in the physical universe, from subatomic particles to the biosphere, is a manifestation of the emergent properties of a digital computation that takes place at the smallest spacetime scale. Emergence in computation is an immensely creative force, whose relevance for theoretical physics is still largely underestimated. However, if the universe must be at all scientifically comprehensible, as suggested by a famous einsteinian quote, we have to additionally postulate this computation to sit at the bottom of a multi-level hierarchy of emergent phenomena satisfying appropriate requirements. In particular, we expect 'interesting things' to emerge at all levels, including the lowest ones. The digital/computational universe hypothesis gives us a great opportunity to achieve a concise, background independent theory, if the 'background' – a lively spacetime substratum – is equated with a finite causal set.

1   Introduction

There exists a tiniest scale at which the fabric of spacetime appears as a pomegranate (Figure 1), made of indivisible atoms, or seeds. This view is reflected in models such as Penrose's spin networks and foams, and is adopted in theories such as Loop Quantum Gravity [14] and in the so called Causal Set Programme [6, 13].

At that level, a universal computation keeps running. We do not know yet the program code, but, in accordance with a fundamental principle of minimality ('Occam razor'), we like to believe that it is small, at least initially. Perhaps it is a self-modifying program: code and manipulated data might coincide. This does not mean that we have to postulate the existence of a divine digital Computer that sits in some outer space and executes that code, for the same reason that, under a continuous mathematics viewpoint, we do not need a transcendental analog Computer that runs the Einstein field equations for animating spacetime. Computations may exist even without computers (and, incidentally, the concept of computation is much older than computer technology).

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Figure 1: The fabric of spacetime.

Humans are a part of reality. When we have emerged and started to look around us, things in the physical universe had already evolved to a high level of complexity, high enough to support the existence of speculating entities like us! And from this high observation viewpoint, the simple, fundamental digital laws of physics are almost unaccessible, buried as they are at the bottom of a *hierarchy of emergent phenomena*. However, the universe appears to be comprehensible, as suggested by the history of scientific progress and a famous Einsteinian quote, and we do find simple mathematical laws for explaining phenomena we observe at our level, such as gravitation. Furthermore, sometimes we identify new, unifying laws that allow us to jump one level *down*: laws that appeared as primitive (e.g. Newton's law of gravitation) are shown to derive from deeper laws (e.g. General Relativity).

Emergence in reality calls for abstraction in description, and implies accuracy loss. Abstraction - e.g., assuming perfectly spherical planets of uniform density - is the price we pay for keeping mathematical formalizations simple at all levels. Historically, science proceeds downwards, trying to explain laws that have been experimentally validated at some level, in terms of more accurate and more widely applicable laws at a conceptually lower level. Science is the process of reverse-engineering the hierarchy of emergence.

In this essay we shall try to clarify and expand these ideas. In Section 2 we briefly illustrate the idea of emergence in computation, which nicely combines with the assumption of reality being discrete. In Section 3 we discuss the crucial problem of experimental validation, for a theory that attempts to describe reality at scales many orders of magnitude below the reach or current technology. In Section 4 we argue that causal sets represent the ideal discrete structure based on which the digital/computational universe conjecture can be formulated, and we mention two of the experimental results that we have recently obtained by computer simulations of algorithmic causets.
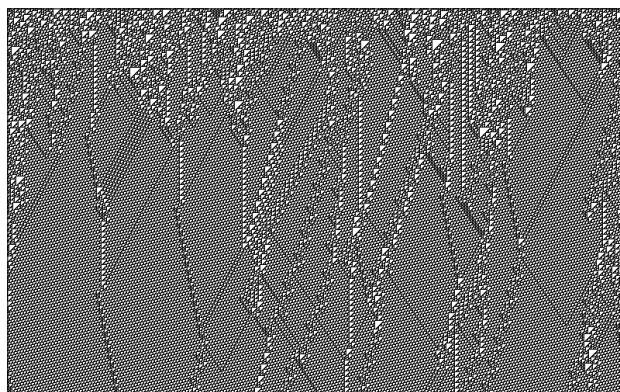
Figure 2: Emergent structures in Wolfram's cellular automaton n. 110.

