Does a single formula underlie the fabric of our universe? David L. Chandler reports on the uncanny successes of

In the beginning was the Rule

●"RIGHT now, we're inside a computer program?" asks Neo in the movie *The Matrix*. "Is it really so hard to believe?" Morpheus replies. Not for Ed Fredkin. He too claims the universe we perceive is a computer program. To be precise, it is the kind of program known as a cellular automaton, in which patterns form and evolve on a grid according to a simple rule. If only we can figure out the right kind of grid and the right rule, says Fredkin, we should be able to model the universe, and all of physics.

Fredkin, who is a physicist at the Massachusetts Institute of Technology, has already produced cellular automata in which clusters of bits move and behave in a way that resembles electrons and photons. He is convinced that all the particles and forces in the universe can be modelled in the same way. As Fredkin sees it, this is not just a simulation like the computer-generated world in which Neo and Morpheus found themselves, but the real thing. While mainstream physics turns to abstract concepts like particles and fields to describe the behaviour of the matter and energy that make up the universe, Fredkin says they are formed from a pattern of bits. Cosmology is simply the repeated application of the rule that governs how the pattern evolves. The universe's program is just a few lines of clean and elegant code.
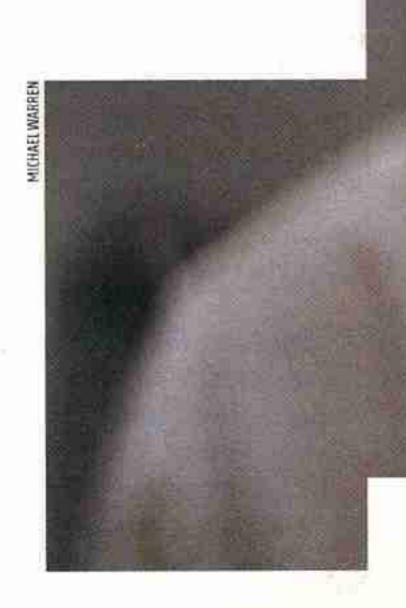
Cellular automata of one kind or another date back decades. Perhaps the most famous is John Conway's 1970 game of Life, which starts with a grid of squares or "cells". Some of the cells selected at random are filled, and are represented by a binary 1, while the rest remain empty and are represented by 0. The game proceeds step by step: at each step some of the cells flip from 1 to 0, or vice versa, depending which of its neighbouring cells are filled, and the rules are formulated in such a way that patterns sometimes emerge which appear almost to be alive.
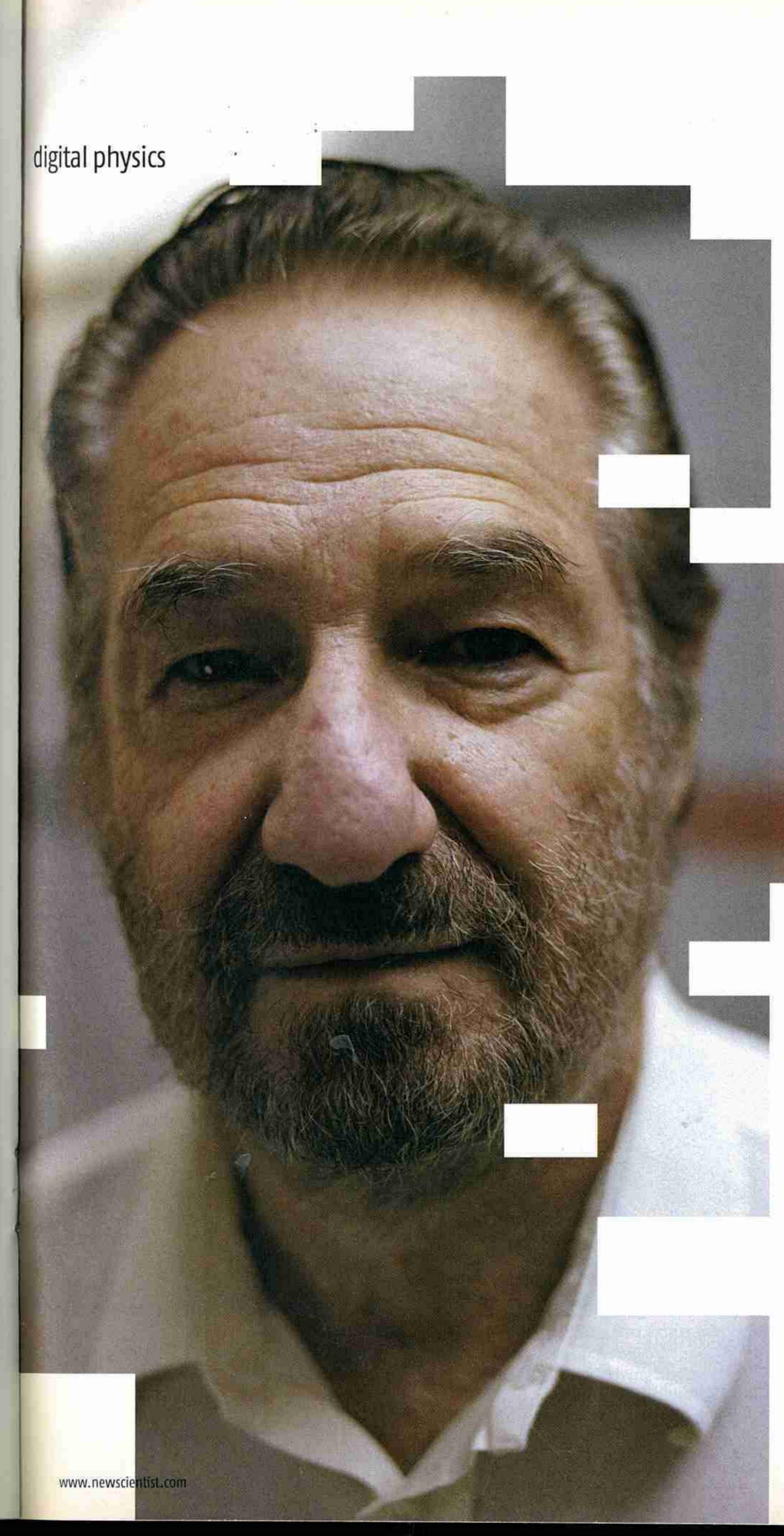
Like Conway's game of Life, Fredkin's model of physics consists of bits – units of binary information – plus a grid for them to inhabit. The cellular automaton is like a loom in which the long threads, or warp, correspond to time and form the framework upon which the weaving will take place line by line. At each time-step, a cross-thread of the tapestry of the universe is laid down. Where the cross-thread crosses the warp, it has two possibilities: over or under. It's a binary decision, to be made anew as each line of the weaving unfolds. So, for example, if the whole universe could be described by six bits of information, there would be six warp threads along which two-dimensional patterns of 1s and 0s would build up as the weaving progresses step by step.

