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GOD IS THE MACHINE

IN THE BEGINNING THERE WAS 0. AND THEN THERE WAS 1. A MIND-BENDING MEDITATION ON THE TRANSCENDENT POWER OF DIGITAL COMPUTATION.

At today's rates of compression, you could download the entire 3 billion digits of your DNA onto about four CDs. That 3-gigabyte genome sequence represents the prime coding information of a human body — your life as numbers. Biology, that pulsating mass of plant and animal flesh, is conceived by science today as an information process. As computers keep shrinking, we can imagine our complex bodies being numerically condensed to the size of two tiny cells. These micro-memory devices are called the egg and sperm. They are packed with information.

Alex Ostroy

That life might be information, as biologists propose, is far more intuitive than the corresponding idea that hard matter is information as well. When we bang a knee against a table leg, it sure doesn't feel like we knocked into information. But that's the idea many physicists are formulating.

The spooky nature of material things is not new. Once science examined matter below the level of fleeting quarks and muons, it knew the world was incorporeal. What could be less substantial than a realm built out of waves of quantum probabilities? And what could be weirder? Digital physics is both. It suggests that those strange and insubstantial quantum wavicles, along with everything else in the universe, are themselves made of nothing but 1s and 0s. The physical world itself is digital.

The scientist John Archibald Wheeler (coiner of the term "black hole") was onto this in the '80s. He claimed that, fundamentally, atoms are made up of of bits of information. As he put it in a 1989 lecture, "Its are from bits." He elaborated: "Every it — every particle, every field of force, even the space-time continuum itself — derives its function, its meaning, its very existence entirely from binary choices, bits. What we call reality arises in the last analysis from the posing of yes/no questions."

To get a sense of the challenge of describing physics as a software program, picture three atoms: two hydrogen and one oxygen. Put on the magic glasses of digital physics and watch as the three atoms bind together to form a water molecule. As they merge, each seems to be calculating the optimal angle and distance at which to attach itself to the others. The oxygen atom uses yes/no decisions to evaluate all possible courses toward the hydrogen atom, then usually selects the optimal 104.45 degrees by moving toward the other hydrogen at that very angle. Every chemical bond is thus calculated.

If this sounds like a simulation of physics, then you understand perfectly, because in a world made up of bits, physics is exactly the same as a simulation of physics. There's no difference in kind, just in degree of exactness. In the movie The Matrix, simulations are so good you can't tell if you're in one. In a universe run on bits, everything is a simulation.

An ultimate simulation needs an ultimate computer, and the new science of digitalism says that the universe itself is the ultimate computer — actually the only computer. Further, it says, all the computation of the human world, especially our puny little PCs, merely piggybacks on cycles of the great computer. Weaving together the esoteric teachings of quantum physics with the latest theories in computer science, pioneering digital thinkers are outlining a way of understanding all of physics as a form of computation.

From this perspective, computation seems almost a theological process. It takes as its fodder the primeval choice between yes or no, the fundamental state of 1 or 0. After stripping away all externalities, all material embellishments, what remains is the purest state of existence: here/not here. Am/not am. In the Old Testament, when Moses asks the Creator, "Who are you?" the being says, in effect, "Am." One bit. One almighty bit. Yes. One. Exist. It is the simplest statement possible.

All creation, from this perch, is made from this irreducible foundation. Every mountain, every star, the smallest salamander or woodland tick, each thought in our mind, each flight of a ball is but a web of elemental yes/nos woven together. If the theory of digital physics holds up, movement ($f = ma$), energy ($E = mc^2$), gravity, dark matter, and antimatter can all be explained by elaborate programs of 1/0 decisions. Bits can be seen as a digital version of the "atoms" of classical Greece: the tiniest constituent of existence. But these new digital atoms are the basis not only of matter, as the Greeks thought, but of energy, motion, mind, and life.

From this perspective, computation, which juggles and manipulates these primal bits, is a silent reckoning that uses a small amount of energy to rearrange symbols. And its result is a signal that makes a difference — a difference that can be felt as a bruised knee. The input of computation is energy and information; the output is order, structure, extropy.

Our awakening to the true power of computation rests on two suspicions. The first is that computation can describe all things. To date, computer scientists have been able to encapsulate every logical argument, scientific equation, and literary work that we know about into the basic notation of computation. Now, with the advent of digital signal processing, we can capture video, music, and art in the same form. Even emotion is not immune. Researchers Cynthia Breazeal at MIT and Charles Guerin and Albert Mehrabian in Quebec have built Kismet and EMIR (Emotional Model for Intelligent Response), two systems that exhibit primitive feelings.

