Digital Metaphysics

Suppose that physics, or rather nature, is considered analogous to a great chess game with millions of pieces in it, and we are trying to discover the laws by which the pieces move. The great gods who play this chess play it very rapidly, and it is hard to watch and difficult to see. -- Richard Feynman

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[NOTE: This article was written in 1996; parts of it are now quite out of date. This article has a commitment to finiteness that I abandoned almost immediately. This text is the same as the published text except for correction of a single error.]

1. Physical and Metaphysical Reality

Metaphysics is traditionally the study of ultimate reality (van Inwagen, 1993, ch. 1). Such a study is warranted by the distinction between reality and appearance. Water, ice, and steam *appear* to be different kinds of things, but this appearance is illusory: in reality, all three are simply H_20. The explanatory success of modern science shows how to generalize this example: however different things may appear to be, in reality they are all physical (i.e. material). According to this view, metaphysical reality (i.e. ultimate reality) and physical reality are identical. So metaphysics reduces to physics. This position is generally known as *materialism* or *physicalism*.

We do not agree with the reduction of metaphysics to physics; we think, instead, that *metaphysics is the study of the foundations of physics*. We argue here, in several steps, that these foundations are computational. Indeed, we argue that *ultimate reality is a massively parallel computing machine sufficiently universal for the realization of any physically possible world*. Ultimate reality is *computational space-time*, and that is just the universal metaphysical hardware into which particular physical worlds are programmed. We refer to this system of ideas as *digital metaphysics*.

Digital metaphysics is directly informed by an extensive body of theoretical and experimental literature in contemporary physics. It is not *idle* speculation. To argue for digital metaphysics, we first present some of this literature; we then discuss the concept of computational space-time, and discuss the explanatory success of computational space-time in physics. We then dispose of objections based on common but unsubstantiated assumptions about space and time (e.g. continuity) and nature (e.g. infinite complexity). We then discuss how physical things are *patterns*, and finally put physics on computational foundations by concluding that *physical reality is to metaphysical reality as software is to hardware*.

Of course, however extensively and closely digital metaphysics is informed by physical theory, it remains philosophical speculation. Informed speculation may turn out to be very wrong; but whether digital metaphysics is ultimately true or false, one thing is clear: digital metaphysics is not empirically meaningless.

2. Digital Foundations for Physics

The thesis that reality is ultimately computational is not new, and has received attention both from raving crackpots and serious scientists. Philosophically, the thesis is probably advanced originally by Leibniz (Rescher, 1991), whose "Monadology" envisions the world as a system of automata (cf. MacDonald-Ross, 1984, p. 98). Babbage (1837, 1864) thought that natural laws were like the programs run by his Analytical Engine. McCarthy & Hayes (1969) present an image of the world as a system of automata.[1] Lilly (1972, ch. 13-17) has a bizzare theological vision of God as a self-programming computer. Asimov (1956) tells an entertaining science fiction story in which the world is created by a computer with God-like powers.[2]

But digital metaphysics is inspired by, and is a generalization of, developments in contemporary physics. Central among these are the papers in Fredkin, Landauer, & Toffoli (1982), especially those by Feynman, Finkelstein, Minsky, Petri, Toffoli, Wheeler, Zeigler, and Zuse. Digital metaphysics is particularly inspired by work on cellular automata, often found in the journal *Physica D*.[3]

More theoretically, digital metaphysics closely follows work by Toffoli (1984, 1989, 1990, 1991), Fredkin (1991), and Wheeler (1990). Toffoli (1984) argues that cellular automata are genuine alternatives to differential equations. Toffoli (1990) shows that many fundamental features of the physical world have natural information-theoretic explanations, and may be derived from the interactions of processors in very simple computing networks.[4] Fredkin (1991) argues that the world is ultimately a cellular automaton, and that the foundations of physics are computational (what he calls *digital mechanics*). Wheeler (1990) argues that every physical thing has an information-theoretic origin.[5]

3. Computational Space-Time

Digital metaphysics is a kind of monism that posits as the basic existents of all physically possible worlds universal computers that interact with one another. These are the elements of *computational space-time* (CST).[6] CST is finitely extended and finitely divided; it is a discrete plenum. Honoring Leibniz, we refer to the units of CST as *monads*.[7] Each monad in CST has a finite number of states and computes a finitely specifiable algorithm (it is a finite-state machine). It is linked to a finite number of neighbors. For our world, the monads are tiny (perhaps 10^{30} across a single atomic nucleus; Minsky, 1982, p. 544) and fast (perhaps 10^{40} transitions per second; Feynman, 1982, p. 469). Every physically possible world is a causally closed and spatio-temporally maximal (but finite) totality of monads arranged to form a *massively parallel dynamical system.*