2 Emergence in computation

The fact that simple programs can produce complex patterns, sometimes similar to those found in nature, is widely recognized today, and has been divulgated, in particular, by S. Wolfram [17]. Typical examples of emergence in computations from cellular automata include the 'gun gliders' of Conway's Game of Life (for an animation, see [16]), and the 'interacting particles' of Wolfram's elementary automaton n. 110 (Figure 2). Interestingly, it has been proved that both models are Turing-complete: in principle one can use their emergent structures for executing any conceivable algorithm.

These facts can be summarized by the conceptual equation:

"complexity in physics = emergence in computation",

which is taken by some researchers – not without considerable skepticism by others – as a basis for trying to devise a radically new, computation-based, spectacularly simple fundamental theory of physics.

Emergence occurs whenever complex patterns arise from a multiplicity of interactions based on simple rules; the *whole* offers more than the plain sum of its *parts*. What we see in the diagram of Figure 2 is a pattern of interacting particle trajectories; these are upper level, emergent entities, and we might even succeed in formulating some theory (call it T_1) that describes their behavior *directly*. But no notion of particle and no collision laws are built into the behavioral law (call it T_0) of the cells one level below, which simply consists of a boolean function of three variables.

The cellular automaton example precisely illustrates the idea of building a hierarchy of physical theories reflecting that of emergence. We should now imagine particle trajectories as playing the role, in turn, of lower level entities, and ask what new entities, behaviors, and laws will emerge when their interactions are described by theory T_1. Incidentally, we believe that cellular automata
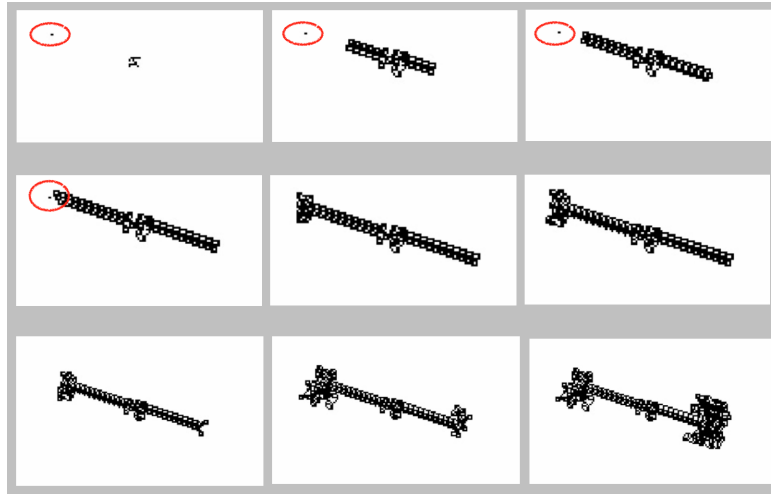
Figure 3: The progressive formation of two coupled highways in Turmite 21 with non-uniform initial condition, and the breaking of regularity at both growth fronts when a defect is present at one side only.

provide only a nice metaphor for learning about emergence, not a satisfactory choice for an actual fundamental theory of physics, due to the annoying presence of a predefined background and the costly assumption of global synchrony for cell updating.

Let us now provide another, original, and quite surprising example of emergent phenomena, in the context of a different model of computation, in which at least the global synchrony assumption is dropped. *Turmites* [10] are two dimensional Turing machines: the finite-state control head moves now on a 2-D array of binary cells. The behaviors of 44 different turmites can be explored by the demonstration in [11]. In spite of the simple initial condition – an array of white cells – several of these machines develop interesting structures, either regular or pseudo-random.