The second supposition is that all things can compute. We have begun to see that almost any kind of material can serve as a computer. Human brains, which are mostly water, compute fairly well. (The first "calculators" were clerical workers figuring mathematical tables by hand.) So can sticks and strings. In 1975, as an undergraduate student, engineer Danny Hillis constructed a digital computer out of skinny Tinkertoys. In 2000, Hillis designed a digital computer made of only steel and tungsten that is indirectly powered by human muscle. This slow-moving device turns a clock intended to tick for 10,000 years. He hasn't made a computer with pipes and pumps, but, he says, he could. Recently, scientists have used both quantum particles and minute strands of DNA to perform computations.

A third postulate ties the first two together into a remarkable new view: All computation is one.

In 1937, Alan Turing, Alonso Church, and Emil Post worked out the logical underpinnings of useful computers. They called the most basic loop — which has become the foundation of all working computers — a finite-state machine. Based on their analysis of the finite-state machine, Turing and Church proved a theorem now bearing their names. Their conjecture states that any computation executed by one finite-state machine, writing on an infinite tape (known later as a Turing machine), can be done by any other finite-state machine on an infinite tape, no matter what its configuration. In other words, all computation is equivalent. They called this universal computation.

When John von Neumann and others jump-started the first electronic computers in the 1950s, they immediately began extending the laws of computation away from math proofs and into the natural world. They tentatively applied the laws of loops and cybernetics to ecology, culture, families, weather, and biological systems. Evolution and learning, they declared, were types of computation. Nature computed.

If nature computed, why not the entire universe? The first to put down on paper the outrageous idea of a universe-wide computer was science fiction writer Isaac Asimov. In his 1956 short story "The Last Question," humans create a computer smart enough to bootstrap new computers smarter than itself. These analytical engines recursively grow super smarter and super bigger until they act as a single giant computer filling the universe. At each stage of development, humans ask the mighty machine if it knows how to reverse entropy. Each time it answers: "Insufficient data for a meaningful reply." The story ends when human minds merge into the ultimate computer mind, which takes over the entire mass and energy of the universe. Then the universal computer figures out how to reverse entropy and create a universe.

Such a wacky idea was primed to be spoofed, and that's what Douglas Adams did when he wrote The Hitchhiker's Guide to the Galaxy. In Adams' story the earth is a computer, and to the world's last question it gives the answer: 42.

Few ideas are so preposterous that no one at all takes them seriously, and this idea — that God, or at least the universe, might be the ultimate large-scale computer — is actually less preposterous than most. The first scientist to consider it, minus the whimsy or irony, was Konrad Zuse, a little-known German who conceived of programmable digital computers 10 years before von Neumann and friends. In 1967, Zuse outlined his idea that the universe ran on a grid of cellular automata, or CA. Simultaneously, Ed Fredkin was considering the same idea. Self-educated, opinionated, and independently wealthy, Fredkin hung around early computer scientists exploring CAs. In the 1960s, he began to wonder if he could use computation as the basis for an understanding of physics.

Fredkin didn't make much headway until 1970, when mathematician John Conway unveiled the Game of Life, a particularly robust version of cellular automata. The Game of Life, as its name suggests, was a simple computational model that mimicked the growth and evolution of living things. Fredkin began to play with other CAs to see if they could mimic physics. You needed very large ones, but they seemed to scale up nicely, so he was soon fantasizing huge — really huge — CAs that would extend to include everything. Maybe the universe itself was nothing but a great CA.

The more Fredkin investigated the metaphor, the more real it looked to him. By the mid-'80s, he was saying things like, "I've come to the conclusion that the most concrete thing in the world is information."

Many of his colleagues felt that if Fredkin had left his observations at the level of metaphor — "the universe behaves as if it was a computer" — he would have been more famous. As it is, Fredkin is not as well known as his colleague Marvin Minsky, who shares some of his views. Fredkin insisted, flouting moderation, that the universeis a large field of cellular automata, not merely like one, and that everything we see and feel is information.

Many others besides Fredkin recognized the beauty of CAs as a model for investigating the real world. One of the early explorers was the prodigy Stephen Wolfram. Wolfram took the lead in systematically investigating possible CA structures in the early 1980s. By programmatically tweaking the rules in tens of thousands of alterations, then running them out and visually inspecting them, he acquired a sense of what was possible. He was able to generate patterns identical to those seen in seashells, animal skins, leaves, and sea creatures. His simple rules could generate a wildly complicated beauty, just as life could. Wolfram was working from the same inspiration that Fredkin did: The universe seems to behave like a vast cellular automaton.