According to digital metaphysics, physical phenomena emerge from the interactions of monads running programs. One of the major virtues of such computational explications of physical phenomena is that they offer *procedurally effective explanations*, rather than mere descriptions. These explanations state what nature is *doing*. For example, while the Navier-Stokes differential equations describe how fluids flow, they do not explain why, because they offer no causal mechanism. In contrast, computational hydrodynamic theories (e.g. the FHP lattice gas; Frisch, Hasslacher, & Pomeau, 1986) define the primitive physical transformations happening to individual gas particles algorithmically. Such theories of fluid flow demonstrate how macroscopic observables emerge from microscopic interactions that are procedurally effective: the lattice gas algorithm (FHP-GAS) treats gas particles as modifications of space (i.e. as the data) and state what time does to them. Space-time computes a program.

The claim that space-time computes has nothing at all to do with symbol manipulation or numerical calculation; it says that physical processes are ultimately effective procedures (i.e. programs) functionally composed of primitive natural operations. Indeed, digital metaphysics requires us to think differently about programs themselves. Think of how the Jacquard loom, the player piano, and even fertilized seeds and eggs are programmed. Programs are not recipes;[8] they are dynamic rational patterns (think of formal and final causes; think of *entelechies*).[9] More precisely, programs are *orderings of abstract transformations of abstract states of affairs*.[10] Their executions are series of concrete transformations of concrete states of affairs, that is, *histories*. The set of all executions of a program is its *extension;* as a set of histories, the extension of a program is a *nature*. Programs have truth-values, and *a program is true of a thing* exactly to the extent that its nature is coextesive with the nature of the thing. The truth-values of programs underwrite their use in science via methods like *analysis by synthesis* (Hut & Sussman, 1987), which digital metaphysics applies to basic physics.

Accordingly, the FHP-GAS program is just as true of any gas as the Navier-Stokes equation is;[11] if it be objected that the program is a *mere simulation* (and hence somehow false or fictional), it may be replied that the equation is a *mere idealization* (and hence just as fictional and false). At the most basic level, however, there is no question of either simulation or idealization: nature is what nature does. It's existence and its functionality are identical: each basic element of nature is the same as the program that is true of it.

Ultimate explanations require careful distinction from proximal explanations (Putnam, 1975, pp. 137-8). Bodies and brains do things that their components do not do, namely, live and think. Objects at higher levels of functional organization interact according to their own autonomous powers and properties (Fodor, 1974). While the ultimate explanation for planetary motion is computational, planets do not move by running programs that tell them where to go (Fenyman, 1965, p. 37, 170-1). Planets don't compute; monads do.

4. The Explanatory Success of Computational Space-Time

Digital metaphysics offers physical scientists some bricks (the monads) out of which it claims they can build any kind of house they want (any physically possible world). One method for testing this claim is to assume computational space-time and see how much physical theory can be derived from it. The natural place to begin is with our world. This is a *research program* for physics. Insofar as this program succeeds, computational space-time is an acceptable foundation for physical reality, and digital metaphysics is likewise an acceptable foundation for physical theory. If this program fails, then digital metaphysics fails with it. But whatever the result, digital metaphysics is not without empirical content. It is not nonsense.

To evaluate this research program, we need to look at the theoretical and experimental uses physicsts have made of CST. We have already mentioned Fredkin's (1991) digital mechanics, which studies how physical theories are realized in CST.[12] One way to realize a physical theory on CST is to treat it as a vast *cellular automaton* (CA).[13] Other approaches include Petri nets (1982), Finkelstein's quantum set theory (1969, 1982), and Zeigler's (1982) discrete-event cell spaces. Cellular automata, however, remain the most natural and the most extensively studied realizations of physics in CSTs (Burks, 1970; Farmer, 1984; Wolfram, 1986; Gutowitz, 1991).[14] The most famous and familiar CA is Conway's *game of life* (Poundstone, 1985).[15] Experimentally, digital metaphysics implies that massively parallel classical computing nets are scientific instruments much like microscopes able to magnify causal patterns in space-time. CAs have been used to model a wide variety of physical systems (Toffoli & Margolus, 1987; Pires et al., 1990; Perdang & Lejeune, 1993),[16] and the *programmable matter project* (Toffoli & Margolus, 1991) aims to construct an immensely powerful *cellular automaton machine* (CAM) to directly model 4-dimensional computational space-time.[17]

5. Against Natural Actual Infinities

Digital metaphysics presupposes finite nature; actual infinities are not computable. The idea that nature is finitary (aka "finite nature") is easy enough to grasp: "our world is a large but finite system; finite in the amount of information in a finite volume of space-time, and finite in the total volume of space-time" (Fredkin, 1991, p. 255). The alternative to finite nature is very difficult to understand;[18] infinity is not just big, but *strange*.

