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An Introduction to Digital Philosophy

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Digital Philosophy (DP) is a new way of thinking about how things work. This paper can be viewed as a continuation of the author's work of 1990[3]; it is based on the general concept of replacing normal mathematical models, such as partial differential equations, with Digital Mechanics (DM). DP is based on two concepts: bits, like the binary digits in a computer, correspond to the most microscopic representation of state information; and the temporal evolution of state is a digital informational process similar to what goes on in the circuitry of a computer processor. We are motivated in this endeavor by the remarkable clarification that DP seems able to provide with regard to many of the most fundamental questions about processes we observe in our world.

KEY WORDS: digital philosophy.

1. WHAT IS DIGITAL PHILOSOPHY?

We are all ever more amazed at the competence of the mathematics of continuous variables as models for physical processes. Digital Philosophy (DP) replaces all that at the most fundamental (microscopic) level by automata theory. We give up what we are used to but strangely enough, in DP, we may find the answers to many fundamental questions, including "Why is it true that mathematics is so good at modeling processes in the physical sciences?" "In physics there are two electrical charges (e^+ and e^-); why *two*?" and "What, exactly, causes the various, wonderful symmetries of our world?" Most important, the kind of understanding that DP makes possible is on a different plane; DP makes fundamental processes so simple and clear as to allow one to understand many such things perfectly and exactly.

On the down side, DP is so new and so undeveloped that its obvious faults might turn off the reader. While some of the models described herein may turn out to be good science, much of what will be explained can be thought of as a fairy tale designed to make a point. The similarity to Aesop's fables is telling: there is a moral to the story.

We hope that it is worth ignoring this tale's reliance on imagination in order to see the beauty of the grand concept. When seen and understood in its entirety

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it can be so overwhelming as to render its shortcomings as works of art. So, we invite the reader to proceed with a difficult and torturous journey through a field of startling ideas, many of which are wrong, but which nevertheless have the ability to open our eyes to something new.

It is easier to understand DP if one first separates what we know about the world into two categories. The first category consists of verified experimental data and mathematical models and relationships that fit that data. The second category consists of the conclusions, concepts, models, pictures, thought experiments, explanations in natural language and everything else that is not a rigorous mathematical derivation or consequence of the first category. Things in the second category may be consistent with experimental data but they are not the *only* things consistent with that data. When thinking about DP, try embracing the first category while ignoring apparent conflicts between DP and things in the second category. It is not that we imagine "nothing is correct" in the second category; but we mustn't allow ourselves to drown in contradictions until we learn to swim in the sea of DP.

2. BASIC PRINCIPLES

Having tried to clear our minds of unnecessary baggage, we allow ourselves to be guided by a few simple heuristics: simplicity, economy, and Occam's razor.[2] In particular, DP is a totally atomistic system. Everything fundamental is assumed to be atomic or discrete; and thereby so is everything else. In physics, DP assumes that space and time are discrete. There are two mathematical models of such systems. The first is Diophantine analysis; the mathematics of the integers. The second is automata theory; the mathematics of digital processes. We choose the latter as it also has the property of explicitly representing a discrete temporal process, while the mathematics of the integers simply establishes a set of true theorems and thus can represent implicitly only temporal processes. Tremendous progress in the sciences followed the discovery of the calculus (and partial differential equations) as a way of mathematically representing physical–temporal relationships. But we look elsewhere with respect to the most fundamental models of physical processes. What we must demand of DP is the eventual ability to derive, from our DP models of fundamental processes, the same mathematical equations that constitute the basis of science today.

Conway's game of Life (Gardner, 1970) is a good example of a simple digital system and the consequent emergent properties. We arbitrarily assume that DP represents state by patterns of bits, as is done in ordinary computers. All of the

[2] "Occam's Razor," also called *law of economy* (or *law of parsimony*): a principle, stated by William of Occam (1285–1347/49), a scholastic, that *Pluralitas non est ponenda sine necessitate*, that is, "Plurality should not be posited without necessity." The principle gives precedence to simplicity; of two competing theories, the simplest explanation of an entity is to be preferred. The principle is also expressed "Entities are not to be multiplied beyond necessity" [From *Encyclopedia Britannica*].

fundamental transformations we can do with bits in a computer are really a subset of what mathematics can do with the integers. We usually think of bits as either 1 or 0, but in the Digital Mechanics (DM) of physics we choose to use two symmetric integers, $+1$ and -1. The bits of DM exist at points in a regular digital spacetime, where each point contains one bit of information. We think of spacetime as digital since it is made up only of points located where all of the coordinates are integers. Automata theory and computer science lead us to believe that the representation of state by bits imposes no limitations beyond the fact that everything is ultimately quantized. Computers and their software are the most complex things ever made by man. However, computation is based on the simplest principles ever discovered. Our world is complex and we are looking for simple models that might be at the bottom.

The principles of DP require us to find and start with the simplest possible models. Thus the unit of state is the bit, which is considerably simpler than a real number. Of course, it is possible that a 3- or 4-state system might result in an even greater overall simplicity. Our task at this time is to pick a set of reasonable assumptions, and not to worry too much over every choice.

The main subject of this paper is the application of DM to physics. Having established the basic concepts of DP, we choose to develop the further application of these concepts to physics in two major steps. The first involves mapping properties of physical state onto a binary representation, and the second involves finding digital processes that cause our binary representations to evolve in concert with the laws of physics. In this paper, we will be focusing mostly on the first step. We make a list of physical facts that are likely to be most basic and fundamental. Our current list includes the following: $(3 + 1)$-dimensional spacetime, CPT invariance, Planck's constant, the speed of light, the conservation laws (linear and angular momentum, energy, charge, etc.), certain facts about particles, and certain discrete symmetries. It is not an oversight that continuous symmetries are not on this list: the above conserved quantities are assigned to configurations of bits in a discrete spacetime lattice. It is easy to achieve in this way one or two such facts, but more difficult when we try to consistently represent many facts simultaneously. We proceed by trying to fit in as much as possible while trying to maintain self-consistency; sometimes we don't succeed. Thus, the development of DP's first step can be seen as a process of synthesis. We have many pieces of a large puzzle, and we try to fit them together so that as many as possible of the known facts of physics are represented by a particular model. Such models, consistent with DP, are called DM. DP is defined by a set of global assumptions; DM expands and adds to those assumptions to create more specific models of physical processes.

Given all this, we have a definite methodology for proceeding with the development of DP. The result so far is that we can now demonstrate a particular DM model that simultaneously represents many known facts of physics in a consistent way. However, the reader must understand that, while what we will explain in this paper represents progress, it is far from a finished theory. In physics, we have the problem that quantum mechanics, relativity, and Gravity are not consistent aspects of one model. The DM model given in this paper is grossly less comprehensive while far more inconsistent than conventional physics, but it is a newborn baby—while conventional physics is mature. On the other hand, this DM model represents great progress compared with other DM models produced over the last 40 years.

The DP representations as to what constitutes energy, linear and angular momentum, electrical and color charge, etc., are as simple as possible and, we hope, not too simple. There are two major models of space and interactions: the first involves fields, waves, and other complex properties of the vacuum, and the other involves nothing but particles. Both views are useful, but getting DP to be consistent with both simultaneously makes DP more complex. The principle of simplicity has driven us to reluctantly make a decision—in this paper DP is a particle model and all processes in DP are consequences of the motions and interactions of particles. The properties of the vacuum are consequently the properties of particles inhabiting the so-called empty vacuum. We know that interesting physics can come from simple, easy-to-understand assumptions. The kind of physics one gets from DP is not directly mathematical in a conventional sense; rather it is a microscopic working model that can be programmed up on a computer.

If spacetime is discrete, then we believe that one of the simpler representations of dynamics is by means of a *reversible universal cellular automaton* (RUCA[3]), specifically, a *discrete second-order system* (DSOS). A DSOS RUCA can do everything demanded by physics with regard to reversibility obeying CPT symmetry, and do it so efficiently that we feel compelled to look more closely at such systems.

The particular system we will describe may appear quite foreign; however, it has the amazing property that given its design, some properties of physics are naturally represented by configurations of bits. Once the general ideas are understood we will be able to show how charge, angular momentum, linear momentum, and energy can be represented within the model. We will also be able to argue why DP predicts angular isotropy above the scale of quantization and predicts why the laws of physics are independent of the choice of unaccelerated reference frame (at scales much greater than the lattice spacing).

The lattice of a DM RUCA is not the spacetime of physics. It is the engine of an informational process. In essence, the RUCA runs a computation. As a consequence of that process and of appropriate initial conditions, various stable structures will exist in the lattice. For each such stable structure, we expect that its behavior will mimic the behavior of some particle—such as a muon or a photon. What we demand of a correct model is that the behavior of those particles obeys the laws of physics and that we can identify the particles of the RUCA with the particles of physics. When DM is mature, measurements made of the behavior

[3] Abbreviations used: CA, cellular automaton; UCA, universal CA; RUCA, reversible UCA.

of the particles in the RUCA must be consistent with all the laws of physics; including quantum mechanics and special and general relativity. The lattice, on the other hand, is a not part of physics and its space is not the space of physics, and it does not have to obey the laws of physics. Critics often complain that a Cartesian lattice has no place in a relativistically correct model of physics. Such comments are due to a simple misunderstanding. The statement that a Cartesian RUCA cannot produce relativistically correct physics is equivalent to stating that a particular brand of supercomputer is unsuitable for 3-D models of physics because the geometry of the bits in its memory chips are basically 2-dimensional.[4] Of course, it is not an accident that the local geometry of the RUCA is very similar to the local geometry of space. But the definition of a geodesic is not some straight line across the RUCA lattice, it is the path taken by a photon working its way across the RUCA lattice while reacting properly to gravitational fields and other effects that should influence its path.

The first concepts of DP[5] incorporated a rational cosmogony, modeled the concept of temporal evolution well, and modeled certain laws of physics in an ad hoc and unattractive way. The idea was no more than that of viewing fundamental physics as a computational process on an ordinary computer. However, it established two of the most important features of DP, *universality* and *digital cosmogony*. Thinking about that model led the author to conclude that computational universality had to be a property of physics. Whatever the most basic laws of physics were, it had to be true that they were *computationally universal*,[6] otherwise computers as we know them would be unable to exist. The cosmogonical problem of physics disappears in DP. The puzzle is: given the laws of physics (especially conservation laws), it is a stretch of the imagination to conceive of the universe (spacetime, its contents and laws) being created out of nothing, consistent with those laws. In DP, the computation that is physics runs on an engine that exists in some place that we call “Other”. There is no reason to suppose that Other suffers the same kinds of restrictive laws present in this universe. Computation is such a general idea that it can exist in worlds drastically different than this one; any number of regular spatial dimensions or almost any kind of spacetime structure with almost any kind of connectivity. There is no reason to think that concepts of matter

[4] For insight into how a CA model can be relativistic, see Margolus (XXXX), Smith (1994), and Toffoli (1989).

[5] The idea of representing physics as a computer program occurred to the author in the mid 1950s. The earliest form of DP involved little more than the concept that underlying physics there might be some kind of computational process.

[6] Early works on automata theory defined *universal computer* as a system with an infinite memory that could emulate the behavior of any other computer. A more modern definition (and the one used in this paper) defines universal computer as one with enough memory to hold an emulation program (which is usually very small) plus the contents of the memory of whatever finite computer it will emulate. It’s the nature of the computer, not the infiniteness of its memory, that determines whether or not it is universal. All modern computers (such as ordinary PCs) are universal computers.

and energy, of conservation laws and symmetries, and of beginnings and endings are applicable to Other. DP even offers us a few commonsense conclusions about Other. In Other the RUCA is loaded with the initial conditions and the computation is put into operation. DP has no problem with cosmogony (Fredkin, 1992).

The author considered the fact that DP solved the universality and cosmogonical problems in physics as sufficient motivation to pursue the study of DP, despite the fact that the first DM models didn't have much more to recommend them.

It was a great advance to go to cellular automata as a basis for DM models. The author's first CA model, the XOR rule, was a step forward in being a direct model of a spacetime that was locally Cartesian. It replicated patterns and displayed a superposition principle, but it was a step backwards in that it did not model universality or any other aspects of physics.

After being shown that first DM cellular automaton model and understanding the concept of DP, Marvin Minsky challenged the author to see if there was any simple rule that exhibited spherical propagation as opposed to the typical diamond-shaped figures seen from rules like the XOR rule. This was a brilliant insight, combining a known property of physics with what might be possible within the then primitive understanding of CA models. Minsky's challenge took a while to get answered, but it was an important step in the evolution of DP. The early CA models of DP faced seemingly insuperable obstacles. No simple CA was known to be computation-universal,[7] and no known universal computer models were known to be reversible. Those two facts were enough to cause almost any rational person to abandon DP as a sensible model for physics. The author was forced to take three detours. First to show that simple CA models could be computation-universal, second, to show that there were reversible models of universal computation, and third, to gain understanding and familiarity with RUCAs and their properties. After completing the first of these three tasks, there appeared, out of the blue, Conway's remarkable "Game of Life." It was a CA and it had stable particles that moved! This was another fantastic step that arrived unexpectedly. Gosper was able to demonstrate that the Game of Life was actually a UCA (Dewdney, 1985). We then discovered Konrad Zuse, who in the late 1960s, came up with a similar general concept of DP, and published a book called *Rechnender Raum* ("Calculating space") (Zuse, 1969). We invited him to come to MIT where (according to his account) he found the ideas in his book appreciated for the first and only time during his life. Finally all of these tasks were accomplished by the mid 1970s by the author who, with his students and colleagues,

[7] The universality of CAs was first established by von Neumann (1996). The problem was that von Neumann's UCA was a 23-state machine with a 4-cell neighborhood, totally ad hoc, designed to show that it could build a replica of itself as a partial model of a living organism. Codd reduced the complexity of a universal CA with a von Neumann neighborhood to an 8-state machine, and Roger Banks accomplished the ultimate in finding a 2-state version.

including Roger Banks, Tommaso Toffoli,[8] and Norman Margolus expanded and elaborated these concepts. Charles Bennett (1973) had independently discovered a model of reversible computation, but his motivation was unrelated to DP. Gaining a thorough understanding of reversible processes took a number of years. The development of Digital Physics and DM has been a strange process but we have no shame.

To summarize, DP carries atomism to an extreme in that we assume that everything is based on some very simple discrete process, with space, time, and state all being discrete. The workings of DM are like the workings of a hypothetical computer processor: there are bits of information, there are discrete instants of time, and there are rules that govern how the state at one instant in time is translated into the state at the next instant of time. Today, our understanding of how to incorporate universality and reversibility into CA models is so advanced that we take it as a matter of course that all our DM models incorporate these two principles.

In physics, atoms and particles are complex objects with diverse properties. DP deals with just two kinds of objects—and they are the very simplest kind of things possible. We call them "bits" (though it doesn't really matter exactly what we call them). In DM, we choose to use $+1$ and -1 for the two values of a bit. All bits are the same in every way except every one is either $+1$ or it is -1. A bit is a 2-state object and has no other intrinsic structure. The only properties that a bit (such as $+1$) has are that it is absolutely identical to all other $+1$ bits, and different than all -1 bits. Similarly, -1 bits are the same as all other -1 bits and different than all $+1$ bits. Of course, every bit is located by 4 integers, which are its spacetime coordinates. Properties of physics such as charge, energy, momentum, and spin are all made up of spacetime configurations of bits. There is space, there is time, there are bits, there is a simple digital process—and there is nothing else in DP. In creating the DM model described in this paper, we have had to define a large number of very simple digital constructs, digital processes, geometrical arrangements, and ad hoc concepts. However, every one of the things defined is extraordinarily simple. We think that the totality of a final and correct DM model (if one is ever found) will be much simpler than what we present here. It's like Emerson's comment when he apologized to a friend for writing such a long letter: he didn't have time to write a short one!

The bits of DP differ from the bits in an ordinary digital computer in that the bits of DP cannot be changed, created, or destroyed. Arithmetically, our $(+1, -1)$ binary system has an obvious multiplication table, but the addition table is not so obvious. We assume that we must always add an odd number of addends. Note that in this way $+1 + 1 + 1 = -1$ and $-1 - 1 - 1 = +1$. Sometimes we use an alternative label where the bits are named $+i$ and $-i$. The reason has to do with bits

[8] Toffoli (1976) was the first to invent a RUCA; his approach was to retain some "garbage" from the past states in an added dimension. Margolus (XXXX) invented the first RUCA that did not require an added dimension.

that operate in the opposite phase to the $(+1, -1)$ bits. In the $(+i, -i)$ system, both sums and products must both always involve an odd number of arguments. If we make a rule that arithmetic operations always involve an odd number of arguments, then sums in the $(+i, -i)$ system use a sign rule that is the same as for ordinary products, while sums in the $(+1, -1)$ system give the *opposite* (i.e., sign-reversed). The details of the kinds of bits we propose for our DM models impose no hindrance on the computational generality of these models. The arithmetic properties of the bits only matter when we want to analytically derive the standard equations of physics from digital state information.