The patterns become more obvious if colour is added. If the warp threads are black and the weft thread is white then each point where the thread goes under will result in a black cell represented by a 0 bit; points where the thread passes over will show as a white cell, a 1 bit. The final weaving should look like a blotchy pattern of black and white cells: the history of the universe produced by the patterning of evolving cellular automata.

The way the automata evolve is controlled by a rule – or as Fredkin calls it, the Rule, with a capital R. The Rule applies to every single cell in the grid and it stipulates whether the state will change at the next time-step, depending on the states of neighbouring cells. Essentially, the Rule is a look-up table that relates changes in the state of a cell to the states of nearby cells at an earlier time. The table can be converted into a string of bits that is a single whole number, a constant that Fredkin calls R. The simplest example of a rule might be this: if an odd number of the three bits directly and diagonally above a bit are 1 (thread is above) then a bit will become 0 (thread below); if the number is even, it becomes 1.

If this all sounds vaguely familiar, that

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might be because Stephen Wolfram, who has had occasional discussions with Fredkin about these concepts over the years, last year published a book that includes some similar sounding ideas. In *A New Kind of Science*, Wolfram gave countless examples of starkly simple rules generating astoundingly complex patterns that mimic those found in nature. In Wolfram's simple two-dimensional grids, a range of entirely different patterns could emerge depending on which of 256 possible rules were applied. Wolfram, in fact, was initially sceptical of the applicability of cellular automata to a fundamental theory of physics when Fredkin first described the idea on a visit Wolfram made to the MIT Lab for Computer Science. According to his spokeswoman, Wolfram is still sceptical.

Today, the automata Fredkin builds are far more ambitious. He works in a three-dimensional space, in which the state of each point is determined by the state of nearest neighbours in the previous time-steps.

So how does physics itself come out of this model? The most basic unit of motion is for two cells to swap their contents. Fredkin defines mass to be a form of information in his model, so swapping two bits constitutes motion, or a change in momentum. The conservation of momentum is something that has to be respected by the Rule: no matter how bits move in the grid, the total amount of momentum must remain unchanged.

The most basic unit of energy is nearly as simple. It is the swapping of cells in different states. So if a black cell is followed by a white one, and a white cell by a black one, then action is taking place and therefore energy is involved. This may sound contrived, but in mainstream physics the concept of energy as "doing work" is a much vaguer definition. Just as with conservation of momentum, the Rule ensures that even when action takes place, the total amount of energy is conserved.