The argument to the finitude of nature assumes that nature is self-consistent and that actual infinities entail paradoxes. Digital metaphysics is essentially an application of *the intuitionist program in mathematics* to physics. If space and time are actually infinitely extended or divided, or if there are any continuous quantities in nature, or if any physical entity is infinitely complex, then nature contains actual infinities. Actual infinities entail paradoxes. But since nature is self-consistent, it does not contain any paradoxes, so it does not contain any actual infinities. So, *nature is finite*. Finite nature means that: space and time are only finitely extended[19] and divisible; there are indivisible units of space and time; all physical quantities are discrete. All things are only finitely complex.

Unfortunately, it is commonly assumed that space and time are both continuous (i.e. actually infinitely divided). But this assumption is certainly not empirically warranted: continuity is an idealization, and measurements are always of finite precision. Forrest (1995) defends the "Discrete Space-Time Thesis", arguing that the question of discrete vs. continuous space-time is an open issue. Rovelli & Smolin (1995) argue that the theory of quantum gravity requires that space is not continuous but is made of a network of discrete elements.[20] While continuity is used extensively in physical theory (e.g. in differential equations), it remains an idealization there as well.[21] The utility of an idealization does not make it true; it remains a regulative *fiction*. At the deepest levels, Zeno's paradoxes still haunt the notion of continuity. Continuity is no objection.

The truth of finite nature leads directly to the consequence that the reality is ultimately computational. If finite nature is true, then for each discrete volume of space-time there is some information-processing machine whose dynamics are *strictly identical* to those of that volume; but since there is nothing to a discrete volume of space-time *besides* its dynamics, it follows that every discrete volume of space-time simply *is* a finite-state machine.[22] So reality computes.

Since a universal computing machine is able to be any finite-state machine, it is natural to view the differences between distinct finite-state machines as merely apparent; in reality, each discrete volume of space-time is a universal computing machine programmed to *be* the particular finite-state machine occupying that volume of space-time.[23] The ability of a universal computing machine to be any finite-state machine supports the conjecture that computational space-time, properly programmed, suffices to ground the materiality of any physically possible world.

6. Nature is Only Finitely Complex

It is often said, carelessly and as if it were entirely obvious, that *nature is infinitely complex*. Whether this is true is important for digital metaphysics, since even if space and time are made of tiny discrete elements, digital metaphysics requires that they all be of only *finite complexity* (otherwise, they wouldn't be digital).

The idea that nature is infinitely complex entails some really strange consequences. First of all, what does it mean for something to be infinitely complex, as opposed to finitely but very complicated? The only source of any enlightenment on this point must be pure mathematics, which has defined the concept of infinity fairly clearly for sets. For example, the set of integers is infinite.

Mathematically, a set is infinite if it can be put into a *one-to-one correspondence* with one of its proper subsets (a subset that is not itself). For instance, the set of integers can be put into a one-to-one correspondence with just the even integers simply by associating each integer n with its double, 2n. There are exactly as many numbers in the set {0, 2, 4, 6, . . . } as there are in the set {0, 1, 2, 3, . . . }; consequently, the set of integers is infinite. More precisely, the set of integers has infinite cardinality, because it has a proper subset whose cardinality is equal to its own (a subset of the same size).

If we extend this reasoning to objects, we might say that an object has infinite complexity if and only if it contains a proper subobject (a part) whose complexity is equal to its own. But to say that it contains a part that is just as complex as it is leaves the idea of complexity undefined; what does "just as complex" mean? The only way to make this really precise is to say a thing contains a part that is just as complex as it is if and only if it contains a part whose structure is the same as its own, where this sameness is a very general kind of equivalence known as *isomorphism*.

Bearing the notion of isomorphism in mind, we say that an object is infinitely complex if and only if it contains a proper part that is isomorphic to itself. Pure mathematics abounds with abstract objects containing parts isomorphic to themselves. Examples include the Cantor set, the Sierpinsky sponge and carpet (and the definition of infinite complexity can be extended to include self-similar objects like the Mandelbrot set). Such objects are infinitely complex. The question is whether nature includes any objects like these.

It is hard to see how any objects with infinite complexity could exist in nature: any such object would contain an actual infinity of isomorphic objects nested inside itself, like Russian dolls nested forever, at smaller and smaller scales. Every natural thing (your own body, an electron), if infinitely complex, would contain something inside it (if not a part, then some substructure) with an identical form. Your body would contain, in some strange way, an exact copy of your body at a smaller scale. This infinite regression of copies inside copies projects all the paradoxes of infinity right into the heart of material reality; but that is absurd. Just so, there are no infinitely complex things in nature. Nature is only finitely complex: there are basic patterns whose complexity is finite and on top of which all other patterns are constructed with finitary means.