Choosing which DP assumptions to make ends up as an arbitrary process, with guidance coming from some kind of esthetic sense developed over the years. We try to stick to our goal of simplicity and consistency while trying to be comprehensive.

DP allows us to think about the most microscopic things and events of our world from a new perspective. At the bottom, DP offers nothing but digital information, where the only way the digital information can change is as a consequence of a digital process. A good DM model requires that the digital processes at the heart of DP must have certain basic properties corresponding to the laws of physics. For instance. the laws that govern the evolution of state of a DM model must be CPT-invariant. Of course; physics is CPT invariant. However in the DM model, it is crystal clear that CPT invariance implies a very strong kind of *conservation of information*. In ordinary physics, conservation of information is not something that has the same absolute character as conservation of momentum. If DP makes sense, then that would mean that in the real world information could never be lost, and as a consequence we might conclude that information would be conserved, absolutely, just as momentum is conserved. Currently, we know of no experimental result that supports the conclusion that sometimes information is not conserved. This leads to the question "Could physics have a strong law of conservation of information?" If so, we would have to rethink particle disintegrations and inelastic collisions and quantum mechanics to better understand what is happening to the information. The appearance of a single truly random event is absolutely incompatible with a strong law of conservation of information. A great deal of information is obviously associated with the trajectory of every particle and that information must be conserved. This is a big issue in DP, yet such issues are seldom considered in conventional physics.

Conservation of information and the idea that the laws of physics must be computation-universal arise from thinking about DP. With regard to computational universality there is a way to experimentally verify whether it is true of physics. In automata theory, we prove that a system is computation-universal by demonstrating the possibility of constructing a universal machine within that system. If, in our world, we can build and operate even one universal computer, then that is hard experimental evidence that physics must be computation-universal. This experiment has already been done and verified.[9] To prove the converse, we would have had to demonstrate the impossibility of constructing a universal computer.

DP further assumes that a program running in an ordinary computer can be an exact model of the digital representations and digital processes underlying how various real-world systems work. DP supports the beliefs that, at different levels, information is often best thought of as digital and processes can often be best understood as digital processes. Thus anything in the world of DP that is changing or moving does so in a manner similar to how things are made to change or move in the memory of a computer.

The discreteness of DP time and space implies that there must be some kind of atom of motion. We use our heuristic principle of simplicity to ask, "What is the very simplest kind of digital motion that conserves information and that is reversible?" A possible atom of motion that comes to mind is that two nearest spatial neighbors *swap* places. In DP, all ordinary motion is a consequence of multitudes of some such kinds of atomic motions. The spin of a DP particle is a consequence of an orbital component to all motion, and this orbital component spans three lattice steps (looking at one bit that is swapped three times) per cycle; in a Cartesian lattice, this is the minimum size and complexity possible for such an orbital component. As will be explained, it is easy to use a basic operation as simple as a swap to build systems that are universal and reversible and that model many aspects of physics in a natural manner.

We pop up to the top level here to ask the prime question about DP: "Why bother?" The answer is that DP might reflect how microscopic things actually work. DP specifies a working model. Every DM model can be put into a computer where it runs and evolves, showing us things that we could not know without creating the model and putting it into motion. We expect that a good DM model of physics will be a subject for the same kind of mathematical treatment as has been accorded to physics. However, the DM model ought to allow us to also derive the mathematical aspects analytically, from the basic rule of the DM model.

Unlike contemporary cognitive psychology, biology, and physics, every normal person, including children ready to learn algebra, would be able to understand the most fundamental laws of digital nature as exactly and completely as they can be understood by anyone.

Again, the two main attributes of DP are

- Ultimately, all information must have a digital means of representation.
- All change in information is a consequence of digital informational processes.

[9] Every human being and every personal computer meet the standards set by automata theory for being recognized as universal computers!

Where there is state information there must be digital representation. Where there is change-of-state information, there must be a digital process that effects that change.

3. DP AND BIOLOGY

In biology, there has been a tremendous revolution in the understanding of the basis of all living things, but the enormity of that change has not yet had an effect on our philosophy. The change is that we used to think that the characteristics of the progeny of any living thing were determined by some unknown and mysterious mechanisms. Sixty years ago science had already given up on vitalistic concepts, but nevertheless accepted that chemistry worked in ways not understood with regard to the mysteries of biology.

Today it is obvious that attributes of living things are written down in a digital code. We now know that some process, involving information encoded in DNA, is at the heart of cell differentiation as a zygote develops into an embryo. Could we have anticipated all this before the discovery of DNA? The answer is, “Yes!”

Mendel’s laws involve small integers (like 1 and 0, male and female, or true and false) and simple ratios like 1/4 or 1/2. A world of nothing but continuous variables with mysterious interactions amongst those variables has little chance of producing laws similar to Mendel’s.

There is obviously a lot of information in a seed. Gametes bring information together to form a zygote. DP could have predicted that the underlying mechanisms of inheritance and growth were most likely to have at their core a system of digitally represented information.

Three key elements that lend support to the possibility of an underlying digital model are

- The appearance of small integers in mathematical laws.
- Hierarchies of structures (or small groups of structures, such as male–female pairs), each of which is functionally identical to others of the same species.
- The existence of inherent information and inherent information processing.

Insofar as normal chemistry is concerned, each atom of a given element is functionally identical to every other atom of the same element. Of course there are isotopes, but normal chemistry is usually blind to that distinction. In the case of life, we have atoms, simple molecules, proteins, and finally DNA and cells, with the G and C plus A and T as the elements of a genetic code where the details of the atoms that make up a molecule of guanine, for example, do not matter in the ensuing informational processes of a DNA molecule. Functionally identical structures extend all the way up to all the males or all the females of the same species. While each such member of a species has distinct characteristics, they all share the fact that they can all interbreed with each other; that is a functional identity.

The characteristics of all the different species of living things represent a great deal of additional information. Further, the precise characteristics of each of the members of a given species also represent a great deal of information. Most biologists do not think about the processes of life in the same ways as would a Digital Philosopher. Yet some kind of information processing in living things begins with the informational process of sperm and egg combining and continues with differentiation as a kind of computation based on inherited information and finally, as is obvious for all creatures that move, behavior involves information processing on a more familiar level.

What we have been describing are some of the clues that could have allowed believers in DP to hypothesize that the basic, most microscopic representation of information, that governs heredity and growth, must be a digital representation. Years ago there were no practitioners or followers of DP, and the digital basis of genetic information remained outside of the conscious thoughts of most biologists, even as a possibility, until the discovery of the structure and nature of DNA.

Today, a follower of DP could still predict that we will discover that digital processes govern the growth and development of living things. Perhaps life is based on digital-informational processes involving the digital information encoded in DNA. It is obvious to a few (including the author and Stephen Wolfram) that such digital processes as seen in cellular automata are possible explanations and models for many of the informational processes in biology.

4. DP AND PHYSICS

When a Digital Philosopher looks at physics he or she can see many similarities to biology. The thought that biology might be leading the way towards a better understanding of physical processes must seem very spooky to a physicist. Are there "hierarchies of structures" (or small groups of structures, such as $+$ or $-$ pairs), each of which is functionally identical to others of the same species? Wow! The particles of physics fit that prescription perfectly. Is there "the existence of inherent information and inherent information processing"? The nature of biological information processes are rather complex. They range from decoding the genetic code and implementing the design so as to grow a new copy of some living thing, all the way to the kinds of information processing that go on in the brain of a creature trying to solve a problem (like, how to not get eaten by that other creature). In physics, when two high energy particles collide, the computational problems are much simpler and more like what happens in ordinary computers. For example, the vector sum of the momenta of the incoming particles must be added up and then divided amongst the departing particles, so that the sum of all the individual momentum vectors is not changed by the interaction. Second, the sum of the charges of the incoming particles (usually a number like $-2, -1, 0, +1$, or $+2$, but sometimes a larger integer, in the hundreds) must be divided up amongst the outgoing particles so that the sum remains the same. The same is true for spin and total energy. It's computationally very simple; much like bookkeeping. The ideas about arithmetic belong to mathematics. The actual adding, subtracting, and multiplying done to integers are digital-informational processes.

So far it may seem that we have built a few straw men and then proceeded to knock them down. This is a sign of the incompetence of the author with respect to explaining DP. The story is compelling despite the poor telling of it.

So here is the difference between physics and biology, as seen from the eyes of a Digital Philosopher: Whatever there was before we knew about DNA that could have encouraged the belief that underlying biology, there had to be a digital representation of information, there is much more reason to believe that underlying physics there is a digital representation of information. Every small integer that occurs anywhere in physics is a clue to Digital Philosophers: physical information must have a *digital means* of representation. Examples include

- Number of spatial dimensions: Exactly three
- Number of different electrical charge states: Exactly two, $+$ and $-$.
- Number of chiral parity states: Exactly two, *left-handed* and *right-handed*.
- Number of directions for time: Exactly two, *forwards* and *backwards*.
- Number of CPT modalities: Exactly two out of eight, CPT and $-\mathrm{C} - \mathrm{P} - \mathrm{T}$.
- Number of spin state families: Exactly two, *bosons* and *fermions*.
- Number of measurable spin states of an electron: Exactly two, *up* and *down*.
- Number of particle conjugates: Exactly two: *particle* and *antiparticle*.
- Number of different QCD color charge states: Exactly three, R, G, and B.
- Number of lepton and quark generations: Exactly three.
- Number of leptons or quarks per generation: Exactly two.
- Spin of any particle that is a boson: Exactly n (n always a small integer).
- Spin of any particle that is a fermion: Exactly $n + \frac{1}{2}$.
- Maximum number of inner-orbit electrons in an atom: Exactly two.

The above list is a small sample of the totality of small-integer phenomena in physics. If you have a good imagination, you can dream up worlds where most such things might be any real number. What all this means is that even the facts above need explanations.

DP insists that "things don't just *happen*." When two particles have an elastic collision, the vector sum of the momenta of the outgoing particles is the same as the vector sum of the momenta of the incoming particles. From the point of view of a Digital Philosopher, there are two aspects to such a process that seldom occur to a physicist. The process involves a computation, in that one kind of information (the two momenta prior to the event) has been transformed into another kind of information (the two momenta subsequent to the event). We hypothesize that that process must be a digital informational process. Second, the information related to the event must pass the same conservation test as does the momentum, since information is also conserved. While that seems straightforward in the case of an elastic collision, consider the case of an inelastic process such as the complex decay of a very heavy particle.

A large number of particles stream out in every direction. Since physics is reversible and information is conserved, it is illuminating to look at the time-reversed process. A large number of particles come in from many different directions and all collide to form a single heavy particle. This is why we call the process "inelastic." While not very likely, it's still good physics. However there is one problem, all of the information represented by all of the tracks of all of the incoming particles must still exist after they all collide to form one particle! Where is all that information? Conversely, by reversing our reversed example, we see that all of the information that is represented by all of the tracks of all of the decay products must have existed before the decay of the heavy particle. DP must take on the burden to find the answers to such questions.

5. FINITE NATURE

Physicists often make discrete spacetime models. These models can be programmed on a computer as a digital approximation of a continuous model. Space and time are discrete in these models in the form of a lattice of points. For example, a computer can use difference equations on a lattice to approximate partial differential equations in a continuum. The values at each cell in the lattice are typically computer numbers with about 20 digits of precision. The ad hoc nature of such discrete models relegates them to their role as approximations to physical reality.

Finite Nature (FN) is the hypothesis that assumes space, time, and all other quantities of physics are ultimately discrete and finite. DP is certain to come into vogue if we were to discover that FN is true. If all were digital, our views as to how all things work, microscopically, would have to change. In any case, we can still understand the nature of DP before we know whether or not FN is a true fact of nature. DP suggests that not only can computers model all aspects of physics, but in theory, a computer could model those aspects exactly. It is clear that for much of physics, the idea of an exact computer model can never be realized, as the physical size of such a computational process would simply be too large to implement.

DM models are meant to be simple models but not directly based on differential equations or even ordinary difference equations. Automata theory, on which DM is based, defines such concepts as *finite-state machine*,[10] automata, cellular

[10] Consider time as a sequence of integers that are counting up. At time t, a finite-state machine (FSM) is in one of a number of states. The FSM has a number of possible input states and can generate a number of possible output states. The FSM is defined by a table. Each entry in the table consists of

automata,[11] universal computer,[12] and the *speed-up theorem*. The finite-state machine is the mathematical model that deals with the most microscopic behavior of automata. FN implies certain other restrictions such as no infinities and no infinitesimals. DM models do not have infinities, infinitesimals, continuity, or locally determined random variables, but microscopic randomness is everywhere from the continual inflow of information, orthogonal to any local process.

Research in DP has addressed the following questions: Are there reasonable models of reversible computation? How might cellular automata models (DM) capture more and more attributes of physics? What can we learn by trying to create DM models of physics? How might we verify the FN hypothesis? We have so far discovered that we can easily create DM models of many laws and characteristics of physics. We are encouraged by the steady progress that DM has made. We will be trying to convey more of the flavor of DP by explaining in some detail the interesting characteristics of one class of DM models.

6. DP AND QUANTUM MECHANICS

DP takes a definite view of quantum mechanics (QM) that is not aligned with the Copenhagen Interpretation or even with any other contemporary view of QM. We reject the idea that there is such a thing as the irreversible act of observation or that there is the classical world and the quantum world. DP assumes that some DM system is all there is, while imposing informational laws that include conservation of information.

We know that there is no shortcut, in general, to computing the exact future state of an arbitrary computation. But a DM model is not an arbitrary computation. It is an extraordinarily regular and fundamentally very simple computation. Thus, DP allows for an analytical methodology that can compute the probabilities of sufficiently microscopic events. This is a process that stands astride the enormous gap between the kind of simplistic determinism seen in Newton's Laws governing the motions of the planets, and the fact that exact analytical formulas are essentially helpless at providing shortcuts to the future state of a general process running

4 items: the FSM state, the input state, a new FSM state and the output state. The way that an FSM transitions is by taking the FSM state and the input state and looking them up in the table to find the new FSM state and the new output state. The process is then repeated. (cf. Minsky, 1967)

[11] An approximate definition of a CA as used in DM: A CA is a uniform, basically 3-D Cartesian lattice. Two time states are always present (the present and the past). A neighborhood is a small, local group of cells identified by coordinates x, y, z, and t. We consider every neighborhood as a finite-state machine (FSM) where the FSM state and input state are both the state of the local neighborhood, and the output state and the new FSM state are the state of the local neighborhood for the next instant of time. The FSM table is the CA rule. The rule is applied simultaneously to every x, y, z neighborhood as one time step in the evolution of the CA.

[12] A universal machine is basically some kind of computer that could, given enough memory, exhibit behavior isomorphic to any other computer. In this context, we require of all DM models that they are universal.

on a universal computer. DP inexorably leads us to conclude that the analytical methodology that allows one to compute the probabilities is called "quantum mechanics."

> QM is not a theory about reality, it is a prescription for making the best possible predictions about the future if we have certain information about the past. [Gerard 't Hooft]

Thus DP adopts 't Hooft's dictum that "QM is not a theory about reality." DP assumes that QM is a set of analytical, mathematical methodologies for computing the probabilities of future states of a DM process, from the limited information we can have about the possible initial states of that process. One might wonder whether it is reasonable for a discrete, deterministic reversible process to be the substrate for what QM allows us to compute. But QM itself admits that the evolution of the wave function is a deterministic and reversible process.

Those who are not members of the school of DP might ask, "Why doesn't DM model QM?" or "Why is not DM based on QM?" These are questions that have hounded the author since work began on this topic.[13]

While it makes sense for QM to be an analytical shortcut to a computational process, the idea of modeling QM by a computational process cannot pass the test of Occam's razor. A DM model evolves a system along a particular and exact trajectory. QM is a model that looks at all the possible trajectories and lets us calculate the probabilities. We should be able to derive QM from a correct DM model. Even so, QM will still be the most efficient way to get most answers in physics. Since the billiard ball model of universal computation is an idealized Newtonian model, DM is basically Newtonian. This fact should not frighten the reader, as computational models and Newtonian mechanics already have a lot in common. The idea of basing DM on QM makes little sense. As a theory of physics, QM has essentially nothing in common with DP.