Turmite 21 is a regular one. But, by experimenting with more elaborate initial conditions, we have found that *two* coupled 'highways' often appear, that extend from a central, random-like region in opposite directions (Figure 3). The 'ant' is moving up and down the two structures, alternating between one and the other, giving the impression to find its way at each pass across the pseudo-random region, which can be arbitrarily large. Additionally, when one of the highways intercepts a 'defect', its regular behavior is broken, but, surprisingly, a similar effect is immediately transmitted at the other front, which is defect-free.

There is a simple explanation for the apparent entanglement of the two highway fronts, that we leave to the reader. Our point with this example is to show once more that relatively simple, discrete, deterministic computations occurring at some 'ground' level do offer a great potential for revealing the

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trick behind apparently complex physical phenomena; when observed at the appropriate abstraction level, they can manifest strong analogies with some of our direct observations of the physical world, including the least intuitive ones.

3 Experimental validation

No experimental evidence is available today for validating the digital/computational universe conjecture. But this unfortunate circumstance seems to be shared by other 'theories of everything', or of quantum gravity, such as String Theory, Loop Quantum Gravity, Causal Dynamical Triangulations. The latter, for example, predicts value 4 for the dimension of spacetime at our scales [12], which is encouraging, but does not compare with, say, the agreement between relativistic predictions and the increasingly accurate measures of the deflection of light in strong gravitational fields. We are still far from there.

However, chances to comprehend the universe by a computational theory, and to be able to experimentally test it, increase if the following assumptions are made: [1]

1. The universal computation sits at the bottom of a *multi-level* hierarchy of emergence.

2. At all levels, including the lowest ones, something 'interesting' must happen. Objects, localized structures distinguishable from a background, waves, the mix of order and disorder, are examples of 'interesting' things.

3. Patterns emerging at some level should be recognizable, with variations, at several other levels. The digital universe indeed manifests superb creativity in producing, at various scales, variations on a relatively limited repertoire of self-organization patterns.

4. All levels of the hierarchy are eventually understandable and describable in terms of appropriate mathematics, which can be either discrete or continuous. Many phenomena appear indeed analog; in those cases, simplicity is achieved by very effective pieces of continuous mathematics.

We can then add a new work item to the agenda of scientific investigation: the exploration, by simulation, of algorithms that, starting from simple initial conditions and rules, manage to build a hierarchy of emergent phenomena and associated theories as outlined above. Of course, the computational space to be possibly explored includes a huge number of data structures and algorithms. But in the next section we propose to restrict the investigation to just one data structure of particular physical significance.

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[1] The idea that the features and mechanisms that appear fundamental in understanding the universe at our scales should manifest, in duly varied forms, at all scales, and since the very beginning, finds a most elegant and inspired expression in the work of the french paleontologist and philosopher Teilhard de Chardin [7]

4   Algorithmic causal sets

When a physical theory is *background independent*, the objects it describes are not thought of as moving on a stage (spacetime) that is separated from them; rather, they are themselves part of that stage, and made of the same fabric.

A digital/computational universe theory based on emergence would be background independent almost by definition: in its view all the items in the universal catalogue, from particles to living organisms, are shapes of spacetime. And we believe that the stage – the immensely creative substratum and the only thing that really exists – should be equated with a finite, dynamic *causal set*.

A causal set, or *causet*, provides us with the lightest, most flexible, and most obvious way to represent discrete spacetime. It can be depicted as a directed graph, in which both the nodes and the directed links among them are unlabeled: all the information is coded in the interconnection pattern.

Causality among events is widely recognized as a most fundamental aspect of spacetime, and the concept of causal set has been formulated in the homonymous research programme [6, 13, 9] in "an attempt to combine the twin ideas of discreteness and order to produce a structure on which a theory of quantum gravity can be based" [15]. The fundamental idea at the root of the Causal Set Programme is summarized by the conceptual equation:

"spacetime geometry = order + number".

A *causet* is a finitary partially ordered set, that is, a set of events provided with a binary relation '$\prec$' which is reflexive, antisymmetric and transitive, and such that the number of elements between any two events is finite. Elements (nodes) represent atomic events, causality is reflected by the '$\prec$' relation ('order'), and the volume of a spacetime region is measured by the count of nodes in it ('number'). Causets are important because the order and number information that they provide is sufficient for completely determining the metric tensors of General Relativity (see e.g. [13]).