Everything builds up from this simple level. In his newest version, Fredkin sets initial conditions for patterns of bits that have some of the properties of photons and electrons in empty space. A subatomic particle is just a pattern of many bits of information that travel through the grid together "sort of like a swarm of gnats", as Fredkin puts it. In his model, a swarm of several hundred bits is enough to make up a photon or electron. ▶

MIT physicist Ed Fredkin designs computer generated grids in which swarms of bits behave like real particles

The Rule also ensures the particle stays intact and does not break up. Right now, Fredkin is trying to incorporate more of the characteristics of real particles. Ultimately he hopes to be able to sit back and watch while the evolving patterns show particles interacting, moving and scattering off each other. This is a long way from modelling the physics of the whole universe, but the significant point is that the Rule leads to real particle behaviour. Fredkin insists the Rule governing cellular automata should be quite simple. But even if it is quite complex, it will be nothing compared with the 26 constants in standard physics, which include the masses of 13 fundamental particles plus constants that determine how they interact. In the cellular automaton, all the different fundamental particles are changing patterns of bits.

Actually, the Rule and the grid are not quite everything Fredkin needs. To get entirely realistic behaviour from his swarms, Fredkin found he has to be careful about how he structures the evolution of his tapestry. In his current working version of the theory, the Rule is made up of sub-rules that apply at different time-steps. There is a cycle of six micro-steps, after which the first sub-rule is applied again. In this sense, time itself describes a kind of stepped orbit, a cycle within the drumbeat of the digital universe. Fredkin calls this "chiral" time.

Using the concept of chiral time, Fredkin says he can capture more complex properties of particles and their behaviour. For example, he speculates that units of charge are a result of the number of time-steps involved in an electromagnetic interaction. A charge of plus one would typically produce an effect over three full time-steps. A fractional charge of $2/3$ or $1/3$, like that carried by quarks, would produce an effect over two or one steps.
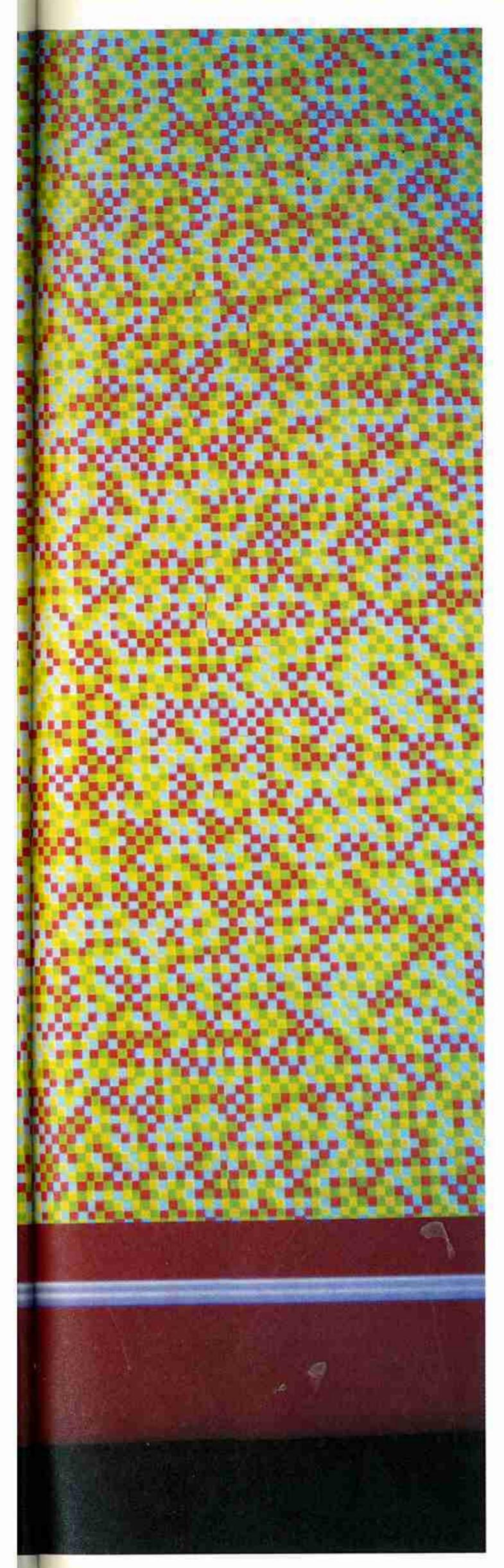
Fredkin's former student, Norman Margolus of MIT and software company Permabit in Cambridge, has taken these ideas in a different direction. Margolus built a simple 2D automaton that runs a pattern in which particles, each made up of just one bit, move and collide with each other. The Rule ensures the proportional relationship between mass and energy, the famous $E = mc^2$ of special relativity, is respected.