Even the infinitesimally small and nutty realm of the quantum can't escape this sort of binary logic. We describe a quantum-level particle's existence as a continuous field of probabilities, which seems to blur the sharp distinction of is/isn't. Yet this uncertainty resolves as soon as information makes a difference (as in, as soon as it's measured). At that moment, all other possibilities collapse to leave only the single yes/no state. Indeed, the very term "quantum" suggests an indefinite realm constantly resolving into discrete increments, precise yes/no states.

For years, Wolfram explored the notion of universal computation in earnest (and in secret) while he built a business selling his popular software Mathematica. So convinced was he of the benefits of looking at the world as a gigantic Turing machine that he penned a 1,200-page magnum opus he modestly calls A New Kind of Science. Self-published in 2002, the book reinterprets nearly every field of science in terms of computation: "All processes, whether they are produced by human effort or occur spontaneously in nature, can be viewed as computation." (See "The Man Who Cracked the Code to Everything," Wired 10.6.)

Wolfram's key advance, however, is more subtly brilliant, and depends on the old Turing-Church hypothesis: All finite-state machines are equivalent. One computer can do anything another can do. This is why your Mac can, with proper software, pretend to be a PC or, with sufficient memory, a slow supercomputer. Wolfram demonstrates that the outputs of this universal computation are also computationally equivalent. Your brain and the physics of a cup being filled with water are equivalent, he says: for your mind to compute a thought and the universe to compute water particles falling, both require the same universal process.

If, as Fredkin and Wolfram suggest, all movement, all actions, all nouns, all functions, all states, all we see, hear, measure, and feel are various elaborate cathedrals built out of this single ubiquitous process, then the foundations of our knowledge are in for a galactic-scale revisioning in the coming decades. Already, the dream of devising a computational explanation for gravity, the speed of light, muons, Higgs bosons, momentum, and molecules has become the holy grail of theoretical physics. It would be a unified explanation of physics (digital physics), relativity (digital relativity), evolution (digital evolution and life), quantum mechanics, and computation itself, and at the bottom of it all would be squirming piles of the universal elements: loops of yes/no bits. Ed Fredkin has been busy honing his idea of digital physics and is completing a book called Digital Mechanics. Others, including Oxford theoretical physicist David Deutsch, are working on the same problem. Deutsch wants to go beyond physics and weave together four golden threads — epistemology, physics, evolutionary theory, and quantum computing — to produce what is unashamedly referred to by researchers as the Theory of Everything. Based on the primitives of quantum computation, it would swallow all other theories.

Any large computer these days can emulate a computer of some other design. You have Dell computers running Amigas. The Amigas, could, if anyone wanted them to, run Commodores. There is no end to how many nested worlds can be built. So imagine what a universal computer might do. If you had a universally equivalent engine, you could pop it in anywhere, including inside the inside of something else. And if you had a universe-sized computer, it could run all kinds of recursive worlds; it could, for instance, simulate an entire galaxy.

If smaller worlds have smaller worlds running within them, however, there has to be a platform that runs the first among them. If the universe is a computer, where is it running? Fredkin says that all this work happens on the "Other." The Other, he says, could be another universe, another dimension, another something. It's just not in this universe, and so he doesn't care too much about it. In other words, he punts. David Deutsch has a different theory. "The universality of computation is the most profound thing in the universe," he says. Since computation is absolutely independent of the "hardware" it runs on, studying it can tell us nothing about the nature or existence of that platform. Deutsch concludes it does not exist: "The universe is not a program running somewhere else. It is a universal computer, and there is nothing outside of it."

Strangely, nearly every mapper of this new digitalism foresees human-made computers taking over the natural universal computer. This is in part because they see nothing to stop the rapid expansion of computation, and in part because — well — why not? But if the entire universe is computing, why build our own expensive machines, especially when chip fabs cost several billion dollars to construct? Tommaso Toffoli, a quantum computer researcher, puts it best: "In a sense, nature has been continually computing the 'next state' of the universe for billions of years; all we have to do — and, actually, all we can do — is 'hitch a ride' on this huge, ongoing Great Computation."

In a June 2002 article published in the Physical Review Letters, MIT professor Seth Lloyd posed this question: If the universe was a computer, how powerful would it be? By analyzing the computing potential of quantum particles, he calculated the upper limit of how much computing power the entire universe (as we know it) has contained since the beginning of time. It's a large number: 10^120 logical operations. There are two interpretations of this number. One is that it represents the performance "specs" of the ultimate computer. The other is that it's the amount required to simulate the universe on a quantum computer. Both statements illustrate the tautological nature of a digital universe: Every computer is the computer.