As is commonly done in cellular automata theory, our DM models assume that the number of possible values (or states) at each point in spacetime is a small integer. We expect that at some scale greater than that of the lattice, DM models will be equivalent to differential equations of physics. This kind of accurate mapping of rules in a cellular automaton to the mathematical equations of physics has already been done successfully in several areas, such as in computational fluid dynamics (Chen *et al.*, in press).

The ultimate goal of DP research is an appropriate theory of the most fundamental physics. This is a difficult and ambitious task. Today, DP bristles with glaring deficiencies. On the positive side older DP theories had even more deficiencies. Even the subgoals of the DP project are quite remarkable. A DP theory of physics, if correct, can allow for perfect and complete understanding of the

[13] Starting in 1962, Richard Feynman never stopped advising the author to think about nothing but using ideas about reversible logic and CA models to do QM. His favorite admonition to the author was "QM is all there is!" Feynman died in 1986 and others have taken up this chore.

ultimate laws of physics. It allows for the possibility of an exact description of the early universe. Finally, in theory, a DM system allows the possibility of predicting the exact evolution of a defined set of initial conditions; however in practice this is always impossible with regard to macroscopic real-world phenomena. What we will be describing is a DM model that illustrates how different aspects of physics might be a part of a correct DM model.

Imagine that it is long ago and for the first time someone had the original idea to model laws of physics using algebra. He might give, as an example, "$T = H/M$, that is, the time it takes an object to fall to the ground is proportional to the height and inversely proportional to the mass."

The idea of using mathematical equations to capture facts of physics is brilliant, wonderful, and correct. The equation above illustrates how this might be done, despite the fact that it happens to be true only under limited circumstances (such as feathers falling through air). In this paper we want to explain a new way to model physics and we are not deterred by the fact that the particular formulations we give are most likely wrong. If you refuse to consider the DM model because of inconsistencies, errors in the physics, or statements that are simply false, you have missed the point. We have come to conclusions and will present specific models and constructs without reasonable justification or verification as to correctness or even self-consistency. Our approach is to communicate, by explanations and examples, the possibilities inherent in a new genre of mathematical thinking about fundamental processes in physics. One should remember that in QM almost every paper published during the last 80 years can be seen as flawed when critically viewed from today's perspective. Yet many such papers contributed crucial concepts in the development of QM. If the idea of a DM model of physics is basically correct, finishing the task of getting it right, once and for all, will be an insignificant task compared with the development of QM. In any case, today DM, as a model of physics, is still work in progress.

A correct DM model allows for other interesting possibilities. It is most likely that the exact definition of physics, including implicitly all laws of science, could be written down unambiguously in one short paragraph. Such a definition would be easily understandable by any intelligent alien.

7. SYMMETRY

There are three very basic and related symmetries of nature, *charge, parity,* and *time*. Charge symmetry (C) implies that the laws of physics are unchanged if every particle is replaced by its antiparticle (charge conjugation). Parity symmetry (P) implies that the physics of any process should be the same for the mirror image of that process. Finally, time symmetry (T) implies that, for a dynamical system, the fundamental laws of physics are the same for the forwards system and the time-reversed system. Symmetry plays a dramatic role in physics. One of the most amazing results of modern physics is the discovery of CPT symmetry. Almost every experiment in physics verifies the rule of T symmetry; that the laws of physics are the same if the direction of time is complemented. The same is true for P symmetry. During the mid- 1950s the results from two new experiments violated the principles of charge symmetry and of parity symmetry. What was then thought was that CP was still a symmetry of physics. This meant that both charge and parity had to be changed at the same time for the laws of physics to remain exactly the same. It was in 1964 that we learned that the decay of the Kaon violated CP symmetry. That experimental result trashed CP symmetry and convinced the world of physics that the fundamental symmetry of nature is CPT. It is crucial to understand that CPT does not mean that C, P, T or other such symmetries (involving combinations of charge, parity, and time) are inexact or approximate under most circumstances. CP symmetry is essentially correct for all of physics except for situations where K^0 (and perhaps B^0) decays play a role.

8. NOETHER'S THEOREM AND ITS VARIANT

Noether's Theorem (Noether, 1918) states, "For every continuous symmetry of the laws of physics, there must exist a conservation law." This theorem is used in classroom physics to illustrate how one can derive conservation laws from symmetries, e.g., conservation of angular momentum from rotational symmetry. However, as is well known, Noether's theorem itself has an important symmetry! For every conservation law, there must exist a continuous symmetry. In the case of angular momentum, the conserved quantity, spin, cannot vary continuously. The angular momentum of any object can only be changed by some integer multiple of $\hbar/2$.[14] In DM it is clear that the microscopic informational process can exactly conserve quantities such as angular momentum. RUCAs can be designed so that units are neither created nor destroyed. This is because in DM we can have discrete atoms of angular momentum, where the basic process conserves those atoms. Of course, the existence of a cellular array implies angular anisotropy, but this is only at a most microscopic level. A variant of Noether's theorem implies that exact conservation of discrete angular momentum must enforce continuous angular isotropy *asymptotically*, that is, as one looks at processes some level above the scale of the cellular array. Similarly, absolute microscopic conservation of discrete units of momentum must enforce asymptotic continuous translational symmetry. Conservation of discrete units of energy does the same for asymptotic continuous time symmetry. DM opens the possibility of experiments that can provide ways to measure absolute angular orientation and absolute translation with respect to the underlying grid of the DM RUCA.

[14] All objects are either bosons (total spin is an integer multiple of $\hbar$) or fermions (an integer-plus-$\frac{1}{2}$ multiple of $\hbar'$). Any object can be changed from a boson to a fermion or vice versa by the addition of one electron.

9. THE FOUR LAWS OF DIGITAL PHYSICS

I Information is conserved.
II The fundamental process of nature must be a computation-universal process.
III The state of any physical system must have a digital representation.
IV The only kind of change is that caused by a digital informational process.

Laws III and IV assume that the FN hypothesis is true.

I. Conservation of information is a direct consequence of reversibility. If the laws of nature are truly and exactly reversible, then, in principle, if time were reversed in some physical system, its evolution would exactly retrace its steps. This is only possible if no information is lost. Information is lost whenever two or more distinct states of a system lead to a common successor state. In reverse, there would be no basis for choosing which state ought to follow this state. The total number of distinct informational states of any closed reversible system, S, is the same as the total number of states the system will visit before it cycles and starts to repeat itself. The number S always has the same value at any point in time; S is therefore a conserved quantity. Finite irreversible systems must eventually cycle, but the cycle does not include any of the states reached prior to the beginning of the cycle. By having a counter and by saving the initial state, we can make any irreversible system reversible. To get from state t to state $t-1$, the system restores the initial state and then uses the counter to go forward $t-1$ steps. A bit expensive, but mathematicians don't mind. Computers can also be microscopically reversible by building them out of reversible logic gates. Such computers are just as efficient as ordinary computers (in terms of how much hardware and time are needed to do a computation) and they hold the promise of being able to eliminate heat dissipation during computation. The laws of physics make microscopic reversibility an intrinsic part of all microscopic physical processes. We are led to believe that the cost of going forward from some state must be the same as the cost of going backwards from that state. This means that information is microscopically and locally conserved. We postulate that in any volume of spacetime, information that is gained or lost from that volume must be lost to or gained from those regions that are spacetime neighbors of that volume. In this case, conservation of information is much like conservation of energy.

II. A system is computation-universal if one can demonstrate the possibility of constructing within that system a universal computer. Consider the question "Do the laws of physics allow the construction of universal computers?" Of course we know the answer. The fact that we can build computers means that the most fundamental processes in physics must be computation-universal. If the most fundamental processes were not computation-universal, then neither life nor computers could possibly exist. There is an amazing consequence in DP of the second Law. In theory, every sufficiently large computation-universal process can be put into a particular state that is isomorphic[15] with the state of the real universe and would then evolve so as to remain isomorphic to the evolving real universe. This has the bizarre consequence that all questions such as "How many states are there per cell in a true DM model of physics?" have the similar answers: "It is only a matter of esthetics or economy, since we already know that 2-state, 3-state or any larger number of states can all be universal!" This is similar to the fact that there are many different possible proofs for every true mathematical proposition, but we happen to favor the simplest and most elegant of these proofs.

III. In physics we often think of a system as being in a particular state. The exact details of the state are often considered unimportant. Consider the difference between the following two statements:

> The charge state of that ion is −2e (two extra electrons).
> The speed of that ion is 300 m per second.

The first statement is clear, precise, and unambiguous. The second statement is necessarily approximate and needs more information to make it more definite (a reference frame). It is clear how the information about the two extra electrons is represented in the atom. But it is definitely not clear as to how the speed or velocity information is represented in or near the atom. There certainly are areas of contemporary physics that apparently violate Law III. Given the FN hypothesis, it must be true that every state has an exact digital representation. This means that if we could look with a magic magnifying glass we would be able to see and identify the bits that represent the velocity state information. This would then relegate velocity state to the same preciseness as charge state—except that the velocity state of an ion has many more bits of information than does the charge state. The reason all this is true is that there is no other way of representing information given the FN assumption.

IV. Normally we think of things that simply change. We think that objects move and systems evolve. Given FN, all physical state is represented by digital information. Even information about a dynamic state must be represented by some kind of static digital information. This means that if we examine the state of a system at an instant of time, we must be able to find the static representation of both: the static information and the dynamic information. Any change of the digital information that represents the static state requires a digital process to change that digital information, in accordance with the static representation of the information that represents the dynamic state. For a particle to accelerate, there must be a digital process that changes the dynamic information. All particle decays and

[15] By *isomorphic* we mean that there esist informational processes that can simply translate between the two states. "Simply translate" means that the work of the translation task is proportional only to the number of bits translated. We have in mind that looking up one neighborhood configuration in a table to obtain the state of a cell in the isomorphic CA should approximate the computational work to determine each bit of the isomorphic CA.

interactions are simply digital-informational processes involving the information that represents the particles and their states. In DP we generalize these observations and claim that there are no other kinds of change.

10. RELATIVITY

The theory of relativity is one of the most fundamental discoveries in all of physics. Relativity implies that in every unaccelerated, irrotational reference frame the laws of physics remain the same. What this means is that it doesn't matter what such reference frame you use to make your measurements, the laws of physics that we know about will turn out to be the same in every such reference frame. Experiments to measure the earth's speed through the ether, starting with the Michelson–Morley experiment, have all given negative results. We know of nothing in any experimental data (or in the mathematical models that correspond to them) that compels us to reject the concept of a single, fixed reference frame. Nevertheless the community of physics has chosen to do so as a heuristic. This turned out to be such a useful concept that the idea that there cannot be a fixed reference frame has become a dogma in contemporary physics. The experimental evidence is merely that we have tried to detect a fixed reference frame and have failed. The mathematical laws of physics certainly do not rule out such a fixed reference frame; on the contrary, they admit to every unaccelerated, irrotational reference frame as being consistent with the law of physics. Therefore, as should be obvious to the kind of child that notices that the emperor has no clothes, a particular, single, fixed reference frame will also be consistent with the laws of physics. It seems that many learned members of the establishment suffer great admiration for the emperor's new clothes. We must remind ourselves that just 50 years ago there was no experimental evidence that indicated that fundamental physics violated charge, parity, and time symmetries.

DP implies that our current physical models correctly encompass almost all physical phenomena, but not 100% of all physical phenomena. DP insists that, in theory, there must be absolute velocity and absolute angular orientation at the most microscopic level in physics. At that level, concepts that we attribute to both Einsteinian and Newtonian relativity would be violated. This does not imply that the mathematics of the laws of relativity is only approximate, rather that there are experiments not yet done that might allow making new measurements. This only changes our nonmathematical understanding of the consequences implied by the correct mathematical theories of physics. It has no effect on the correctness of current mathematical models under almost all circumstances. The overthrow of bare time-reversal symmetry in physics may be a preview of the possible overthrow of translational and rotational invariance.

Since DP motion is related to a fixed reference, the DP energy and the DP momentum of particles are absolute quantities. This is an essential feature of DP, since the information that represents the energy and the momentum of a particle is represented by digital information that is associated with the particle. There is no doubt that absolute translational symmetry and absolute rotational symmetry, as a most basic microscopic property of physics, is an informational impossibility. These two symmetries were developed and became a fixture of physics, starting with Newton and continuing with Poincaré and Einstein. Mathematical models that assume these symmetries are essentially correct. However there are laws about informational processes that are unknown to contemporary physics. These new laws make it clear that, at the most microscopic level of physics, both continuous translational and rotational symmetry must be violated. Further, continuous time symmetry must also be violated at the most microscopic level. Nevertheless it is still reasonable and convenient to make use of these continuous symmetries for all physical processes above the most microscopic levels. Someday it might make sense to look for the Kaon (K^0) of the symmetries of translation and of angular orientation. Wouldn't it be serendipitous if by looking more closely at K^0 decay data, where CP symmetry is violated, one might see something of angular anisotropy? This would require doing a coordinate transformation on all the data to convert track orientations from laboratory angles and local time into right ascension and declination.

An implication of Laws III and IV is that, without the existence of a fixed reference frame, the informational or computational task of dealing with digital representations of processes involving motion could only be accomplished by magic.

11. DISCRETE FIELD THEORY

DP is very different than conventional philosophies of physics. The DM field is totally defined by six fundamental constants. All of the other numerical constants of the model, all the laws, all the differential equations, and the set of particles and their characteristic are all emergent properties of the field. When Einstein said "We must find a way to get rid of the continuum altogether" we believe that he was referring to the difficulties in the concept of particles, and effective constants of length, being emergent properties of a continuum. DP has neither the continuum nor the difficulties.[16] With two additional constants, all of cosmology and cosmogony becomes implicit in the theory. Given a correct DM model, a simpler and more accurate statement is the following: "All of physics and cosmology are emergent properties of the DM field."

Of the eight constants of our DM model, four are already known exactly. The fifth must be a small integer. The sixth constant is the rule of the CA, which defines the process. The first six constants determine all fundamental facts about physics; the seventh and eight are the cosmological constants. In any case all these constants can be represented exactly by eight integers. What is somewhat

[16] DM doesn't have the difficulty Einstein was thinking of, but it still has the very important difficulty in that it is, at this point, a grossly incorrect model of physics. We are jumping the gun, speaking as though it had already evolved into a correct model.

amazing about DP is that the eight constants all by themselves, with nothing else added, implicitly define every fact about the entire universe—all the laws of physics and the exact entire history and complete future of the universe.[17] The fact that these eight constants can, in principle, determine all these things exactly does not mean that we, living in this universe, would be able to calculate them all.

DP suggests that the Universe, with finite resources, is busy computing its future as fast as it can. The success of QM gives us good reason to assume that the most fundamental laws of physics are neither computationally trivial nor computationally inscrutable. What the speed-up theorem suggests is that in general there is no way, from within the DM universe, to predict exact future states sooner than the universe will get to those states. If we could step outside of our universe into some larger place we can call "Other," then even in Other there could be no way to get an exact future state of our universe (before the universe gets to that state) without expending even more local resources than our universe requires. The speed-up theorem is a mathematical theorem that in no way depends on the laws of physics. If there is a question whose answer depends on the exact future evolution of part of the universe, then there is no faster way, in general, to get to that exact answer other than by letting that part of the universe continue its evolution. This basically mathematical observation has some bearing on understanding the nature of DP. While DP is absolutely deterministic, we choose to call it "unknowable determinism." The knowledge that it is deterministic cannot allow us, who live in the universe, to make any exact prediction of the future. In this sense DM is like QM. However, in principle everything in the future or in the past could be calculated exactly (in some other, bigger universe!) from knowledge of the eight constants and a suitable computing engine.

> If we imagine an intellect which at any given moment knew all the forces that animate Nature and the mutual positions of the beings that comprise it—if this intellect were vast enough to submit its data to analysis—could condense into a single formula the movement of the greatest bodies of the universe and that of the lightest atom. For such an intellect nothing could be uncertain and the future just like the past would be present before its eyes. [Pierre–Simon de Laplace, *Philosophical Essays on Probability*[18]]

12. THE *B, L, T, P, D, R, A,* AND *I* UNITS

In physics we make use of a number of physical dimensions or units. The prime examples are *length*, *mass*, and *time*. The so-called rationalized MKS system

[17] The meanings of the seventh and eighth constants requires the one-time definition of two simple canonical computers, as these two constants are each, in effect, a small program for a computer.

[18] This famous remark is a restatement of the same concept as given earlier by Boscovich. Laplace was infamous for failing to give credit to those whose ideas found their way into his papers. The kind of determinism inherent in Laplace's statement was alluded to by Omar Khayyam.