If the universe is discrete and *computational*, if it all emerges from spacetime, and if spacetime is best represented as a *causet*, the question becomes: *how can we associate a causal set to a generic computation?* [2] The answer is surpringly simple (see also [3]). A computation is defined as a sequence of composite states, and a computation step as a pair of adjacent states. Each computation step becomes an event in the causet. Then, a causal link is created from event e_i to event e_j, with $i < j$, whenever e_j is the first event occurring after e_i to read a global state component that was affected by e_i: that state component has acted as a *causality mediator* between the two events. [3] Finally, letting R denote the relation defined by the above links, the full causality relation is obtained by

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[2]The idea of describing computations as networks of causally related events has been first introduced by Levin [8], but it is only by the more recent work of Wolfram [17] that these directed graphs are viewed as possible instances of physical spacetime.

[3]The total order of computation steps does not represent physical time; the latter, as well as space, can only emerge (if ever) from the growing structure of the causet, which does not keep explicit track (e.g. by node labels) of that total order.

taking the *transitive closure* of R. Note that R is antisymmetric by construction. It may be sometimes useful to also consider the *transitive reduction* of R, which is the minimal relation whose transitive closure is the same as that of R. When R is antisymmetric and finite, the transitive reduction is unique.

We have explored causet families for a number of models of computation, including various classes of Turing machines, mobile automata on tape, string rewrite systems and tag systems, that operate on one-dimensional supports, such as a tape or a string of symbols [5], as well as higher-dimensional supports, namely 2-D arrays of cells and planar trivalent graphs [4]. Our study has focused on a number of quantitative and qualitative emergent properties of these causets, including dimension, curvature and localized structures, or 'particles'.

In this short essay we single out and sketch just two of these results, that illustrate, once more, in the specific case of causets, the potential of emergence in computation.

4.1 'Particle' detection: global vs. local view

For several computation models that we have considered, it can be proved that the associated causets are planar and *totally ordered* [5]. Especially the second property may really appear bizarre and unphysical, since a spacetime in which *all* events are pairwise causally related may support some notion of time, but certainly not of space. For space to exist we expect some events to be in a space-like relation: there should be no causal path connecting them. Yet, things may look different when switching from a global to a local view.

Consider the highly regular causet in Figure 4 (left), that we derived from a turmite computation. If we transitively reduce it globally, the interesting thing that we observe in the original graph – the spiral motion of the 'particle' that deflects when crossing each of the four radii – is washed away, and we are left with a totally ordered, and totally uninteresting, one dimensional spacetime, with no
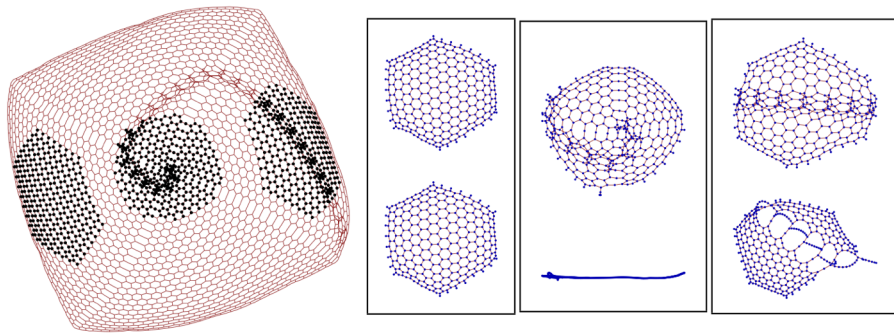

Figure 4: Causet from 4000-step computation of turmite 4, with three highlighted observation disks (left); the same disks (upper-right) and their local transitive reductions (lower-right).

spatial extension.

But if we only allow ourselves to observe a relatively small disk of spacetime around us, then structures are preserved, perhaps with slight modifications, as illustrated in the diagrams at the right of the figure. Interestingly, the outcome of the localized transitive reduction also depends on whether or not the root node, found at the center of the graph, is included in the disk.