Continuing in this vein, Lloyd estimated the total amount of computation that has been accomplished by all human-made computers that have ever run. He came up with 10^31 ops. (Because of the fantastic doubling of Moore's law, over half of this total was produced in the past two years!) He then tallied up the total energy-matter available in the known universe and divided that by the total energy-matter of human computers expanding at the rate of Moore's law. "We need 300 Moore's law doublings, or 600 years at one doubling every two years," he figures, "before all the available energy in the universe is taken up in computing. Of course, if one takes the perspective that the universe is already essentially performing a computation, then we don't have to wait at all. In this case, we may just have to wait for 600 years until the universe is running Windows or Linux."

The relative nearness of 600 years says more about exponential increases than it does about computers. Neither Lloyd nor any other scientist mentioned here realistically expects a second universal computer in 600 years. But what Lloyd's calculation proves is that over the long term, there is nothing theoretical to stop the expansion of computers. "In the end, the whole of space and its contents will be the computer. The universe will in the end consist, literally, of intelligent thought processes," David Deutsch proclaims in Fabric of Reality. These assertions echo those of the physicist Freeman Dyson, who also sees minds — amplified by computers — expanding into the cosmos "infinite in all directions."

Yet while there is no theoretical hitch to an ever-expanding computer matrix that may in the end resemble Asimov's universal machine, no one wants to see themselves as someone else's program running on someone else's computer. Put that way, life seems a bit secondhand.

Yet the notion that our existence is derived, like a string of bits, is an old and familiar one. Central to the evolution of Western civilization from its early Hellenistic roots has been the notion of logic, abstraction, and disembodied information. The saintly

Christian guru John writes from Greece in the first century: "In the beginning was the Word, and the Word was with God, and the Word was God." Charles Babbage, credited with constructing the first computer in 1832, saw the world as one gigantic instantiation of a calculating machine, hammered out of brass by God. He argued that in this heavenly computer universe, miracles were accomplished by divinely altering the rules of computation. Even miracles were logical bits, manipulated by God.

There's still confusion. Is God the Word itself, the Ultimate Software and Source Code, or is God the Ultimate Programmer? Or is God the necessary Other, the off-universe platform where this universe is computed?

But each of these three possibilities has at its root the mystical doctrine of universal computation. Somehow, according to digitalism, we are linked to one another, all beings alive and inert, because we share, as John Wheeler said, "at the bottom — at a very deep bottom, in most instances — an immaterial source." This commonality, spoken of by mystics of many beliefs in different terms, also has a scientific name: computation. Bits — minute logical atoms, spiritual in form — amass into quantum quarks and gravity waves, raw thoughts and rapid motions.

The computation of these bits is a precise, definable, yet invisible process that is immaterial yet produces matter.

"Computation is a process that is perhaps the process," says Danny Hillis, whose new book, The Pattern on the Stone, explains the formidable nature of computation. "It has an almost mystical character because it seems to have some deep relationship to the underlying order of the universe. Exactly what that relationship is, we cannot say. At least for now."

Probably the trippiest science book ever written is The Physics of Immortality, by Frank Tipler. If this book was labeled standard science fiction, no one would notice, but Tipler is a reputable physicist and Tulane University professor who writes papers for the International Journal of Theoretical Physics. In Immortality, he uses current understandings of cosmology and computation to declare that all living beings will be bodily resurrected after the universe dies. His argument runs roughly as follows: As the universe collapses upon itself in the last minutes of time, the final space-time singularity creates (just once) infinite energy and computing capacity. In other words, as the giant universal computer keeps shrinking in size, its power increases to the point at which it can simulate precisely the entire historical universe, past and present and possible. He calls this state the Omega Point. It is a computational space that can resurrect "from the dead" all the minds and bodies that have ever lived. The weird thing is that Tipler was an atheist when he developed this theory and discounted as mere "coincidence" the parallels between his ideas and the Christian doctrine of Heavenly Resurrection. Since then, he says, science has convinced him that the two may be identical.

While not everyone goes along with Tipler's eschatological speculations, theorists like Deutsch endorse his physics. An Omega Computer is possible and probably likely, they say.

I asked Tipler which side of the Fredkin gap he is on. Does he go along with the weak version of the ultimate computer, the metaphorical one, that says the universe only seems like a computer? Or does he embrace Fredkin's strong version, that the universe is a 12 billion-year-old computer and we are the killer app? "I regard the two statements as equivalent," he answered. "If the universe in all ways acts as if it was a computer, then what meaning could there be in saying that it is not a computer?"

Only hubris.