(now SI) uses the meter, kilogram, and second for the units of length, mass, and time, respectively. All three of these units have arbitrary magnitudes. The meter was originally defined as one ten-millionth of the distance from the equator to the North pole. The kilogram was conceived as equal to the amount of mass in 1/1000 of a cubic meter of water. The second was defined as 1/60 of a minute, which is 1/60 of an hour, which is 1/24 of a mean solar day. Despite the common geocentric origins of the units of the metric system, we now have better and more precise definitions of these units. Obviously, if one takes a universal view as opposed to a geocentric view then these new definitions are still arbitrary. Sometimes physicists like to simplify things by giving some units or combinations of units the measure 1. This is most commonly done by setting Planck's constant and the speed of light to 1. This has the convenient consequence that mass and energy become equal, and e^2 (the electron charge squared) equals the fine structure constant (approximately 1/137). In DM, it makes perfect sense for c and $\hbar$ to equal 1.

What is amazing is that given just the SI physical-mathematical definitions of the second, the meter, and Planck's constant, the relationships of the L and T units to the meter and second can, in theory, be calculated from within the DM model, with no need for any physical experiments! This is because, in theory, the number of T units in one second could be calculated within a successful DM theory by modeling the atomic system that defines the second.[19]

The speed of light could be determined as the measured or calculated speed of DM photons. Since the SI definition of the meter is the distance traveled by light in a vacuum during a time interval of 1/299792458 of a second, we could within the DM model calculate the number of L units in the meter.

The way we are defining our DM model of physics is not like rolling dice, not like pulling a rabbit out of a hat, and not like having a flight of fancy. There is a consistent logic that guides the selection of possibilities that we put into the DM model; as opposed to the very large number of other construct we might dream up. We are trying to find models that can result in having emergent properties that make physical sense. What might be unusual is how we order the importance of properties of physics. In DM, perfect CPT symmetry is at the top of our list. Next we have the property of computation-universality. Having CPT, we then plant conservation laws and reap other symmetries. When we come up with something as bizarre as 6-phase time, it is not an idle whim; we know of no simpler way to have CPT and conservation of charge. So try to bear with us as we describe the DM model that we have, and then we will discuss why we can expect a number of properties of physics to simultaneously emerge from the dynamical behavior of what we have described.

[19] The second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

In DM, there are three basic dimensions or units. However, unlike conventional physics there is no need for assigning arbitrary values to these units because, for all three, their actual value is exactly 1. Further these are not just units; each of them is a constant of nature. While it may seem unusual for a constant of nature to have the exact value 1, that is indeed the case in the DM theory. The three units are B, L, and T. B stands for the *bit*, which is the unit of information, L is the unit of length, and T is the unit of time. These three units replace all the dimensions of conventional physics. Associated with the three units are three constants with the same names. These constants and their values are, $B = 1$, $L = 1$, and $T = 1$. In the SI system of units, B has the same dimensions as angular momentum or action, $\mathrm{ML}^2\mathrm{T}^{-1}$. The value of B is the same as the value of $\hbar$—the reduced Planck's constant. Because the constant B has angular momentum, when the direction of time is reversed the angular momentum of B must change handedness (from right-handed to left-handed and vice versa. We represent this by the sign of B, which is plus $(+)$ for time going in one direction and minus $(-)$ for time going in the opposite direction. Also, the sign of B at even microtime steps is the opposite of the sign of B at odd microtime steps.

The reason that the bit has angular momentum has to do with the nature of the cellular automaton rule we employ. In DM all microscopic angular momentum (spin) is orbital. The motion of bits always has an orbital component superimposed on possible translational motion. One might now ask, "Why call it 'bit'? Why not call it 'spin'?" The reason is that the bit is a 2-state system and configurations of bits represent every kind of information in physics. The information can be quantitative, e.g., information representing a vector such as velocity or a scalar such as energy. The information can be procedural, e.g., defining the processes that result in the behaviors and properties of all the various particles of physics. The reason the two states of the bit are $+1$ and -1 instead of 1 and 0 has to do with the fact that the atom of B can have vakues $+\hbar$ or $-\hbar$, but not zero.

The unit of length, L, is related to the dimensions of the cellular array in a simple way. However, we do not yet have a method of defining both L and T directly from the RUCA lattice parameters. On the other hand, we define T as one cycle of microtime steps. This means that T/P represents one microtime step. We use the Greek letter τ to signify the time for one microtime step. Given an independent definition of T, we define L as Tc (T times the speed of light).

Both T and P are related to the automaton time. Each time cycle T consists of a number of phases (P phases consisting of P microtime steps). In this DM model, $P = 6$. Nothing happens between microtime ticks as microscopically, there is no continuous motion in an automaton. An automaton is in some state at time τ, and is in a different state at time $\tau + 1$. It makes no sense to think about the amount of time that passes between ticks of the automaton clock. Time is defined by the sequence of states. In the DM model, time is not quite as simple as the ordinary time of physics. For a number of reasons it appears that it is logical to consider time to repeatedly cycle through a number of phases. While this paper is basically about a DM model with $P = 6$, we will first, briefly, describe a model where $P = 2$. The rule that is, in effect, the fundamental law of physics can either be thought of as a rule that has P as a parameter and the microtime as an argument or it can be thought of as P microrules applied over and over again in rotation. The state of any region of spacetime is always made up of two adjacent time states, in that DM is a second-order system. When time is reversed, we replace T with $-T$, and a consequence is that B becomes $-B$. Thus B and T both change signs under time reversal while L remains the same.

Amazingly, the DM, $P = 6$ model has perfect T symmetry. When T is changed to $-T$ the consequences in DM are exactly the same as changing CPT to $-C - P - T$ in ordinary physics.

The fourth constant of the DM theory is the number of space dimensions, namely $D = 3$. Of course it seems obvious that space is three-dimensional. While it is conventional in physics to consider ordinary spacetime as a simple 4-dimensional manifold, this does not appear to be most appropriate in DM.

We call the space of the DM model that we will be describing as SALT. The lattice of the RUCA is a lattice made up of two sublattices. This is similar to a salt crystal (NaCl) where there is a regular Cartesian lattice of ions; half are sodium ions and the other half are chloride ions. Both of the sublattices are *face-centered cubic* (FCC) structures. Stacking of cells in an FCC crystal is similar to the stacking of cannon balls where each ball (inside the array) is in contact with 12 nearest neighbors; 6 on the same level, 3 below and 3 above. A simple way to think about it is to give each cell in the salt lattice three integer Cartesian coordinates, x, y, and z. If $x + y + z$ is odd, we have a *chloride* ion, and if $x + y + z$ is even, we have a *sodium* ion. In DM, when the microtime, τ, is even the even cells (sodium) represent the *present* state and the odd cells represent the *past* state. Thus $x + y + z + \tau$ is always an even number for every cell, *past*, *present*, and *future*.

The presence of two time states in the SALT array (the past and the present), allowing DM to be defined as a second-order system, facilitates reversibility and the static representation of dynamical information. A requirement of all DM systems is inherent CPT symmetry and the SALT array facilitates the incorporation of such features into a DM model.

The next constant of the DM theory is R. R is the *rule* defined by an algorithm. The algorithm for R is best specified by a lookup table, as is done in automata theory for a finite-state machine, or more precisely, as is done for a cellular automaton. R is not a normal number where the magnitude of the number has significance. The bits in R represent the rule table of a cellular automaton; they are like the digits in a multiplication table. The meaning of R requires the definition of a standard,

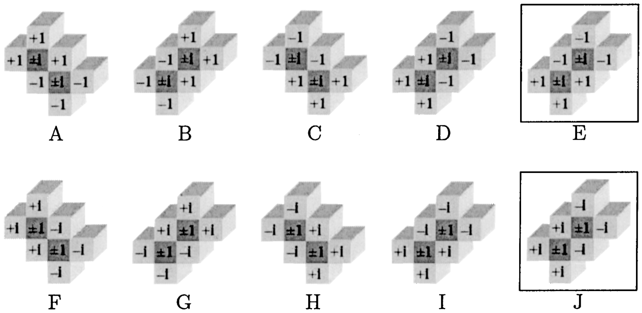

Fig. 1. A DM rule (see text for explanations). Light gray denotes a state in the "present," dark gray, in the "past." Rules A, B, C, and D are applied to xy planes as R_0, xz planes as R_2, and yz planes as R_4. Rules F, G, H, and I are applied to yz planes as R_1, xz planes as R_3, and xy planes as R_5.

canonical way to represent CA rules. We all know and understand the concept of *number* so well that when we use a number we normally don't have to worry about defining what it means. In DP this is not the case, as numbers are sometimes used in ways where the magnitudes of the numbers have no meaning. We give an example of a definite rule in Fig. 1.

Computer programs, algorithms, and automata are something new and there are no accepted canonical ways of expressing their representations. However what we know for sure is that any algorithm or CA can be represented by a transition table or by a string of instructions for any universal computer and that each representation can be made exactly equivalent to an integer. Thus every computational algorithm can be represented by a set of integers (computer words) or it can be represented of as one very large integer (a block of computer words). Such integers are concatenated sets of instructions for some canonical computer model. In the DM model, a simple, short table gives the definition of the rule. R defines the process that converts the present state of the universe into the next state. This is done every unit of microtime, τ (with $\tau = T/P$). At microtime $t = 1$, R_1 is simultaneously applied to all neighborhoods to convert the CA to the next state, that is, that at microtime $t = 2$. R is defined as P subrules; for $P = 6$ we have subrules $R_0, R_1, \ldots, R_5$.

The last two are the "cosmological constants." A is the age of the Universe in T time units, and I is the initial condition. A is quite unique in that it has the character of a cosmological *constant of nature*, yet its value is always changing. A is the number of units of time, T, from the beginning of the universe until the present moment. We currently do not know A very accurately. Its value is the equivalent of approximately 15 billion years. If T equaled 10^{-30} seconds then A

would be approximately 5×10^{47} and counting at a rate of 10^{30} per second. α equals the age of the Universe in microtime steps. A is equal to the integer part of α/P. Assuming $P = 6$, each successive integer value for A is subdivided into 6 microtime steps,

$$
\begin{array}{ll}
\alpha_0 = 6A & \alpha_6 = 6(A+1) \\
\alpha_1 = 6A+1 & \alpha_7 = 6(A+1)+1 \\
\alpha_2 = 6A+2 & \alpha_8 = 6(A+1)+2 \\
\alpha_3 = 6A+3 & \quad\cdot \qquad\qquad \cdot \\
\alpha_4 = 6A+4 & \quad\cdot \qquad\qquad \cdot \\
\alpha_5 = 6A+5 & \quad\cdot \qquad\qquad \cdot
\end{array}
$$

In other words, the spacetime phase is microtime modulo 6, and that determines which of the six subrules is used at that time.

The constant I is the initial condition of the SALT array when $\alpha = 1$. I is defined by means of an algorithm—a conventional computer program. We do not know whether the initial state of the universe was something complex or simple. We already know enough about RUCAs to be certain that the level of total complexity that we see in this universe could be the result of an extraordinarily simple initial condition. If I was very simple, then a short algorithm would be able to compute the initial state. If I was extraordinarily complex, then it would take a much longer algorithm to describe it exactly. While it is difficult for us to imagine what the initial conditions were, it is easy for us to imagine that within the concept of DM an algorithm exists that will produce that state. I is the last of the eight constants of the DM theory and is the one that we're least likely to be able to figure out. The initial condition, I, is defined by an algorithm because of the fact that we need an algorithm to specify the initial state of every bit in the entire RUCA. In DP empty space is filled up with bits just as are matter and energy. What we know is that defining I by means of an algorithm means that if I is simple, the algorithm itself will be short and simple, even though it generates initial conditions that fill the entire space.

While within ordinary physics the fine structure constant, Planck's constant, and other fundamental constants are usually expressed as a decimal number with as many digits as we can measure, there are some constants of nature that we know exactly. For example, the number of charge states of an electron is two: $+e$ and $-e$. The number of lepton species is three (e.g., electron, muon, and tau). We don't normally consider these simple numbers like 2 and 3 to be "physical constants." We often associate the idea of a physical constant with experimental measurements wherein we try to make ever more accurate measurements. In DM, it should be possible to computationally derive all such numbers from the first six constants.

13. PHYSICAL DIMENSIONS: ORDINARY PHYSICS VS. DM

	M, L, T	B, L, T	"gain"
Mass	M	$BL^{-2}T$	−3
Angular momentum, action	ML^2T^{-1}	B	3
Energy	ML^2T^{-2}	BT^{-1}	3
Momentum	MLT^{-1}	BL^{-1}	1
Force	MLT^{-2}	$BL^{-1}T^{-1}$	1
Power	ML^2T^{-3}	BT^{-2}	3
Pressure	$ML^{-1}T^{-2}$	$BL^{-3}T^{-1}$	3
Rotational inertia	ML^2	BT	1
Charge squared (q^2)	ML^3T^{-2}	BLT^{-1}	3
Viscosity	$ML^{-1}T^{-1}$	BL^{-3}	−1

In DM, mass, as a fundamental unit, is replaced by the *bit*, which has the same dimensions, called B here, as *angular momentum*. While any choice of units is somewhat arbitrary, the *BLT* system (for which we are using italic letters for clarity) has several esthetic advantages over the MLT system insofar as fundamental physics is concerned. First of all, there is a natural unit of B (Planck's constant, $\hbar$) while there is no known natural unit of Mass. Second, the number of units needed to represent useful physical quantities is generally less in the *BLT* system. For example, the MLT representation for energy is ML^2T^{-2} or MLL/TT—five instances of a unit. In the *BLT* system, energy is BT^{-1}, or just two instances of a unit; so, for energy, the *BLT* system has a three-unit advantage as indicated in the last column ("gain") of the table above. Third, for energy, momentum and viscosity, in the chart above, the *BLT* system makes particular intuitive sense when compared with the MLT system. B/T as energy is the *temporal frequency* of bits, while B/L is the *spatial frequency* of bits. This corresponds to the quantum-mechanical viewpoint associating energy with temporal frequency and momentum with spatial frequency. BL^{-3} for viscosity is charming from an intuitive point of view.

Under time reversal, B and T both change sign. Therefore all physical quantities (in DM) that have an odd number of occurrences of B and T combined (computed by taking the sum of the exponents of B and T) change sign under time reversal; those that have an even number of occurrences do not change signs. Thus, angular momentum (B), linear momentum (BL^{-1}), power (BT^{-2}), and dynamic viscosity (BL^{-3}) all change sign under time reversal, as does velocity (LT^{-1}). Charge, $B^{1/2}L^{1/2}T^{-1/2}$, actually has an odd number of B and T units, one half of each making a total of one unit, so that charge changes sign under time reversal. Mass ($BL^{-2}T$), energy (BT^{-1}), force ($BL^{-1}T^{-1}$), pressure ($BL^{-3}T^{-1}$), rotational inertia (BT), acceleration (LT^{-2}), and charge squared (BLT^{-1}) do not reverse sign under time reversal.

Under the MLT system things are somewhat simpler: units with an odd power of T change sign under time reversal. In DM, as in physics, charge certainly does reverse sign and all particles become their conjugates under time reversal.

The DM mechanisms that cause proper CPT symmetry are discussed in Section 24.

14. FUNDAMENTAL UNITS: ORDINARY PHYSICS (SI) VS DM

Dimension	SI units (m,[a] kg,[b] s[c])	BLT units (B,[d] L,[e] T[f])
Length	m	L
Mass	kg	$BL^{-2}T$
Time	s	T
Angular momentum	m^2kg s^{-1}	B
Energy	m^2kg s^{-2}	BT^{-1}
Momentum	m kg s^{-1}	BL^{-1}
Force	m kg s^{-2}	$BL^{-1}T^{-1}$
Power	m^2kg s^{-3}	BT^{-2}
Pressure	m^{-1}kg s^{-2}	$BL^{-3}T^{-1}$
Moment of inertia	m^2kg	BT
Charge squared	C^2	BLT^{-1}
Viscosity	m^2s^{-1}	BL^{-3}

[a] How far light travels in 1/299792458 s.
[b] The mass of a standard from 1901.
[c] 9,192,631,770 cycles of the Cesium[133] hyperfine transition.
[d] Equal to $\hbar$, the reduced Planck's constant.
[e] c times T.
[f] The natural unit of time.

The point of the above units table is to illustrate that, in DM, B, L, and T each stand for a fundamental physical dimension (such as length) but at the same time, each is the fundamental unit of that dimension. Thus L stands for the dimension of length and L stands for the fundamental unit of length. Except for charge, which involves the fine structure constant, there is no need to have meetings to update or revise these constants: the value of all the other constants is exactly 1.