Clearly we cannot expect any causet hidden behind the scenes of our physical universe to be that regular, but analyzing regular cases is quite useful for preliminary investigations on the repertoire of what can possibly happen, and for tuning analytical tools.

4.2   Emergent causet compartmentation

Much more interesting causets can be obtained when the computation assumes a pseudo-random character. In these cases of deterministic chaos, which occur very rarely with simple models of computation, we cannot visually detect regularity – periodicity or selfsimilarity – in a way that would allow us to effectively predict evolution on a long range.

What type of feature might we expect to see emerge in algorithmic causets with pseudo-random character? We suggest that one of the key features would be the self-organization into components that achieve some form of partial independence from one another, as a necessary basis for being able to cook complexity in the upper levels of the hierarchy, up to the domains of chemistry and biology.

We have identified [1, 2] a few interesting examples of pseudo-random computation for network mobile automata, a model in which a stateless control head moves on a trivalent planar network, at each step modifying the local topology by three elementary graph rewrite rules (Pachner moves) familiar also in Loop Quantum Gravity. One of these causets is shown, with fat colored nodes, in Figure 5 (right). This causet exhibits an emergent phenomenon that we have
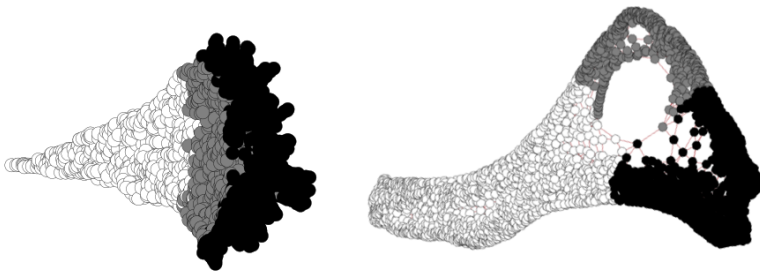

Figure 5: Truncated pseudo-random causet from a computation of a trivalent network mobile automaton from [1]; nodes are white up to event 4020, then gray up to event 4649, then black up to event 6000 (right). Genuinely random causet with analogous node coloring scheme (left).

called 'causal compartmentation', that we regard indeed as a prerequisite for the occurrence of *anything* of physical interest in the evolution of spacetime. The graph is partitioned into three sub-segments, colored in white, gray, and black, in a progression that reflects the sequence of computation steps. All grey events have occurred between white and black events, and yet the white and black portions are in direct causal contact.

This phenomenon reflects the confinement of the control head *inside* some region of the growing trivalent network for a relatively large number of steps. The way we see it, this behavior provides a primitive implementation of the distinction between the 'inside' and the 'outside' of things. [4] As one would expect, with 'genuinely random' causets no spontaneous formation of similar macroscopic compartments can be observed (Figure 5, left).

5   Conclusions

We have provided arguments in favor of a digital/computational view at the universe, based on some benign assumptions on the hierarchy of emergent phenomena that constitutes its architecture. In our view, a corresponding background-independent theory should be based on the algorithmic growth of finite causets. Requirements of minimality suggest that the processing be performed by an elementary control unit that operates locally, sequentially and deterministically, analogous to a Turing machine head.

Any such theory should eventually encompass, among others, the laws of Relativity and Quantum Mechanics. However, starting the investigation from the bottom of the hierarchy of emergence, we may need to be very patient before features such as Lorentz invariance start to emerge. On the other hand, by running computer simulations at the lower end of the architecture, we might still be able to spot and recognize variants of the recurrent, familiar phenomena that we are used to detect and measure, by actual experiments, at the upper levels. The digital universe is eager to manifest all of its beauty even it its very early configurations, much before there is enough room for the appearance of humans and telescopes.

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[4]This recurrently emergent feature plays a central role in the already mentioned evolutionary picture of the universe by Teilhard de Chardin [7].

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