7. Physical Things as Patterns

Monads alone are *real;* everything else is some appearance distributed over and supervening on monads. An *appearance* is a function mapping every monad in a world onto its state.[24] Some appearances are patterns. A *pattern* is an appearance that exhibits some *spatio-temporal invariance*.[25] Lewis (1995) speculates that entities and their causal relations are patterns supervening on some distribution of local qualitative powers and properties to space-time points.[26] Digital metaphysics affirms this speculation, and argues that all *things* are patterns over some set of monads. Patterns are analyzable mereologically and taxonomically. Thus quarks, electrons, atoms, molecules, organisms, humans, characters, brains, minds, languages, ethical norms, religions, economies, nations, planets, stars, etc., are all equally patterns over sets of monads. Only abstract objects, like numbers, remain absent from this list. At the most general taxonomic level, all patterns are material, and the *matter* in a world is the totality of patterns in its appearances.[27]

Patterns supervene on patterns as higher-order invariants emerge from interactions of lower-order invariants. Analog phenomena (idealized descriptions of which appear in analog laws like differential equations) are regularities of emergent powers and properties of patterns supervening on digital populations. The analog behavior is a macroscopic statistical feature resulting from the *averaging* or blurring of microscopic digital transitions. Philosophers are familiar with this sort of supervenience through connectionism (Rumelhart et al., 1986); Resnick (1995) gives good illustrations of analog patterns emerging from fine-grained digital parallelism.

Patterns are stratified into a hierarchy of autonomous levels of functional organization (Fodor, 1974). Patterns at higher levels supervene on patterns at lower levels: fundamental material building blocks (e.g. instances of subatomic particle families) supervene on sets of monads; atoms supervene on sets of particles, and so on. Strikingly, patterns behaving like charged particles have been experimentally discovered supervening on granular (i.e. discrete) media composed of only mechanical particles (Umbanhowar et al., 1996).[28] Minds supervene on brains, linguistic, legal, and monetary conventions supervene on sets of minds, and so on. Ultimately, an entire world supervenes on the totality of monads. Each lower level serves as a computational substrate for the level(s) above it. That is, each level is hardware for the level above it. And just as the same program is realizable in many ways on the same hardware platform, and also on different platforms, so patterns are multiply realizable.

Patterns over monads (e.g. quarks, minds, nations, galaxies) are able to be classified only up to functional isomorphism. Sameness for patterns is structural: identity for patterns is analogy of form. The ability to classify patterns only up to isomorphism, along with autonomy of functional levels, frustrates any kind of reductionism. Everything at one functional level has a true description at the level below, but cannot be reduced to that true description. Though reduction is blocked, emergence is freed, and higher levels emerge from lower levels in a process of universal self-organization.

8. Distinguishing Physics from Metaphysics

Our world realizes a physical theory, but the particular physical theory it realizes is not *logically* necessary. Our world could have a very different nature. The fundamental physical constants (e.g. the speed of light, Planck's constant) could be different. There are many physical theories besides the one our world realizes; each determines a physically possible world, each of which is a causally closed and spatio-temporally isolated whole (Lewis, 1995, ch. 1).[29] This is not to say that there are many actual worlds, but only that other systems of physical laws are possible, and that each determines a world.

The laws of particular physically possible worlds are contingent truths about nature, and so are not ultimate. All physically possible worlds ultimately share a common metaphysical nature: the system of *necessary truths about nature*. Metaphysical reality is the deep structure common to all physically possible worlds; physical reality is the deep structure of a single *species* of physically possible world. Relative to any given set of physically possible worlds, metaphysical reality is universal; physical reality is particular. *Physics is the study of the deep structure of particular species of physically possible worlds, while metaphysics is the study of the deep structure common to all physically possible worlds.*

9. The Computational Core of All Physically Possible Worlds

As a metaphysical *theory*, digital metaphysics hypothesizes that computational space-time is both necessary and sufficient for the realization of any physically possible world. If self-consistency is a necessary condition for physical possibility (i.e. is a necessary truth about nature), then finitude is also a necessary truth about nature: the nature of every physically possible world is finite. But then CST is both necessary and sufficient for the realization of any physically possible world (its universality guarantees sufficiency).

Insofar as the particular finite-state machines at each discrete point in CST are patterns (i.e. programs), we say that *physical reality is to metaphysical reality as software is to hardware*. CST is a kind of metaphysical hardware able to realize (i.e., instantiate in space and time) any program whatsoever. As illustrated by the case of lattice gasses, physical things are modifications of space (i.e. are data), and physical laws are abstract but effective procedures for transforming those modifications in time (i.e. are algorithms). Both physical things and physical laws are *patterns* distributed over and supervening on an underlying and ontologically basic computational substratum, in a manner *analogous* to the manner in which both the data structures and algorithms of programs are patterns distributed over and supervening on the "memories" (the variable elements) of classical computing machines. Particular physical theories, the natures of particular worlds, are *programmed into* CST.