But even if Fredkin manages to extend his model to include more particles and more realistic forces, who's to say that that this is anything more than a simulation? Creating a matrix of his own doesn't prove we are living in one. It doesn't mean the universe actually works this way.

To deal with this objection, Fredkin is working on finding observable consequences of his ideas. If the universe has its own "clock speed", then no event can take less time than that. Similarly, if the universe is the outcome of a digital process consisting of discrete bits,

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"A model of black holes might come more naturally from cellular automata"

then space itself must also be discrete, as there is a limit on the number of bits that can fit into a particular volume of space. The very fabric of the universe, in this view, has a finite "thread count", an absolute size limit below which measurements become meaningless.

Most physicists' first reaction is to say "Hold it right there." The idea that space and time are quantised, surely, has nothing to do with cellular automata. Most approaches to unifying quantum mechanics and gravity require space itself to be quantised in units of the smallest measurable length, 10^{-35} metres. Measuring such a small length is not possible with current techniques, but even if it were, there would still be no way of distinguishing between the discreteness of standard physics and the discreteness of Fredkin's matrix.

Fredkin gets really frustrated at this point. Nobody seems to get it. The scale of the matrix in which the Rule is being applied does not directly control the limits of what we can measure, he says. Our measurements are based on the information carried by the particle. This could include encoded information at scales that are smaller than the scale of the cells in the grid. Rather than being near the tiny scale of the Planck length, "The cells might be almost the size of a particle," he says, without contradicting quantum equations.

Mainstream researchers disagree with this point-blank. If there is any kind of discrete nature to space "it is certainly below 10^{-22} metres", says high-energy astrophysicist Philip Morrison of MIT. "We know it's not true down to that point, because our calculations come out so well without it." Fredkin says such objections arise because other people do not understand the concept of space he is working with. "The space of physics isn't defined by the cellular array," he says. "It's defined by the paths that free particles take in the cellular array." The physics we see is a projection of information out from the matrix. There is no reason to think that the grid the information is encoded in should appear in a straightforward way.

So how should it appear? In Fredkin's model, the one aspect of the grid that cannot change is the idea that there is an absolute coordinate system that things happen in. Because particles are made out of bits in the grid, their behaviour has to be constrained in some way by the shape of the grid. This opens the door to the possibility that data might exist that shows there is a preferred reference frame. Fredkin believes the underlying digital structure of space-time will reveal itself through an unexpected lack of symmetry when particles interact, with respect to at least some frame of reference. But until Fredkin has developed a cellular automaton that accounts for all of physics, he can make no specific predictions of the energies such effects would emerge at, or what exactly the effects would be. What he is saying is that such a model would be testable once it was developed, making the approach worth pursuing.

Perhaps a more serious objection is the clash between the determinism of the Rule and the indeterminism of quantum mechanics. "When it comes to quantum mechanics, Fredkin doesn't get it," says Pierre Noyes of the SLAC accelerator at Stanford University in California, who has looked closely at Fredkin's work. But Fredkin says apparently random behaviour so easily appears spontaneously in cellular automata that he is sure they can capture the quantum properties of matter without actually being random.

Even if the effort to build an automaton that captures all of physics fails, it could still be worth trying. How far physicists can get by thinking of matter and energy as information depends on deep assumptions about the underlying nature of reality – like the idea that quantum mechanics is the most basic theory. "Physicists don't think about this stuff," says Margolus, but it could still be valuable to try.

Morrison agrees. Even though he does not accept the notion that the universe is made of bits, he recognises that the idea could shed some light on an important problem in theoretical physics: what exactly goes inside black holes. Beyond describing black holes as singularities, points where the laws of physics break down because there is infinite density of mass and energy, conventional physics does not say much about what happens inside the event horizons of black holes. "I don't think they are literally described by the singularity, which is all relativity can do," says Morrison. A better theory is needed, and a model of black holes might come more naturally from cellular automata.

But do insights like these really count as evidence for the idea that matter, energy and all of space are constructed out of information? Even Margolus, a staunch supporter of Fredkin's digital physics, backs away from this. "To understand the universe, one reasonable approach is to study cellular automata," he says. "That's not the same thing as saying that the universe is a cellular automaton."

Convincing people to the contrary won't be easy. Fredkin himself is now writing his own book. Just like Wolfram, he has a vision to preach. After years of playing with cellular automata, building one to describe the universe is, he thinks, a project too great for just one man. But if he can inspire students and colleagues to try out digital physics, it may indeed bring about a totally new kind of science. ●