15. DP MOMENTUM

The quantity B/L has the dimension of *momentum*. It is proportional to the spatial frequency of bits. Given a momentum wave in a DM model, we can identify certain qualities of that wave: the wavelength and the orientation. However momentum is a signed quantity, so that a given orientation of the wave must be able to exist in two phases. All of this is extraordinarily simple in a DM model. The beauty of DP is that it lets us understand exactly, the nature of a smallest part of a momentum wave—a kind of momentum atom. It must be two spatially adjacent cells that are, at the same point in time, in different states. This is nice, because in the DM RUCA each cell has 12 spatial nearest neighbors at the same point in time. When we use the time subscript $2t$, it means that τ is an even number. We use a subscript like $2t + 1$ (or $2t + k$, where k is any odd integer) to indicate that τ is an odd number. The subscript t is used when it does not matter whether or not τ is even or odd.

Example. The greatest possible momentum density occurs when two different-valued bits lie adjacent to one another, as in

$$S_{2x-1,2y,2z,2t+1} = -1 \qquad S_{2x,2y+1,2z,2t+1} = +1.$$

The combined space and state parities of the two cells determine the signs of the components of the momentum vector, which in this case are (1, 1, 0).

Example. For

$$S_{2x,2y+1,2z,2t+1} = +1 \qquad S_{2x+1,2y+1,2z+1,2t+1} = -1$$

the momentum vector would be be $(-1, -1, 0)$.

We have now given an unambiguous and exact definition of the DM representation of an atom of momentum. This is what was promised. While this may not be the best definition of momentum, there is no doubt that it is a possible definition given the general power of a RUCA. However what is very likely is that there will be found a set of different definitions that, overall, make for a better model.

At this point, we are going to go into depth on the exact meaning of DP "momentum." We know that the momentum of a composite thing is the vector sum of the momenta of its parts. The converse argument is that every nonatomic object with momentum is the composite of parts, where the vector sum of the momenta of the parts equals the momentum of the object. In a finite world, this kind of argument leads to atoms of momentum. In DP we have atoms of both angular momentum and of linear momentum. Such atoms of momentum are found in particles.

There is also something we must think of as momentum information. These are bits, and if they could be examined and decoded they would give us information as to an amount of momentum. They can be thought of as instructions for some computer program. What a particle has to do, in some sense, is to interpret the momentum instructions and then "execute" it by accordingly moving the whole particle itself along with the instructions. Programmers understand the concepts of instructions and of data, and this is very similar. It is very easy to write a block of computer code that has in it some vector to a new location in the memory where the block moves itself to, including the code, if it is executed.

We are not going to worry about the details, such as the mass or velocity of what is moved, but rather just concentrate on the most microscopic aspects of the process. The momentum information must also get moved because we expect it to stay in the vicinity of the thing being moved. An approximate statement about DP momentum is, "An atom of momentum ought to, every so often, move itself and an atom of energy one unit of space in one unit of time." It is actually more complicated, but that is the general idea. The fundamental atom of motion is a swap of the states of two nearby cells. It may seem that DM momentum is doomed to always be zero if, whenever something moves to the right, something else moves to the left. But even that will soon make sense. To understand all of this you need to understand the DP vacuum.

The DP vacuum contains bits and particles made of bits, $+1$'s and -1's (or $+i$'s and $-i$'s). Nothing is ever empty—there are no 0's. Matter and energy, the vacuum and all else are full of bits. Particles are little machines that have particular patterns of design. In this model of DM, in a region with no particles, all of the bits are in the vacuum state. We assume that the vacuum state is the same for an ordinary particle and for an antimatter particle. This implies that, in a 2-state DM model, empty space must be some kind of pattern that is symmetrical with respect to matter and antimatter. This particular problem is considerably simpler in the case of a 3-state system, where the states could be $+1$, 0, and -1. It is somewhat unclear at this time as to the advantages and disadvantages of 2-state versus 3-state systems, but it is certain that either can be Universal, and so either can be forced into being a correct model. We expect that one or the other will be a better model.

When a particle moves, it does not move into a completely empty vacuum, it moves through the bits of the vacuum or the bits of parts of particles. It might do so by somehow shoving aside the bits it encounters, as happens when a body moves through a fluid. This poses a number of problems for DP models. It cannot do so by ordinary superposition because everything is 2-state. Everything that moves in this DP model does so by a method called *earthworm motion* (EM). As the leading cells of a particle move forwards into the vacuum or parts of other particles, the particle's bits are swapped ahead. Of course the vacuum bits or other particle bits are swapped into the particle. In fact a particle can be thought of as mostly vacuum. The vacuum states are transported through the particle as the particle inches forward. The trail behind the moving particle contains vacuum bits that have been displaced back along the path the particle is taking. Thus EM implements a different kind of superposition process than occurs in ordinary physics. EM is different than any kind of classical motion, although it bears some kind of resemblance to the way a jet engine transports itself through the air.

What must happen is that the existence of the pattern of bits that our DM model calls "momentum" must be interpreted by the DM rule in such a way as to cause the swapping of bits that in turn causes some fermion to end up as a quantity of mass moving at a speed proportional to what is indicated by the momentum information. In Fig. 1 there is an example of a DM rule that makes it clear how it is that momentum information might be interpreted in order to cause causes the appropriate motion.

The definition of momentum must also take into account the implication of CPT that the signs of momentum are complemented when time is reversed. This poses an interesting problem for DM models in that momentum is represented by a purely spatial wave (with no explicit temporal information), yet the sign of the momentum must change under time reversal. In this DM model, that happens because the sign of B changes under time reversal. The sign of B changes because the six rules (if $P = 6$) are executed in the opposite order when time is reversed.

We generalize the concept of a momentum wave to define the total momentum of a particle in a region of DM spacetime: it is the vector sum of all the momentum atoms associated and traveling with that particle. The sum must include both of the time states, past and present. We require of the DM rule, R, that the evolution of state conserve momentum.

16. DP FORCE

Neighboring cells in different states, that are simultaneously neighbors in time and in space represent the possibility of force, $BL^{-1}T^{-1}$. Force is the thing that changes momentum. The DM rule results in a change in momentum going from the past to the future, based on the present. Force involves two spacetime neighbors that differ in state.

Example. Given $S_{2x,2y,2z,t} = +1$ and $S_{2x+1,2y,2z,t+1} = -1$, the force vector may be $(-1, -1, +1)$ but the fact that it is acting on a system with angular momentum needs to be taken into account.

The sign of a force vector remains the same under time reversal, while the sign of a momentum vector is complemented. When we give a particular DM rule as an example, in Fig. 1, this is based on a configuration of cells in the present that cause two spatial nearest-neighboring cells in the past to swap places. However, the rule that we give coincides with the concept of force as the changer of momentum despite the fact that force must necessarily involve cells both in the present and the past, while the rule that decides swap or no swap must do so only on the basis of the state of cells in the present. This is in line with the goal of the consistent representation of properties of physics as step one in the exposition of DP.

The relationship between force and momentum is interesting. In the SALT array there are six possible atomic force vectors; one associated with each face of a smallest cube in the lattice. There are twelve possible atomic momentum vectors, one associated with each of the 12 edges of the cube.

The six force vectors are

$$\pm\{(0, 0, 1), (0, 1, 0), (1, 0, 0)\},$$

each associated with a face of the cube. The 12 momentum vectors are

$$\pm\frac{\sqrt{2}}{2}\{(1, 1, 0), (1, 0, 1), (0, 1, 1), (1, -1, 0), (1, 0, -1), (0, 1, -1)\}.$$

Note that there is no microscopic momentum vector that is aligned with a force vector. On the other hand, every momentum vector is the vector sum of two force vectors. Every edge of the cube is associated with the two faces that have the edge in common. We take these facts into account in formulating our best DM rule.

17. DP INERTIA

In ordinary physics there is a mystery as to Mass and Inertia. In this DM model two atoms of force can change one atom of momentum. The momentum of a particle is related to the vector sum of the momentum atoms. Momentum and energy are much intertwined, as the presence of momentum creates energy. The amount of motion that a momentum atom can impart to a particle is inversely related to the amount of energy in the particle. All of the elements of the particle, including the informational representations of momentum and energy, must be moved along with the rest of the particle. As a particle gains speed, it gains energy and the force needed to accelerate it increases as the energy increases, because of relativistic effects.

18. DP ENERGY

Energy, B/T, is the temporal frequency of bits. An "atom" of energy consists of two cells that are

- colocated spatially,
- temporal neighbors, and
- have different states.

The two cells need to have the same spatial coordinates but different temporal coordinates. The consequence is that the two cells must be separated by two units of time (in this case 2τ, or two microtime steps). Notice that energy is not explicitly present if you stop the DM model, since it requires two cells that are separated by two units of time. The SALT array consists of two subarrays separated by one unit of time. Energy is implicitly present since by looking at the rule, we can tell what the next state will be. One atom of energy exists in every location where a rule has caused two neighboring cells that differ in state to swap. It exists nowhere else. Unlike charge, energy has the same value going forwards and in reverse. This means that energy does not need a second-order representation in two adjacent time steps! CPT requires that the sign of energy be not affected by the direction of time. The definition of energy must take into account the rule and the time phase, α modulo 6.

Example. Cell values of $S_{2x,2y,2z,t} = +1$ and $S_{2x,2y,2z,t+2} = -1$ give one-half unit of energy, $1/2B\tau$. This combination represents the greatest possible energy density. Since we are supposing that the basic atom of motion is a bit swap, then units of energy must be created in *pairs*; this means that the atom of energy is worth two half-units, or B/τ.

Thus, whenever a swap occurs where the pair of swapped states are not identical, the result will be energy; energy, then, is present whenever *temporal change* occurs.

In this DM model, all energy is found in particles. It may not be true that all particles carry appreciable energy. What we know about the vacuum of ordinary physics makes it clear that there has to be a background flux of essentially random particles in the vacuum. Of course that apparent randomness is the result of a deterministic computational process that conserves information. Nothing is actually random, but it can be orthogonal to local phenomena. Cellular automata are wonderful mechanisms for producing endless apparent randomness from simple initial states (Wolfram, in press). In DP we confine that behavior to the trajectories of the particles. In a way similar to kinetic theory, the apparent randomness is in the deterministic microscopic motion and interactions of the particles. In general, the DM equivalents to randomness are processes that are usually orthogonal to most other things. As with momentum, we require of the DM rule, R, that the evolution of state conserves energy.

Energy is a conserved quantity on the basis of nothing other than the rule. As we shall see, many of the observed symmetries of physics can be consequences of the more primitive conservation laws. Since the DM model has energy conservation, it is natural to expect that asymptotic continuous time reversal symmetry will be a consequence.

It should be clear that energy and momentum are intimately connected in this DM model. When some structure moves, the configurations of bits that represent its momentum are both the generators of its motion and the producers of energy. The microscopic discrete representation of energy and momentum in DP do not depend on the reference frame chosen by an observer; they are absolute and are based on a common fixed reference frame. Nevertheless, the mathematics of energy and momentum allow the use of arbitrary translational reference frames for processes above the most microscopic.

19. CHIRAL TIME

The rules we are considering all have the property time; this is slightly less simple than one might imagine. In a CA, we think of time as an integer. When time becomes the next integer, the new state is modified from the old state according to the rule; otherwise, nothing happens. The sequence of states has a one-to-one correspondence with the integer time states that correspond to the sequence of temporal steps. The idea of time with two distinct phases is due to Norman Margolus. Our concept is a generalization of that idea. We will illustrate how perfect CPT symmetry of the physics can be achieved in an RUCA with 6-phase time. What will be explained in detail is exactly how the simplest possible T symmetry of the DM RUCA gives perfect CPT symmetry of the physics being modeled. Always remember that if any RUCA can emulate physics, every RUCA can. That means that 6-phase time is not necessary but we believe that it is economical.

20. DM WITH $P = 2$

We include this brief discussion of a $P = 2$ system as an introduction to multiphase time. The DM model is currently based on $P = 6$. We have found that defining a DM with a simple, single-phase clock necessitates inelegant and clumsy processes. A 2-phase clock solves some of those problems and a 6-phase clock actually appears simplest while modeling more of physics in a natural way. If we use a 3-phase clock, we get chiral time as . . . , 1, 2, 3, 1, 2, 3, . . . , which is different than . . . ,1, 3, 2, 1, 3, 2, . . . A 3-phase clock has other problems related to being awkward with a DSOS (digital second-order system). A 2-phase clock does not have that inherent chiral property. In fact, . . . , 1, 2, 1, 2, 1, 2, . . . is the same as the reverse . . . , 2, 1, 2, 1, 2, 1, ... Nevertheless, an RUCA can have any kind of time, any kind of spatial connectivity and still do physics exactly. The object in considering these details is nothing but simplification as opposed to necessity.

A two-phase SALT RUCA has a state that consists of an ordered pair (S_{2t}, $S_{2t\pm1}$). The element with an even time subscript stands for the state of the sodium subarray and the other element with an odd time subscript stands for the state of the chloride subarray. The state with an even time subscript is always the first of the pair, and the one with an odd subscript is always on the right. The state with the higher time subscript is the present and the state with the lower time subscript is the past. There are only two rules, R_0 and R_1, that are applied alternately. R_1 is used when the microtime, τ, is an odd integer and R_0 is used when τ is an even integer. $R1$ changes every local neighborhood in the past (the sodium subarray, which is the past when time is odd) where what the change does is dependent only on the local neighborhood in the present (the chloride subarray, odd subscripts). In the following example, S_1 refers to a spatial pattern of cells in the chloride subarray that will, by their state, control what happens to a neighborhood of cells in the S_0

neighborhood in order to transform the state of those cells into S_2. Of course, the result for some neighborhoods might be that $S_2 = S_0$.

$$R_1(S_0, S_1) \mapsto (S_2, S_1)$$

R_0 then changes every local neighborhood in the past (now the chloride subarray) where what the change does is dependent on only the local neighborhood in the present (the Sodium subarray, even subscripts).

$$R_0(S_2, S_1) \mapsto (S_2, S_3)$$

By limiting R to functions that have the property that $R_t(R_t(u, v)) \mapsto (u, v)$ the system has a strong form of reversibility. There is no doubt that such a limitation does not make it difficult to achieve computational universality or T symmetry. The author has not yet found a simple process, $P = 2$, that handles CPT symmetry while remaining consistent with other demands of a good DM model. It might be an easy task for someone else to do.

$$\text{While } R_0(S_2, S_1) \mapsto (S_2, S_3), \qquad R_0(S_2, S_3) \mapsto (S_2, S_1)$$

In a nutshell we have defined a wonderful form of reversibility, which works well in $P = 2$ or $P = 6$, where the continued application of the same rules in forwards or backward temporal order will drive the system either forwards or backwards. (For “rules,” think “laws of physics.”)

21. DM WITH $P = 6$

A 6-phase clock can produce chiral time as does a 3-phase clock. If each of the three phases of time is associated with a CA coordinate axis, then the sequence x, y, z is chiral, (and different than the sequence z, y, x). There appears to be good reasons for assuming that discrete time goes through six phases. This added complexity to the nature of time seems a good compromise in reducing the overall complexity of the DM model. The author is ready and willing to be proven wrong. The rule R that governs how things change is actually best represented as six rules, R_0, R_1, R_2, R_3, R_4, and R_5. Each of the rules are the same except for orientation in the array. An example of the different orientations for each phase is the following *rule-orientation map*:

$$\begin{array}{llll}
R_0 & (xy, -x-y), & (x-y, -xy) & \text{Na Red} \\
R_1 & (yz, -y-z), & (y-z, -yz) & \text{Cl Anti-Green} \\
R_2 & (xz, -x-z), & (x-z, -xz) & \text{Na Blue} \\
R_3 & (xz, -x-z), & (x-z, -xz) & \text{Cl Anti-Blue} \\
R_4 & (yz, -y-z), & (y-z, -yz) & \text{Na Green} \\
R_5 & (xy, -x-y), & (x-z, -xz) & \text{Cl Anti-Red}
\end{array} \tag{1}$$

This rule-orientation map (the colors Red, Anti-Green, etc. are relevant to QCD and will be discussed in Section 23) can be understood by thinking of a cube in the *xyz* lattice. Every rule neighborhood is in a plane parallel to some face of the cube. Entry "R_1 $(yz, -y-z), (y-z, -yz)$" means that the neighborhood pattern for Rule 1 is in the *yz* plane and oriented in a direction specified by (y, z), $(-y, -z)$, $(y, -z)$, or $(-y, z)$. Since even rules govern movement in the chloride subarray and odd rules govern movement in the sodium subarray, it must be true that some series of odd rule applications can cause Na bits to make progress in any direction. The same is true for a series of even rule vectors and the Cl subarray.