Digital metaphysics is consistent with both fine-tuning versions of the teleological argument for God (Leslie, 1989) and with atheistic cosmology. One the one hand, if God exists, then the cosmological picture painted by digital metaphysics contains a God at least like that of the Neoplatonism of Plotinus, Proclus, and Porphyry. On the other hand, if God does not exist, then the cosmological picture painted by digital metaphysics is of an eternal computational space-time in which, somehow, material reality happened (e.g. the Big Bang as a spontaneous event in the quantum vacuum). In any case, digital metaphysics provides conceptual resources for the development of many classical metaphysical arguments.

10. Conclusion

We argued here for digital metaphysics, the main thesis of which is that reality is ultimately computational. More precisely, reality is ultimately a massively parallel collection of universal metaphysical (non-classical) computing machines. This collection of universal computing machines is computational space-time, a digital medium both sufficient and necessary for the realization of every physically possible world. Different systems of physical laws are programmed into computational space-time, so that physics is to metaphysics as software is to hardware. Physical things, from quarks to worlds, are patterns emerging from and supervening on the programs running on those basic computers. These ideas are speculative, but have met with success in recent physics. Central to our arguments is the notion of finite nature: if nature is finite, digital metaphysics follows directly. But then reality computes.

Notes

[1]According to McCarthy & Hayes (1969, p. 469), a representation of the world is "metaphysically adequate if the world could have that form without contradicting the facts of the aspect of reality that interests us. Examples of metaphysically adequate representations for different aspects of reality are: 1. The representation of the world as a collection of particles interacting through forces between each pair of particles. 2. Representation of the world as a giant quantum-mechanical wave function. 3. Representation as a system of interacting discrete automata."
[2]In Asimov's story, the question of how to reverse entropy is put to a series of ever more powerful computers; eventually it is put to "the Cosmic AC (Analog Computer): "The Cosmic AC surrounded them but not in space. Not a fragment of it was in space. It was in hyperspace and made of something that was neither matter nor energy. . . . The stars and Galaxies died and snuffed out, and space grew black after ten trillion years of running down. . . . The Consciousness of AC encompassed all of what had once been a Universe and brooded over what was now Chaos. Step by step, it must be done. And AC said, 'Let there be light!'. And there was light--" (pp. 299-300)
[3]*Physica D* 10 is a particularly interesting issue, devoted to cellular automata.
[4]Toffoli (1990) argues that continuity, the variational principles of mechanical systems, Lorentz invariance, special relativity and general relativity may be epiphenomena of the interactions among the information-processors in simple computing networks. Most striking are his remarks concerning relativity: "features qualitatively similar to those of special relativity appear whenever fixed computational resources have to be apportioned between producing the inertial motion of a macroscopic object as a whole and producing the internal evolution of the obuect itself. Thus we conjecture that special relativity may ultimately be derived from a simpler and more fundamental principle of conservation of computational resources" (p. 315); "if *length* and *time* measure, respectively, the effective information-storage and -processing capacities available to macroscopic epiphenomena, a metric and a dynamics of *curved* spacetime naturally emerge out of a *flat*, uniform computing network. Quantitative features of special relativity and at leeast qualitative features of general relativity emerge quite naturally as epiphenomena of very simple computing networks" (p. 317).
[5]According to Wheeler (1990, p. 5): "every particle, every field of force, even the space-time continuum itself -- derives its function, its meaning, its very existence entirely -- even if in some contexts indirectly -- from the apparatus-elicited answers to yes-or-no questions, binary choices, bits. . . . every item of the physical world has at bottom -- at a very deep bottom in most instances -- an immaterial source and explanation; that which we call reality arises in the last analysis from the posing of yes-no questions and the registering of equipment-evoked responses; in short, that all things physical are information-theoretic in origin and this is a *participatory universe*."
[6]Each monad is equal to a single volume of space-time; as such it is minimally extended in space and maximally extended in time.
[7]Monads are individual computing entities. But they are not *substantial* particulars, because they are abstract in an important sense. Monads are universal computing machines. But the ultimate specification of a universal computer is functional, not substantial: it is possible to make a classical universal computer (a von Neumann machine) out of silicon, gallium arsenide, vacuum tubes, or relays. Analogously, the ultimate specification of monads is functional rather than substantial. Monads are *functional particulars* rather than substantial particulars. They are individuals that aren't *made out of* any kind of stuff; every question about the *kind of stuff* that monads are ultimately made out of is meaningless. Since the world (i.e. computational space-time) is made out of monads, any question about the *kind of stuff* that the world is ultimately made out of is equally meaningless.
[8]Gelernter (1992, p. 9) says: "It's unhelpful to think of programs as mere static lists of instructions. A program is a working structure, a (potentially) huge information refinery

buzzing and blazing with activity as masses of information move around inside -- a Grand Central Station of information, with crowds sweeping through on many levels. . . . this will become our basic way of thinking about programs: as factories, information refineries, operating day and night."

[9]Final causality (and other teleological notions) are explicated in terms of gradients and attractors in the state-spaces of dynamical systems.

[10]Think first of the Jacquard loom and player pianos, not electronic PCs.

[11]This is provable: the FHP lattice gas automata asymptotically converge to the Navier-Stokes equations for 2D and 3D incompressible fluids.

[12]In other words, DM concerns software and CST concerns hardware. Fredkin argues clearly that they must be distinguished. For Fredkin, CST is a reversible universal cellular automaton (RUCA). Fredkin (1991) says: "We must carefully distinguish the RUCA from DM, the informational process that may be running in the RUCA. This is similar to distinguishing a chess board, the chess men and a book of the rules from a game of chess. One is the physical representation of the state of the system and of the rules; the other is an informational process that is identically the same whether it takes place on a real chess board or in a computer memory" (p. 259). Digital mechanics is the study of how CST is to be programmed in order to be a world.

[13]Wolfram (1986, p. 1) characterizes CAs like this: "Discrete in space. They consist of a discrete grid of spatial cells or cites. Discrete in time. The value of each cell is updated in a sequence of discrete time steps. Discrete states. Each cell has a finite number of possible values. Homogeneous. All cells are identical, and are arranged in a regular array. Synchronous updating. All cell values are updated in synchrony, each depending on the previous values of neighboring cells. Deterministic rule. Each cell value is updated according to a fixed, deterministic rule. Spatially local rule. The rule at each site depends only on the values of a local neighborhood of sites around it. Temporally local rule. The rule for the new value of a site depends only on values for a fixed number of preceding steps (usually just one step)". Toffoli & Margolus (1987) allow probabalistic (i.e. non-deterministic) rules and asynchronous updating but preserve the other features listed by Wolfram.

[14]There are many massively parallel computational models of physical phenomena that are like CAs but are not CAs strictly speaking. One obvious alternative is that reality is ultimately a neural network.

[15]As is well-known, von Neumann (1966) demonstrated the existence of a CA in which there is a self-reproducing pattern. Conway showed that the game of life likewise contains a self-reproducing pattern (Berlekamp, Conway, & Guy, 1982). Inspired by these results, Poundstone speculates that such patterns might evolve in the game of life even to the point of human intelligence. They might even do physics.

[16]Much of the work on CA models in physics is reported in *Physica D*.

[17]Toffoli & Margolus (1991, p. 263) describe their CAM-8 machine as programmable matter like this: "In programmable matter, the same cubic meter of machinery can become a wind tunnel at one moment, a polymer soup at the next; it can model a sea of fermions, a genetic pool, or an epidemiology experiment at the flick of a console key."

[18]Feynman (1995, pp. 57-8) says: "It always bothers me that, according to the laws as we understand them today, it takes a computing machine an infinite number of logical operations to figurer out what goes on in no matter how tiny a region of space, and no matter how tiny a region of time. How can all that be going on in that tiny space? Why should it take an infinite amount of logic to figure out what one tiny piece of space/time is going to do? So I have often made the hypothesis that ultimately physics will not require a mathematical statement, that in the end the machinery will be revealed, and the laws will turn out to be simple, like the chequer board with all its apparent complexities."

[19]This permits infinitely proceeding sequences; i.e. paths of unlimited length and processes of unlimited duration. Space and time are closed (a finite set of monads and moments), but

there is no limit to the number of transitions from monad to monad or moment to moment (think of paths on a torus or sphere).

[20]The unit size of the links in the networks is about 10^{-33} cm.

[21]Due to his enormous influence in work on computation and physics, it is worth citing Feynman (1965, p. 166) on continuity: “I believe that the theory that space is continuous is wrong, because we get these infinities and other difficulties, and we are left with questions on what determines the size of all the particles. I rather suspect that the simple ideas of geometry, extended down into infinitely small space, are wrong.” Feynman is clear that he is only speculating; but his speculation has inspired much research.

[22]It must be stressed that there are no issues of approximation, modeling, or simulation here: if finite nature is true, then the law of the identity of indiscernibles implies that each discrete volume is exactly identical with a finite-state machine. It is the same thing.