In one 6-step cycle, each subarray undergoes three possible steps. In the Na subarray at time R0 a particular bit might remain in place or it might take a step in one of four directions. Since that makes five possibilities in each of three steps, there are 125 (53) possible moves in that cycle. Not all three step moves lead to unique endpoints. There are actually 63 different endpoints arrayed symmetrically about the starting point, with n of these 63 being at distance d as follows:

n	d	n	d	n	d
1	0	12	$\sqrt{2}$	6	$\sqrt{4}$
24	$\sqrt{6}$	12	$\sqrt{8}$	8	$\sqrt{12}$

It is best to think of the progress of a particular bit, even though its motion is always a consequence of two bits swapping places. If Rule R_1 is about to cause a swap, then a particular bit of the pair of bits will take a diagonal step to its nearest spatial neighbor in one of four directions. The four directions for R_1 are a change in position of $(0, 1, 1)$, $(0, -1, -1)$, $(0, 1, -1)$, or $(0, -1, 1)$.

The explanation for the rest of the entries in the R_i table is that they were chosen to try to simultaneously capture a number of different properties. First, for both the even-subscripted rules and the odd-subscripted rules, there must be sequences of steps that can make progress in $\pm x$ or in $\pm y$ or in $\pm z$. For example, consider the Na subarray sequence

$$R_0 = +x, +y, \quad R_2 = +x, +z, \quad R_4 = -y, -z;$$

the total motion is $2x$.

The same kind of motion is also possible in the Cl subarray.

A bit may complete a spiral orbit while making progress in the x direction (or any of a large number of other directions) by being swapped three times in one 6-microstep cycle. Other bits will end up being swapped fewer times or perhaps not be swapped for an arbitrary number of microtime steps.

The chirality of the same motion (such as $2x$) is opposite when $2x$ is done in the conjugate subarray. We say "chirality" because every such path is actually a spiral that has the bit in a 2-D triangular orbit perpendicular to the direction of motion. The reason that the rule orientation table is what it is that the sequence R_0, R_2, R_4 must be able to be the same as the sequence R_5, R_3, R_1 for CPT symmetry.

Every particle that has an antiparticle is a structure keyed to either the Na or the Cl subarray. While part of the machinery of every particle is in both subarrays, the difference between a positron and an electron is that every part of the electron that is in the Na subarray corresponds exactly to the same part of the positron in the Cl subarray, and vice versa. Note how the inherent chirality of R_0, R_2, R_4 is exactly the same as R_5, R_3, R_1. The chirality of the Na subarray going forwards in time is the same as that of the Cl subarray going backwards in time. The chirality of the Cl subarray going forwards in time is the same as that of the Na subarray going backwards in time. All that is part of how DM achieves CPT; and how an electron going backwards in time is the same as a positron going forwards in time.

There is a problem with the above example in that the yz plane is treated differently than the xy and xz planes, but only in terms of the order of sequencing. To the author, this appears as a possibly fatal flaw, but this model nevertheless combines many of the right features. This is stage 1 of trying to capture facts of physics, and we have to be very tolerant of the things that are simply wrong or missing.

The rule subscripts correspond to microtime steps taken modulo 6. We assume that the time subscript, τ, counts up every time step. At every point in time, the overall second-order state of the system is represented by two global states, the *past* and the *present*, and by the time phase that will be applied. The smaller time subscript identifies the past substate and the larger time subscript identifies the present substate. One cycle consists of six corresponding second-order states of the system: (S_0, S_1), (S_2, S_1), (S_2, S_3), (S_4, S_3), (S_4, S_5), and (S_6, S_5). The first member of each pair, $(S_{2i}, S_{2i\pm1})$, always has an even subscript and, along with the time phase, represents the overall state of the sodium subarray. The second member of each pair always has an odd subscript and along with the time phase, represents the state of the chloride subarray. Every cell with an even time subscript must have x, y, and z add up to an even number. Every cell with an odd time subscript must have x, y, and z add up to an odd number. R_1 is the rule that changes S_0 into S_2, leaving S_1 unchanged. R_2 is the rule that changes S_1 into S_3, leaving S_2 unchanged. The rule that is applied to a second-order step has the same time subscript modulo 6 as does the state of the present. The rule R must meet the following requirement:

$$R_{2t+1}(S_{2t}, S_{2t+1}) \mapsto (S_{2t+2}, S_{2t+2}),$$

$$R_{2t+1}(S_{2t+2}, S_{2t+2}) \mapsto (S_{2t}, S_{2t+1}).$$

This requirement is easily met by many functions. One large class of such functions is a conditional permutation or swap of two elements. R_1 of two elements of S_0 produces S_2; whether or not the swap takes place depending only on S_1. Notice that a swap done twice is the null operation and the question as to whether or not to do the swap depends only on S_1—not at all on S_0 when going forwards and not at all on S_2 when going in the reverse direction. It is the same function of the same S_1 going forwards in time or going backwards in time. It may be surprising, but it is easy to make such reversible systems computation-universal.

When time is reversed, we have to come up with some new labels in order to avoid confusion. If when going forwards a function of the present changes the past into the *future*, then when time is reversed we will say that a function of the present changes the *future* into the *past*. Say, $R_1(S_2, S_1) \mapsto (S_0, S_1)$ (the larger subscript is the future and the smaller subscript is the present); then the next step would be $R_0(S_0, S_1) \mapsto (S_0, S_{-1})$.

Given an overall state and a phase, we can determine the direction of time in the following way. The phase always specifies the rule that is about to be applied. The present is always the state with the same time subscript as the phase. If the other state has a time subscript that is one less than the phase $(\tau - 1)$, the system is going forwards in time. If the other state has a time subscript that is one more than the phase $(\tau + 1)$, the system is going backwards in time. $R_1(S_0, S_1)$ is going forwards in time, and $R_1(S_2, S_1)$ is going backwards in time.

22. DP CHARGE

From physics we know that $q^2 = \alpha\hbar c$, where q is the charge of an electron, α the fine-structure constant (approximately 1/137), $\hbar$ the Planck's constant, and c the speed of light. In DP, $q^2 = \alpha Bc$. A reasonable interpretation might be that q_2 is the communication of bits at the speed of light. Since all charge interactions in DP are modeled by photons being emitted or absorbed by charged particles, similar to the Feynman picture of QED, we end up with a picture of something being communicated from one charged particle to another. What is different about the DP picture is that conservation of information and the idea that trajectory information is only a property of particles means that a charged particle cannot emit a photon without simultaneously absorbing a photon or some other particle in order to balance the before and after information. We see the charge of every particle as represented by an orbit that has a number of what we call "charge steps." During a 6-microtime cycle, there are three steps taken in the Na subarray and three in the Cl subarray. We hypothesize that the charge of an electron is a consequence of a 3-charge-step cycle. What seems likely is that a charge-step is similar yet different than what might be called a "spin-step." In this DM model, the half unit of spin is also a consequence of the 3-step cycle.

Since the speed of light and electrical charge are intimately connected, we hypothesize that the existence of two electrical charges and six color charges can tell us something about the microstructure of spacetime. We assume this viewpoint on CPT: If hypothetically, time itself was reversed, then particles would be replaced by their conjugates and parity would be reversed. What we mean is that, given the state of a system at a single point in time, if it were possible to stop the system and then restart the system in reverse, we must observe that particles have been replaced by their conjugates and parity has been reversed. If this were not true, than the reversed system would not have the same laws of physics as the forward system. Therefore we need to add that when we hypothetically reverse the system, we posit that the laws of physics remain unchanged. This is further explained in the section on DM and CPT symmetry.

Other attributes of DP charge are described in the next section.

23. QUARKS AND COLOR

The definition of DM charge is a bit complicated. We have to explain separately with the electron (charge -1), the *d* quark (charge $-\frac{1}{3}$), and the *u* quark (charge $\frac{2}{3}$).

Associated with the key structure of an electron is a 3-charge-step orbit. Each charge step takes place in the Na subarray, and therefore the 3-charge-step orbit takes one full cycle of 6 microtime steps. The electron's -1 unit of electrical charge is a consequence of a 3-charge-step per cycle process in the Na subarray.

A *d* quark has a similar key structure, also in the Na subarray. However the *d* quark completes only one charge step per full cycle of six microtime steps. The *d* quark's $-\frac{1}{3}$ electrical charge is a consequence of a 1-charge-step per cycle process in the Na subarray. As should be obvious, there are three possible phases for doing one step per cycle during even time (in the Na subarray). Those correspond to the three possible colors of the up quark. Of course, an anti–*u* quark, with its key structure in the Cl subarray, would have an anticolor. These colors are indicated in the rule-orientation map (Eq. 1).

A *u* quark has a similar key structure which is in the Cl subarray. The *u* quark completes two charge steps per 6-step cycle, which results in an electrical charge of $\frac{2}{3}$. As with the *d* quark, it is obvious that the are three possible phases for the *u* quark, and these again correspond to the quark color.

An antiparticle is the same as a particle but with the key structure in the opposite subarray. Since the 3-step cycle in the Na subarray runs in the opposite direction to the 3-step cycle in the Cl subarray, the handedness of the antiparticle is the opposite of the regular particle. Further, if time is reversed, the 3-step cycles in each subarray run in the opposite order to the way they do when time runs forwards.

Charge squared (q^2) can be thought of as communication. A digital message is communicated at the speed of light. In ordinary physics the square of the electron charge, e^2, is equal to $\alpha\hbar c$. When two charged particles interact, the magnitude of the force is proportional to the product of their charges (q^2) divided by the square of the distance. The QED model for such interactions is the exchange of virtual photons between the two particles. In DM, one interpretation of αBLT^{-1} (the

DM equivalent of $\alpha\hbar c$) is that information is being communicated at the speed of light. Obviously, the most microscopic act of communication involves the swap of two bits that are spatial neighbors. The kind of communication process that involves longer distances is by a photon traveling from one particle to another. When information leaves a particle, conservation of information mandates that the information in the particle be changed. Similarly, the arrival of information must change the state of a particle. This is a basic aspect of charge interaction in this DM model.

Associated with every cell are $P(P = 6)$ different neighborhoods (similar, except for the orientation). An example of a neighborhood is the eight squares that a king can move to from the middle of a chessboard. Those eight cells can be thought of as the *King neighborhood* of the square the king is on. In DM, the cells are organized with parity (each cell being red or black as in checkers, or just plain even or odd). The physics defined by the rule is chiral (left-handedness being different than right-handedness). The function of the rule is to specify how things change. For reasons of economy, we insist that the rule be reversible. It must be universal (the CA must be a UCA, but the logic for DM being a RUCA is overwhelming). A rule is usually defined by a state neighborhood and an input–output neighborhood along with a set of transitions defining how the state neighborhood changes the input state into the output state. At each instant in time (for each successive value of τ), all of the cells are simultaneously involved in executing the neighborhood rules. The system effectively looks at the states of every neighborhood to decide whether or not to change the states of cells in every corresponding result input–output neighborhood. All such systems are called *cellular automata* (CA).

23.1. Rules About the Rules

Eventually every rule must

1. Be as isotropic as possible.
2. Be deterministic and reversible.
3. Have chiral spin associated with motion.
4. Have no net effect when applied twice in succession to the same array.
5. Support all aspects of CPT symmetry.
6. Be able to advance bits into the vacuum.
7. Have no ambiguities as to what happens to every bit.
8. Be able to be applied in all three planar orientations.
9. Be able to be applied in 4 orientations at once, in a plane, without ambiguity.
10. Be computation-universal.
11. Conserve all conserved quantities.
12. Correspond mathematically to the laws of physics.

13. Allow for the creation, annihilation, and motions of particles.
14. Support particles and their conjugates properly.
15. Support charge, color charge, energy, and linear and angular momentum
16. Convert the representation of velocity into the appropriate motion.
17. Be consistent with QM, QED, the Standard Model, Relativity, Gravity.
18. Implement particle stability and half-life characteristics.

The DM rule defined by the templates of Fig. 1 was mentioned several times in the text; it illustrates a way to satisfy many of the above desiderata.

Patterns A, B, C, and D are the rules used during even microtime steps. Patterns F, G, H, and I are the rules used during odd microtime steps. Rule E (which is similar to rule I) is an example of a pattern that cannot be used during an even microtime step because it could result in an ambiguity with rule C, as the two Cl cells (the $\pm i$ cells) would each be enabled to swap to two different cells at the same time. The same is true for rule J, which cannot be used during odd time steps because it could cause an ambiguity with rule F. Each set of 4 patterns is designed so that it is not possible for more than one of the patterns to indicate that a given cell should be swapped. It is easy to see that subrules A, B, C, and D are the same patterns, each rotated 90° from the previous pattern. Rules F, G, H, and I are the mirror images of B, A, D, and C respectively, while the present (light gray cells) are in the Cl subarray ($+i$ and $-i$) and the past cells are in the Na subarray ($+1$ and -1).

These eight subrules make a rule that meets the criteria numbered from 1 through 9 inclusive in the table of rules about the rules. This rule was selected solely on the basis that it illustrates what it takes to meet the simplest criteria. Whether or not this rule meets the other criteria has not yet been investigated. We know that this rule has several fatal flaws. We include it here only to convey the flavor a good rule might have. In all 10 of the diagrams above, the present cells have a light shade and the past cells have a darker shade. The particular neighborhood configurations of cells in the present (the present is always shown as light gray) are the only ones that determine whether or not there will be a swap of the two cells in the past (the past is always shown as darker gray). The question as to whether or not to swap is not influenced by the state of the cells being swapped. In the case where the two cells being swapped are in the same state, they are still swapped but there is no consequence of the swap. If there is not an exact match to one of the patterns shown above, no swap will occur.

All four of the upper set of patterns are applied in every xz plane, during τ_{6n+0} to sense all appropriate sets of cells in the present and to swap pairs in the past whenever there is a pattern match in the present. It can be done simultaneously or in any order so long as everything possible is done once and nothing is done more than once.

At time τ_{6n+0}, Rule R_1 is applied next. The situation is similar except the patterns are applied to the yz planes, and since the present will be the imaginary or CI subarray, the cells potentially swapped will be in the real or Na subarray. The four patterns in the lower picture are applied to every appropriate pair in the imaginary or Cl subarray.

Example. $C_{2x,2y,2z+1}$, $C_{2x+1,2y,2z+1}$ for all x, y, and z such that $x + y + z$ is odd.
At time τ_{6n+2}, R_2 is then applied in the xz planes, the upper picture;
At time τ_{6n+3}, R_3 in xz planes, the lower picture;
At time τ_{6n+4}, R_4 in yz planes, the upper picture;
At time τ_{6n+5}, R_5 is applied in xy planes, the lower picture, to complete one full cycle of six microtime steps.

24. DM AND CPT

We have shown how to construct DM models that handle CPT symmetry perfectly. To understand this we have to look at the microscopic aspects of discrete time and state.

In DP we state: "If time is stopped, then properly started up in the opposite direction, then as a consequence of that single action, all charges will be complemented, parity will be complemented and the laws of physics will remain the same."

How is it that changing the direction of time causes charge to be conjugated? When an electron is moving through time in the positive direction (towards the future) that motion through time causes the particle to have a negative charge. If the motion of time were reversed, then we would expect that same electron to be a positron with a positive charge. In this case, we see a great difference between the dimensions of space and of time. If an electron is going west, it will remain an electron if it stops and proceeds to the east. If time is reversed, an electron that was going west must become a positron going east. Further, we know that the reversal of the direction of time must have the effect of changing the handedness of everything.

Let us define what is meant by "one instant in time." It is the smallest interval of time where the dynamic properties of particles are properly represented. Therefore, at one instant in time, we expect particles to have properties such as charge, momentum, and spin. This is related to Zeno's paradox about the arrow in flight. "If, at one instant of time an arrow is perfectly still, why does not it just fall straight down to the Earth?" The answer must be that at that one instant of time, the dynamical information of a particle is somehow represented. Further, there must be a process that looks at the dynamical information and uses that information to move the particle. Yet the state of a system, at that point in time must be different in the two cases: (1) where the system proceeds forward in time from that point; and (2) where the system proceeds in reverse from that point. This is a subtle yet important point. If we assume that, hypothetically, we can look at the state of a system at one instant in time and determine the charge of a particle, then reversing time must be more complex than just going in the other temporal direction, because whenever time is stopped while going in the reversed direction we must find that the charges have been complemented. This is tricky, because we insist that reversing time must not introduce anything new into the laws of physics.