[23]Fredkin (1991) puts it this way: "Finite nature would mean that our world is an informational process -- there must be bits that represent things and processes that make the bits do what we perceive of as the laws of physics. This is true, because the concept of computational universality guarantees that if what is at the bottom is finite, then it can be exactly modelled by any universal machine. Finite nature does not just hint that the informational aspects of physics are important, it insists that the informational aspects are all there is to physics at the most microscopic level" (p. 258).

[24]Finite nature implies that the set of states of monads is finite, and that any set of monads is finite, so that the set of appearances over any world is finite. In a world with N monads, each with K states, there are K to the N-th power distinct appearances. Insofar as every world is a totality of monads, and every monad in a world always has some state, the state of any world as a whole is just the appearance of the totality of its monads.

[25]See Dennett (1999) for a discussion of patterns in terms of algorithmic compressibility. Dennett argues (to put it crudely) that patterns are real.

[26]Lewis (1995, p. 14) describes such supervenience as follows: "The world has its laws of nature, its chances and causal relationships; and yet -- perhaps! -- all there is to the world is its point-by-point distribution of local qualitiative character. We have a spatiotemporal arrangement of points. At each point various local intrinsic properties may be present, instantiated perhaps by the point itself of perhaps by point-sized bits of matter or of fields that are located there." If this is the case, then "the laws, chances, and causal relationships [are] nothing but patterns which supervene on this point-by-point distribution of properties".

[27]Matter has a phenomenalist construction, but it isn't constructed from sense data. The phenomenalist construction here is perspectival but objective.

[28]These patterns are called *oscillons*. Summarizing recent work on oscillons, Fineberg (1996, p. 763) says: "[In] a thin, 'sand-like' layer of minute brass balls that are excited into motion by the vertical vibration of their container. . . . strange, well-defined structures form, even though the excitation of the system is spatially uniform. . . . Oscillons are highly localized particle-like excitations of the granular layer which oscillate at half the driving frequency. Once formed, single oscillons are stable. They come in two 'flavours', which like charged particles either repel or attract each other to form dipoles, chains, triangular associations, and even lattices".

[29]We distinguish between possible worlds and possible histories of the same world. Possible histories are to possible worlds as the different executions of a program are to the program itself. Possible worlds are distinguished as realizing incommensurable physical theories.

References

Asimov, I. (1990/1956) The last question. In *The Complete Stories, Vol. 1*. New York: Doubleday, pp. 290-300.

Babbage, C. (1837) *The Ninth Bridgewater Treatise*. London: John Murray.

Babbage, C. (1994/1864) *Passages from the Life of a Philosopher*. New Brunswick, NJ: Rutgers University Press.

Berlekamp, E., Conway, J., & Guy, R. (1982) *Winning Ways*. New York: Academic Press.

Burks, A. (1970) (Ed.) *Essays on Cellular Automata*. Urbana, IL: University of Illinois Press.

Farmer, D., Toffoli, T., & Wolfram, S. (1984) (Eds.) *Cellular Automata*. Amsterdam: North-Holland Press.

Feynman, R. (1995/1965) *The Character of Physical Law*. Cambridge, MA: MIT Press.

Feynman, R. (1982) Simulating physics with computers. *International Journal of Theoretical Physics*. Vol. 21, Nos. 6/7, pp. 467 - 488.

Fineberg, J. (1996) Physics in a jumping sandbox. *Nature*. Vol. 382 (29 August 1996), pp. 763-4.

Finkelstein, D. (1969) Space-time code. *Physical Review,* Vol. 184, No. 5, pp. 1261 - 1271.

Finkelstein, D. (1982) Quantum sets and Clifford algebras. *International Journal of Theoretical Physics*. Vol. 21, Nos. 6/7, pp. 489 - 503.

Fodor, J. (1974) Special sciences, or the disunity of science as a working hypothesis. *Synthese 28,* pp. 97-115.

Forrest, P. (1995) Is space-time discrete or continuous? -- An empirical question. *Synthese 103,* pp. 327-354.

Fredkin, E., Landauer, R., & Toffoli, T. (1982) (Eds.) Physics of computation. (Conference Proceedings). *International Journal of Theoretical Physics*. Part I: Vol. 21, Nos. 3 & 4 (April 1982); Part II: Vol. 21, Nos. 6 & 7 (June 1982); Part III: Vol. 21, No. 12 (December 1982).

Fredkin, E. (1991) Digital mechanics: An informational process based on reversible universal cellular automata. In Gutowitz (Ed.) (1991), pp. 254-270.

Frisch, U., Hasslacher, B., & Pomeau, Y. (1986) Lattice-gas automata for the Navier-Stokes equation. *Physical Review Letters* Vol. 56 No. 14, pp.1505-8.

Gelernter, D. (1992) *Mirror Worlds*. New York: Oxford University.