Assume we are in control of a small, closed DM system that operates in ways consistent with the laws of physics. We can stop the process and then we can start it up in either the forward or the reverse direction. If the system is running forwards and we stop the system, we can look at the bits that define the momentum of each particle and we can look at other static representations of the dynamical state information. We can restart in the forward direction and all is well. If the system is running in the backward direction, we can look at the state of each particle and note that each particle is the conjugate of the forwards-running particle. Again, when we stop the backwards-running system, we can see that the static representation of the dynamical information is consistent with CPT symmetry. If we restart it continuing in the reverse direction, all is well. Between going forwards and going backwards there must be some kind of transformation that can change the static representation of the dynamical state information of a stopped forwards-going system into the proper static representation for a stopped backwards-going system. Only after that transformation can the system proceed in reverse according to the laws of physics. That transformation itself ought to be nothing more than an application of the laws of physics, as opposed to some special ad hoc process. To summarize, the way that time must be reversed in a system that obeys the laws of physics seems to be that the system must be stopped, the information that is the static representation of the dynamical state must be changed to be consistent with CPT reversal; then time can proceed in the reverse direction. While we find it difficult to imagine how this might happen in a model with continuous spacetime, it is easy to imagine in a subclass of RUCAs (with discrete spacetime).

All that is necessary in order to accomplish the task of reversing time perfectly is that the reversal be accomplished in the following manner (at time α_t we apply R_t):

- Time flows as follows: $\ldots, \alpha_{2t-3}, \alpha_{2t-2}, \alpha_{2t-1}, \alpha_{2t}$.
- Time is stopped after the completion of α_{2t} and before α_{2t+1}.
- Then time again flows as follows: $\alpha_{2t}, \alpha_{2t-1}, \alpha_{2t-2}, \alpha_{2t-3}, \ldots$. The last rule applied in the forward direction was $R_{2t}(S_{2t}, S_2t - 1) \mapsto (S_{2t}, S_{2t+1})$. At that point in time, after R_{2t} and before continuing with the next step, if we examine the state of the RUCA we can determine that the system was stopped while time was progressing in the forward direction. All of

the static representation of dynamic information indicates time is moving forwards.

- We now put time into reverse and the first rule applied is again $R_{2t}(S_{2t}, S_{2t+1}) \mapsto (S_{2t}, S_{2t-1})$. At this point in time, after the second application of R_{2t} and before R_{2t-1}, if we examine the state of the RUCA we can determine that the system is stopped while time is progressing in the reverse direction. The second application of R_{2t} reversed the static representation of all of the dynamic information. All particles have become their conjugates. All spin and momentum have been reversed.

What is beautiful is that the rules are the laws of physics. The simple sequencing of these rules

- drives the system forwards in normal time,
- can change the static representation of all the dynamic information from forward to reverse or from reverse to forward, and
- drives the system backwards in reversed time.

All we need for perfect CPT symmetry is

$$\alpha_{2t-2}, \alpha_{2t-1}, \alpha_{2t}, \alpha_{2t}, \alpha_{2t-1}, \alpha_{2t-2}, \ldots;$$

Of course, it also works perfectly for

$$\ldots, \alpha_{2t-1}, \alpha_{2t}, \alpha_{2t+1}, \alpha_{2t+1}, \alpha_{2t}, \alpha_{2t-1}, \ldots.$$

There is a wonderful consequence of what we have just described. This DM model has T symmetry. However the T symmetry in this DM model is exactly equivalent to CPT symmetry in ordinary physics. If a model like this were to reflect the physics of the real world, then T symmetry would be restored to physics as consistent with all the laws of physics and all experimental evidence. Wonderful discoveries like this that pop up out of the DP approach to physics encourage us to keep exploring DM models of physics. If the sequence of time steps is

$$\ldots \alpha_{2t-1}, \alpha_{2t}, \alpha_{2t+1}, \alpha_{2t}, \alpha_{2t-1}, \ldots, \alpha_{2t-k},$$

then what happens to the system is that a one-step, nonphysical discontinuity is introduced. From then on the system continues to obey the laws of physics, but it is on a new trajectory. Reversibility is not compromised, so that a proper reverse into forward, $\alpha_{2t-k}, \alpha_{2t-k+1}, \ldots$ and then $\ldots, \alpha_{2t-1}, \alpha_{2t}, \alpha_{2t+1}, \alpha_{2t+1}, \alpha_{2t}$ will return the haywire system to the point of the discontinuity and send it into reverse properly, with the damage undone.

25. INFORMATION AND MOTION

All DM models are RUCAs. Since RUCAs are reversible, information is conserved. This poses an interesting problem with regard to things, such as particles, that move. The problem is that seemingly empty DP space is full of information. Consider a small closed system, consisting of a box with 4 g of helium in it. It would contain about 6×10^{23} He molecules all flying about and colliding. Every molecule carries trajectory information—its position and velocity. The paths of the molecules look random. The information process in DP space is similar. Instead of molecules, there are particles. Ordinary physics assumes that the vacuum is not made of nothing, as is clear from the fact that every so often a pair of particles can be promoted up from the vacuum. For QED to be an accurate theory it must take such processes into account. On the other hand, DP argues that particles carry a considerable amount of information, which is a conserved quantity. That is the kind of problem that encouraged the DP point of view that only particles can represent trajectory information. As a consequence DP might imply the existence of new particles in addition to those that are currently known. The DP vacuum needs particles beyond ordinary fermions and bosons since all particle interactions must balance trajectory information before and after every event.

The alternative to positing new particles is to assume that the vacuum is full of some kind of microscopic nonparticle activity, and requires stable particles to be much more robust, as they have to resist interacting with a random vacuum. A particle is an entity with machinery that must travel through that "empty" yet busy space. The complexity of a stable particle able to safely advance into any kind of unknowable vacuum state is some-what greater than one that can advance into a simple vacuum while fending off other particles that it will not interact with.

We should keep in mind two constraints: The passage of a particle must not violate conservation of information as it passes through space, and the passage through other information in space cannot interfere with the conservation of information in the particle. Except for particle interactions, the gross informational process that actually moves the particle through space must remain largely unaffected by the state of that space. Physics must allow for both interaction and superposition. What DP needs is some kind of superposition process. In ordinary physics, where things can be linear and where values can be continuous, superposition occurs naturally and beautifully. In simple cellular automata, with rules like the XOR rule, there is another wonderful kind of superposition principle. In DM, where the atom of motion is a swap, we find a third kind of model of motion with superposition: the *earthworm motion* of Section 15.

Microscopically, the motion of a particle in this DM model is made up of a great many swaps of the states of neighboring cells. If you think about the leading edge of an advancing particle, you can see that as the bits in the particle cells are swapped forwards into the empty space in front, the bits from the empty space are swapped backwards into the particle. This swapping process continues, so that at the trailing edge of the particle, when the last bits belonging to the particle advance by being swapped forwards, bits that had been empty space are swapped back into now again empty space. This means that of the gross volume that belongs to a particle, most of the cells in that volume belong to the empty space that the particle is passing through. In some way, the machinery of such a particle must be limited to only a fraction of the bits that are in the space containing the particle. Of course earthworm motion must be a factor in the kind of superposition that takes place when various particles are sharing the same volume of space. Clues as to how this might work can be garnered by thinking about the differences in how this must happen between fermions and how it must happen between bosons.

There may be fairly simple ways to conduct experiments that could detect the existence of this kind of motion, but the concept is not a necessary part of all DM models.

26. PARTICLE INTERACTIONS

In this discussion, we will develop an ad hoc model that makes informational sense. The only point is to illustrate how DP can guide one's thinking with regard to informational aspects of processes such as particle interactions. In ordinary physics, we accept as good theories those that correspond to mathematical models based on conservation laws or rules for calculating with amplitudes, and these are verified by experimental data. We can quickly throw out proposed mathematical models by showing that they violate one of the standard conservation laws. There is nothing wrong with that process, but DP demands more. In addition, there must be an informational model that also makes sense. DP assumes that there are information laws, including conservation of information, that must also be observed. A useful additional test involves looking at a process in reverse, to see that it still obeys all the laws. We sometimes find it useful (as a heuristic) to look at the reverse of the reversed process.

In order to understand this process we will take a look at the idealized interaction of two colliding billiard balls. For these examples we assume nothing other than translational motion in a plane and that the two balls are identical. If we make a movie of the collision of two perfectly elastic billiard balls, we see that kinetic energy and momentum are both conserved. If we look at the movie going backwards, everything still looks like good physics. From an informational point of view, one must be able to compute the trajectories of the two balls after the collision from information about the trajectories before the collision. No information is lost and the process is perfectly reversible.

Now let us redo the experiment, except that, instead of elastic billiard balls, we are going to use a kind of cohesive putty so that the putty balls will stick to each other and not stick to anything else. Now, two putty balls on a collision course merge into one bigger ball when they collide. A careful set of experiments would reveal that momentum is conserved exactly. The kinetic energy of the two putty balls is not conserved. Instead, we assume that the lost kinetic energy has been converted into heat; the merged putty ball must be somewhat warmer than the two balls were before the collision. If we look at the movie going backwards, there appears to be a mystery as to how the one merged putty ball can separate into two identical balls, which are following the exact original trajectories in reverse.

Where in the one merged putty ball do we find the information defining the two trajectories? The answer is that it is encoded into the motions and vibrations of the molecules of the merged putty balls. The information was not destroyed because the putty had the possibility of lower modes of energy (heat) that could represent the information.

With fundamental particles the situation is much more interesting, since there may not be the possibility of lower modes that can encode information as *heat*. To illustrate what we mean, we will consider the decay of a muon. A muon is much like an electron except that it is about 200 times as massive and it decays with a mean life of about 2μs. It almost always decays into three particles, an electron, a muon neutrino, and an electron antineutrino. A muon has a magnetic dipole field and when it decays, the electron is emitted in a direction that is correlated with the direction of the dipole field. Now we will look at the unlikely but physically correct reverse process. Along come an electron, a muon neutrino, and an electron antineutrino. All three collide in the proper way and the result is a single muon whose magnetic dipole field is correlated with the direction of the electron. What we have is the trajectories of three particles that happen to come together and the result is the trajectory of one particle plus the direction of a magnetic dipole field! That process as stated conserves energy. It conserves momentum. It conserves lepton number. It conserves angular momentum. It conserves charge. However, how does it conserve information? Within DP there is the possibility that the vacuum state of some DM models can represent information the way that heat is able to do for macroscopic events like the collision of two putty balls. Cellular automata are wonderful systems for seeming to generate complexity out of simple beginnings. Computer models might enable us to take a look at how various DM models might deal with this informational situation. QM does so by characterizing the entire process as being the consequences of the reversible evolution of the wave function. However, that approach is not very satisfying. This particular DM model is designed to explore the concept of a particle model, in the Feynman sense, of all aspects of physics.

A long time ago there was a problem in physics associated with beta decay. When a neutron decays, it was observed that the decay products included a proton and an electron. This might have made sense in terms of conservation of energy, momentum and charge; however it could not make sense in terms of spin. This is because each fermion has a spin of $\frac{1}{2}$. There was no way that the combined spin of the proton ($\frac{1}{2}$) and the electron ($\frac{1}{2}$) could add up to $\frac{1}{2}$. The solution was to invent another fermion, the neutrino with spin $\frac{1}{2}$. As it turned out, the neutrino had a lot of other reasons for existence.

While it may all seem obvious today, solving the problem by inventing a new kind of particle was pretty brave.

27. AN INFORMATIONAL FABLE

Whenever we consider particle interactions, we often find asymmetry with regard to the number of independent trajectories that enter the interaction and those that leave it. Perhaps, like the neutrino, there is a boson that we will call "infoton." An infoton need not have appreciable mass, energy, or momentum, but it might have spin. We imagine the infoton as a carrier of information. For fermions, the neutrino might do, but it is possible that something else might be necessary. Again, we are looking for a particle that need not have appreciable mass, energy, or momentum but might have spin. Finally, given that trajectory information is conserved and given that there is a one-to-one correspondence between particles and trajectory information, there is the possibility that the number of particles is conserved. This does not mean that the trajectories themselves are conserved. Whenever there is an interaction, what DP requires is that, in theory, two informational equations must be satisfied. First, the amount of *before* information must equal the amount of *after* information, and second, there must be a way to compute the outgoing trajectories from the incoming trajectories, and vice versa. An amount of information requires a number of bits for its representation. (All this assumes that the DP equivalent of heat, the vacuum information bath, does not absorb or emit trajectories except as particles.) One possibility is that independent trajectories require particles, one per trajectory. This simple-minded informational argument may need adjustment when partial trajectory information has the possibility of being encoded in other forms such as into a magnetic dipole field. Another possibility is the case where a particle with n bits of trajectory information decays into three particles, each carrying about $n/3$ bits of trajectory information; this is possible but carries certain difficulties.

Though the conjectured infoton might not carry an appreciable amount of energy, it would carry trajectory information, charge information, and spin or spin information. The trajectory information controls the motion of the infoton exactly the same way that the momentum of an energetic photon guides its motion. A particle absorbing or emitting an infoton does not gain or lose energy on that account. However, when a charged particle absorbs an infoton, it must simultaneously emit a real photon. When the charge information of the infoton is the conjugate of the charge information of the absorbing particle, the momentum of an emitted energetic photon must be in the same momentum state as the absorbed informational photon. This models the informational machinery of simple situations with opposite charges attracting each other. When the charge information of the infoton is the same as the charge information of the absorbing particle, the emitted energetic photon must have the conjugate momentum (opposite direction) of the informational photon. This models the machinery of like charges repelling each other.

There are situations where the creation and annihilation of infotons might make informational sense. This involves situations where there is QM interference. It is possible for a photon to generate new infotons where that process is informationally balanced. These would be infotons in the same informational state as the original photon. Such ghost photons might be part of a process that models QM interference. It would be logical for this to happen under the circumstances where the wave structure associated with the photon is in some way divided by something that offers more than one alternative for the path of the photon.

In describing what an infoton does not have, we did not mention spin. The reason is that it makes may make sense for an infoton to have spin as opposed to spin information. We know that electrons can be deflected without affecting their spin. If the deflection is a consequence of the absorption and emission of photons, then each step in that process must involve two photons, one absorbed and one emitted.

If we look at the muon decay process, we see that something needs to determine the point in time when the muon decays. It cannot be a simple process within the muon, since the expected lifetime of a muon is known to be independent of its age. A better informational model would involve something in space that has a constant probability, in each unit of time, of precipitating the decay of a muon at rest by interacting with some internal process of the muon. This could be the informational effect of adding trajectory information to the muon before the decay, possibly allowing for informational balance during the decay. We know that every particle decays upon meeting its antiparticle; this makes it seem likely that the particle that precipitates the decay of a muon has something in common with an antimuon. Obviously, any successful DM model must deal with relativistic effects properly. There are several general concepts that enable this, but they are not discussed in this paper.

DP would suggest that a spacetime interaction diagram superficially similar to a Feynman diagram might be useful. Each line entering or leaving the diagram would represent a particle and both its trajectory information and internal state information. The amount of information (the total number of bits) on the lines entering the diagram ought to be equal to the amount of information on the lines leaving the diagram. Further, there must be an algorithm that can transform the information on the lines entering the diagram into the information on the lines leaving the diagram, and vice versa. Like a Feynman diagram, these DP diagrams wouldn't be a picture of what is happening; rather they would be a mnemonic device to aid in understanding the informational process necessarily involved in a DM interaction.

Again, the point is not that we are trying to invent new physics, rather it is to show the consequences of taking reversibility seriously (and consequently taking conservation of information seriously).

You might ask, “Given an event where a photon is absorbed by an electron, what are all the bits of information that the photon communicated?” The answer is, “Four digital messages.” Two of the messages are each just a single bit of information, while the third and fourth messages are normally more than 100 bits of information. Basically,

- The first message that is being communicated is the charge state of the proton (or other charged particle) that emitted the photon, represented by one bit.
- The second message has to do with the spin; effectively one bit.
- The third message is very different, it defines the momentum information or perhaps the velocity information that traveled by photon from the proton to be delivered to the electron. It appears that this message is not a fixed amount of information but it is clear that photons have the capacity to carry a lot of momentum information.
- The fourth message is the energy information. In the case of a massive particle this is obvious. Momentum information would suffice for both the third and fourth messages in the case of a photon, but there are good reasons to believe that, somehow, a photon carries velocity information (a directional vector) and energy information separately. When a photon is diffracted, refracted, or reflected, its directional information may change while its energy information may not change in the reference frame of the medium that causes the change in direction.