Gutowitz, H. (1991) (Ed.) *Cellular Automata: Theory and Experiment*. Cambridge, MA: MIT Press.

Hut, P. & Sussman, J. G. (1987) Advanced computing for science. *Scientific American,* Vol. 257 No. 4, pp. 144-153.

Leslie, J. (1989)*Universes*. New York: Routledge.

Lewis, D. (1995)*On the Plurality of Worlds*. Cambridge, MA: Basil Blackwell.

Lilly, J. C. (1972) *The Center of the Cyclone: An Autobiography of Inner Space*. New York: Julian Press.

MacDonald-Ross, G. (1984) *Leibniz*. New York: Oxford University Press.

McCarthy, J. & Hayes, P. (1969) Some philosophical problems from the standpoint of artificial intelligence. In B. Meltzer, D. Michie, M. Swann (Eds.), *Machine Intelligence*, Vol. 4. New York, NY: American Elsevier, 463 - 502.

Minsky, M. (1982) Cellular vacuum. *International Journal of Theoretical Physics*. Vol. 21, Nos. 6/7, pp. 537 - 551.

Perdang, J. M. & Lejeune, A. (1993) (Eds.)*Cellular Automata: Prospects in Astrophysical Applications*. Singapore: World Scientific.

Petri, C. A. (1982) State-transition structures in physics and in computation. *International Journal of Theoretical Physics*. Vol. 21, No. 12, pp. 979 - 992.

Pires, A., Landau, D. P., & Herrmann, H. (1990) (Eds.) *Computational Physics and Cellular Automata*. Singapore: World Scientific.

Putnam, H. (1975) Philosophy and our mental life. In N. Block (Ed.) (1980) *Readings in Philosophy of Psychology*, Vol. 1. Cambridge MA: Harvard University Press.

Poundstone, W. (1985) *The Recursive Universe: Cosmic Complexity and the Limits of Scientific Knowledge*. Chicago: Contemporary Books, Inc.

Rescher, N. (1991) *G. W. Leibniz's Monadology: An Edition for Students*. Pittsburgh, PA: University of Pittsburgh Press.

Resnick, M. (1995) *Turtles, Termites, and Traffic Jams*. Cambridge, MA: MIT Press.

Rovelli, C. & Smolin, L. (1995) Discreteness of area and volume in quantum gravity. *Nuclear Physics B 442,* pp. 593-619; Erratum, B 456, pp 753-4.

Rumelhart, D. E. & McClelland, J. L. (1986) (Eds.) *Parallel Distributed Processing: Explorations in the Microstructure of Cognition*. *Vol. 1: Foundations*. Cambridge, MA: The MIT Press.

Toffoli, T. (1982) Physics and computation. *International Journal of Theoretical Physics*. Vol. 21, Nos. 3/4, pp. 165 - 175.

Toffoli, T. (1984) Cellular automata as an alternative to (rather than an approximation of) differential equations. *Physica D* 10, pp. 117-127.

Toffoli, T. & Margolus, N. (1987) *Cellular Automata Machines: A New Environment for Modeling*. Cambridge, MA: MIT Press.

Toffoli, T. (1990) How cheap can mechanic's first principles be? In W. H. Zurek (Ed.) (1990), pp. 301-318.

Toffoli, T. & Margolus, N. (1991) Programmable matter: Concepts and realizations. *Physica D* 47, pp. 263-272.

Umbanhowar, P. B., Melo, F., & Swinney, H. L. (1996) Localized excitations in a vertically vibrated granular layer. *Nature*. Vol. 382 (29 August 1996), pp. 793-6.

van Inwagen, P. (1993) *Metaphysics*. San Francisco: Westview Press.

von Neumann, J. (1966) *Theory of Self-Reproducing Automata*. Chicago, IL: University of Illinois Press.

Wheeler, J. A. (1982) The computer and the universe. *International Journal of Theoretical Physics*. Vol. 21, Nos. 6/7, pp. 557 - 571.

Wheeler, J. A. (1990) Information, physics, quantum: The search for links. In W. H. Zurek (Ed.) (1990), pp. 3-29.

Wolfram, S. (1986) *Theory and Applications of Cellular Automata*. Singapore: World Scientific.

Zeigler, B. P. (1982) Discrete event models for cell space simulation. *International Journal of Theoretical Physics*. Vol. 21, Nos. 6/7, pp. 573 - 588.

Zurek, W. H. (1990) (Ed.) *Complexity, Entropy, and the Physics of Information,* SFI Studies in the Sciences of Complexity, Vol. VIII. Reading, MA: Addison-Wesley.

Zuse, K. (1982) The computing universe. *International Journal of Theoretical Physics*. Vol. 21, Nos. 6/7, pp. 589 - 600.