Obviously, the receiving electron can carry away the vector sum of its prior momentum plus the photon’s momentum, but can it carry away both its prior momentum information and the photon’s momentum information? Not very likely.

Thus, the infoton/photon pair (one absorbed and the other emitted) allows for the balancing of the two informational equations, which cannot be done with just one electron interacting with one photon.

The concept we are trying to explain: things don’t just “happen.” Reversibility needs to be taken seriously at the particle level and not just at the level of the wave function.

Assume that the above informational model has some serious deficiencies. Perhaps it gives the wrong answers if both particles are traveling at relativistic speeds. What then? The answer is that both the definition of the infoton in terms of what information it carries, and the definition of the computational process that happens when an informational photon is involved in an interaction with a particle, are all up for grabs (may or may not make sense). The emitted energetic photon does not have to use the same momentum information (or its conjugate) as the informational photon communicated. There does not even need to be such a thing as an infoton.

What DP demands is that there absolutely must be some informational process that models particle interactions exactly and under all circumstances. We are not trying to convince the reader that we know what the correct informational processes are; we are trying to explain why one needs to look for models consistent with the laws of DP.

As an alternative to the half-life decay of a particle being caused by interactions with new particles, DP also suggests another, inconsistent model, going back to the DM model where we imagined that empty space is actually filled with apparently random activity. This second plausible half-life mechanism for an unstable particle would be as follows: the particle is immersed in the seemingly random sea of bits where some subset of the various combined states of the particle and of the orthogonal vacuum states initiate the particle decay. The fact that there is a constant probability of decay in each equal interval of time gives a half-life law. Further, subcategories of the random sea can determine the mode of decay. Stable particles like electrons are interesting, in that they are impervious to decay from any ordinary background state, but they decay quickly on encountering their antiparticle. On the other hand, an isolated neutron decays in 15 min, but a neutron in a He^4 nucleus is stable. In DM, every particle can decay, although so-called "stable" particles, such as an electron, only "decay" in the presence of their antiparticle. We have already indicated some of the problems with these kinds of models.

28. THINKING ABOUT DIGITAL PHILOSOPHY

DP insists on perfectly understandable concepts of time, space, and process, including motion and other forms of temporal evolution. The basic laws at the DM level will certainly be easy for anyone to understand. The complexity is not more difficult than understanding the rules of the game of chess. Much of this paper is actually devoted to the possibility of getting the reader into a frame of mind where he may be able to accept some of the concepts of DP. It is not because DM is difficult, it is because it is foreign and it goes against so many ideas that one has never thought of questioning. Strangely, as one really understands the ideas of DM, the currently accepted models of time, space, and process begin to seem mystical. From a Digital perspective, contemporary models of fundamental physics are a bit like looking at an animated cartoon while assuming that it is reality; that the images are moving continuously. So far, everyone we have interviewed who buys into DP has come to the conclusion that ordinary physics is a subject full of magic. Unfortunately, our sample size, namely one, is quite limited.

29. CRACKPOT THEORIES

Every good physicist must have a crackpot detector to keep himself or herself from wasting time on crackpot theories. Nevertheless, almost all physicists spend almost all of their time working on wrong theories in the hope that they will eventually find a correct theory, or at least, an important wrong theory. Witness Pauli's famous remark, "That theory is worthless, it isn't even wrong!" All of the wrong theories that physicists respect fall into a certain set of accepted classes; they are all trying to mine in fields where pay dirt is found from time to time. DM will not appear to be in any such field. But given a suspension of disbelief, it is possible to grasp the overall picture and to find it actually compelling.

An interesting observation about Universal CAs is that their operation often gives rise to unending complexity despite starting from extraordinary simple initial conditions. A universe that is as cosmologically complex as ours, with planets as complex as the Earth, with phenomena as complex as life and QM; all these are perfectly reasonable consequences of the operation of an RUCA starting from an extremely simple initial condition.

30. THE UNTHINKABLE

We are all prisoners of history. The incredible progress of science has produced an intimidating body of knowledge that is more than any one person can hope to grasp. For scientists, there are a number of basic concepts that are so deeply interwoven with every part of science as to eliminate any curiosity as to their ultimate validity. Most of the time, this is a very good thing. Witness the progress made. The primal such concept is the amazing applicability of mathematics to physics. In particular, there is the encompassing scope of the mathematics of continuous variables (this includes the Calculus invented by Newton and Leibniz).

Given a grand theory, such as Newtonian Mechanics, we find that its range of applicability extends both upwards to the motions of planets and stars, and downwards to the motions of atoms in a gas. Unfortunately no one mathematical framework seems to cover the fullest range of scales; we have QM at the bottom and general relativity at the top. Further, as we go down in scale, we ought to expect greater simplicity, but instead, so far, we often find the opposite.

But once in a while, it is healthy to question why we accept certain concepts as absolute fact. A good example from the past is the Copernican Hypothesis versus the Ptolemaic Hypothesis, that the sun, rather than the earth, is the center of the universe. Many had a hard time giving up the Earth-centric viewpoint. What few realize today is that the real reason for believing in the Copernican Hypothesis had nothing to do with the ultimate truth. It is simply a matter of esthetics, economy,[20] and passing the test of Occam's razor. From a mathematical point of view, the motions of the planets can be represented or calculated under the Copernican system or under the Ptolemaic system, without exception. Of course, the cost of sticking to the Ptolemaic system would grow and grow as the scope of astronomy expanded. Given two competing systems, we choose to believe as the truth the one that results in the greatest overall economy of representation, thought, and computation. Those issues aside, an accepted representational system may be no more correct than another competing system that yields the same predictions regardless of the difficulties involved. What is true is that the factor that represents the relative economic efficiency of one system over another can grow to very large, though still finite, values.

We all would like to know the most basic, ultimate laws of nature, with the hope that all higher-level facts of physics, chemistry, and even biology will be derivable in principle. If FN turned out to be true, then systems like DM might make sense. The problem is that it is very difficult to leap over the intellectual commitment everyone has to the continuum. Intuitively we easily accept, as absolutely correct, the idea that a vector can represent a velocity and that we can represent the resultant of two velocities by the simple addition of two vectors. We have learned how to suspend such beliefs in order to gain an intuitive understanding of the consequences of relativity. In order to understand DP one might have to suspend belief in physical continuity, translational and rotation invariance, and the idea that things like motion *just happen*. Our experience with the awesome scope of the calculus makes our task hard, but we can be encouraged by the remarkable fact that the calculus is spectacularly successful at modeling many processes that we know to be basically discrete. Good examples are in electrical and nuclear-reactor engineering, where users of the calculus assume that charge and rate of fission are continuous, differentiable quantities, and nevertheless they get the right answers. Conversely, discrete computer programs are good at modeling the evolution of systems with continuity. So, try your best to imagine that the ages-old process of admitting discrete models into physics (atoms, electrons, photons, spin, group theory in physics, DNA, . . .) has continued until concepts of space and time come knocking, asking for admission.

31. EXPERIMENTAL TESTS

While the proof is too long to include here, we have shown that if the FN hypothesis is true, then there must be the equivalent of a single fixed reference frame for the entire universe. Thus, microscopically, DM must violate translational and

[20] By "economy" we are referring to the cost—both in terms of man-hours and of being intellectually hobbled. If we had stuck to the Ptolemaic system, astronomers would still be able to predict eclipses, but they would be driven crazy by the amount of unnecessary work needed for celestial mechanics. The progress of science is paced by the simplicity and clarity of the concepts we work with.

rotational symmetry. It seems likely that some clever experiment will be able to detect those violations. Consideration of that problem indicates that it might be easier to detect initially if the apparatus were moving in a straight line (no spatial acceleration), without rotation, for a reasonable amount of time. Up to this time, no scientific experiment has ever been conducted while the experimental apparatus was moving in pure *translational motion* (PTM).[21] Further, most scientific experiments involve averaging data over time while the Earth rotates and the laboratory moves in a complex trajectory. Satellites and other spacecraft that are touring the solar system never move in PTM. While it is impossible to arrange for continuous PTM on Earth or in a spaceship within the solar system, it is nevertheless feasible to build a mechanical platform that corrects, for short periods of time, for the complex motion of the laboratory. While that task is feasible anywhere on Earth (for a minute or two in a reasonably sized laboratory) the task would be conceptually simplified if conducted on a platform that rotated once per sidereal day and that was located at the South Pole. On that slowly rotating platform, another platform could move to take out the residual spatial acceleration of the Earth in orbit around the Earth–Moon center of gravity and of the motion of the Earth–Moon system around the sun. Thus, for periods of time from seconds to a couple of minutes or so, depending on the size of the apparatus, one could have an experimental volume of PTM space—free of rotation and spatial acceleration. If such an experimental environment enhanced our ability to detect a fixed reference frame it is most likely that we would then be able to invent compact devices that detect and measure it and that work in any reference frame, under any circumstances. Hopefully we won't need the kind of apparatus used to generate B^0 particles.

What would it mean if there were a detectable fixed reference frame allowing us to measure absolute translational velocity and absolute angular orientation? Philosophically, quite a lot, but the mathematical laws of physics would remain largely unchanged. We would simply have to accept that, to a large extent, we had hoodwinked ourselves into believing that there must not be a fixed reference frame. If truth be told, we have merely failed to detect and measure such a thing.

There are other aspects of physics where we have a strong belief about some symmetry and that belief would have to be abandoned if there was just one experiment that violated that symmetry. Examples include translational symmetry (which implies that the laws of physics are the same in all unaccelerated reference frames) and rotational symmetry (which implies that the laws of physics are the same for any angular orientation). So far we do not know of any experimental evidence that violates those symmetries. On the other hand, we know of no competent experiments that might have detected such violations.

[21] PTM is rectilinear motion without rotation and without any acceleration. All this with respect to what used to be called "the distant fixed stars." The idea is to imagine a reference system in free space, devoid of gravitational effects or other sources of acceleration or rotation.

Of course, the other interesting tests involve detecting and measuring the units of length and time.

32. DM PARTICLES

There are a number of clues to the nature of a DM particle. The first has to do with stability. A particle has to be stable for some period of time. This means that the machinery that gives a particle its nature must be relatively impervious to the effects of other, noninteracting particles that pass nearby. Every particle has energy, momentum, spin state, and charge; and all particles are capable of motion. What is different about a particle consistent with DP is that it is a little machine where we can find the digital information that represents its energy, velocity, spin, momentum, charge, and other characteristics. In addition, there might be magnetic dipole orientation and other forms of internal state information. Further, the particle must have the informational mechanisms that convert the digital information into the action and characteristics so specified. If the velocity is represented by digital information, then the process must look at that information and move the particle (along with all the information) according to the velocity. If a photon accelerates the particle, the momentum vector information in the photon must get added to the momentum vector information in the particle.

There are many characteristics and attributes of particles we already understand and they will need to be incorporated into a DM model. A good example is the wave structures related to the particles momentum and energy. There is a lot of experimental data and theory that lets us understand many aspects of particles, at various scales of length.

Beyond a particle’s internal information are the mechanisms that interpret that information to produce the actual motion and other behavior of the particle. It seems reasonable that the mechanism of motion is very similar for all particles. DP supports the possibility of representing velocity information by an extended wave structure. It seems likely that representation of the energy of a particle is more compact. While we already know a lot, a great deal of effort will have to go into some kind of combination of efforts ranging from trial and error to the sort of engineering that goes into the design of computer logic or mechanical devices. Of course, if we’re lucky, some clever theorist will figure it out.

33. CONTEMPORARY PHYSICS

For an embarrassing collection of questions ordinary physics has not yet produced *fundamental explanations*; what we have are mathematical relationships and consequent tautologies. We fit together more and more subparts of a jigsaw puzzle called physics, but we have no idea of the big picture! A wonderful example of such progress is the Standard Model. This was a fantastic accomplishment and it put into one coherent theory a great many disparate observations. But it isn't the final answer; it is just one more piece of the puzzle, as were quantum electrodynamics, QM, Einstein's theory of relativity, Maxwell's equations, thermodynamics, Newton's laws, etc. We would like to believe that at some point physics should get simpler, but we aren't there yet. The important thing that DP shows us is the possibility of a different kind of theory that might tell us exactly what things are and exactly how they work. DP could be consistent with common sense and, most important, it might not leave any unanswered questions at the most microscopic level. If DM is ever a good model of physics, we can expect to eventually know and understand the most fundamental processes of physics exactly. But there will still be plenty of mysteries. Most important, DP teaches us that it may be possible for us to gain a new level of understanding as to how things work.

When Newton came up with the calculus, mechanics, and a theory of gravity, various critics raised some interesting objections. It seemed contrary to common sense that a force called gravity could act by unknown mechanisms through vast regions of empty space to keep the Planets confined to their orbits around the sun. Newton's response to his critics was, "I make no hypotheses." This was tongue in cheek, as Newton had by then already devoted considerable efforts to trying to find a mechanism that explained gravity; he and everyone ever since have come up emptyhanded. Newton had developed a set of laws that were descriptive and predictive. This was a good thing, much better than the pre-Newtonian state of affairs. Nevertheless, if one can now throw off the shackles of a lifelong indoctrination as to what we shouldn't question in physics, we observe that universally accepted models of most physical processes contain aspects contrary to common sense. Remarkably, by allowing us to develop one ad hoc, incorrect partial model of physics DP reveals to us that modern science, physics, and mathematics have so far offered no complete, logical, microscopic process-models for relativity, QM, or even Newtonian mechanics. The truth of this revelation does not depend on whether or not DM can actually model physical reality.

The greatest flaw of conventional physics is the acceptance of magic that has been forced upon all of us by our ignorance of the science of informational processes. This is particularly true with respect to Newtonian motion. We have no right to complain about the fact that nowhere in all of contemporary physics is there a commonsense model of motion. We haven't had a way to know better. Newton swept this matter under the rug and Poincaré and Einstein convinced us that we must believe that there is nothing under the rug. Intoxicated by all our fantastic accomplishments since Newton, it is human nature to avoid dwelling on dead-end issues. So, as smart as we all are, concepts of motion have remained in a state similar to the vitalistic theories of life that flourished in the past. "Things move." "Mass has inertia." "Like begets like." The idea that physics can get along without a fixed reference frame is utter nonsense from an informational viewpoint. It does not matter how brilliant and convenient the theory of relativity is or how many experiments validate its formulas. It is our collective misfortune that, until recently, no one has ever had any competent idea of what an informational point of view is.

If nothing else, DP shows us that there are new ways to think about such things.

34. OBSTACLES

Imagine that someday we discover that DP makes sense as a model of the microscopic processes of our world. At that time we might look back and try to figure out what took so long! The germs of DP existed in ancient philosophies such as those of the Greek atomists. They were in the ancient Kalam, which hypothesized about a cellular space. The biggest scientific step was the atomic theory. It wasn't accepted too readily; less than 100 years ago Mach and others mounted a last-ditch stand against the atomic theory.

As recently as 50 years ago a major intellectual barrier to dreaming up DP was the primitive level of our understanding of the various kinds of digital-informational processes. Also, a lot of physics, both experimental and theoretical, needed to get discovered in order to more clearly reveal facts about the world that might be better understood in the light of DP.

In physics and in computer science the amazing pace of discovery and experience during the last 50 years has provided all kinds of clues to the possibilities of DP. The most outstanding clues from physics have to do with the developments of QED and the Standard Model. Especially suggestive are the quarks, their colors and their fractional charges, Noether's Theorem, and CPT Symmetry. It is an interesting task to try to see how CPT symmetry could arise as a property of continuous spacetime.

In the field of computer science we started with Turing and the idea of a *universal computing machine*. Then there was the cellular automaton of von Neumann and Ulam, dreamt up to simulate the biological process of reproduction. Actually the CA predates von Neumann and Ulam. The CA is a computer with a Cartesian space built in. What an idea! Once latched onto the CA, the problems of universality and reversibility stood in the way for 15 years, until they were solved. From that point on, it is merely been a matter of noticing too many funny coincidences.

What is interesting is that the pace of developments in digital computer engineering is the most astonishing achievement in the history of technology. The pace of understanding the implications of what we have called DP have moved so slowly as to be equally astonishing.

John McCarthy was the first person I asked to listen to ideas about DP. It was in 1959. John confided that he had had similar thoughts. That was encouraging. I asked John, "Do you think I ought to continue working on this stuff?"

John thought for a few seconds and replied "Yes, . . ."

That was even more encouraging as I had (and still have) the greatest respect for John.

But he continued "... yes, the world is big enough that it can afford to have one person work on such ideas." Who could imagine that for 40 years, just that "about one man-year per year" was all it could afford?

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