Simulating the replication of life

New ways of simulating the replication of abstract representations of living things are mathematically interesting and may yet reinterpret the second law of thermodynamics.

THAT the persistence of living things is at odds with the second law of thermodynamics is well understood and not especially scandalous. For while the entropy of a plant or animal is plainly less than would be the entropy of its inanimate chemical components at the same temperature, the strong statement of the second law that entropy tends to a maximum applies only to closed systems which, at maximum entropy, are in equilibrium. Living things, whose survival depends on a steady flux of energy and material, are clearly excluded. In what thermo-dynamic framework should living things be placed?

The need for some such setting has been recognized for decades, was clearly spelled out by Delbruck in the 1930s and popularized in the 1940s by Schrödinger's little book *What is Life?* Part of the incentive for Prigogine's monumental development of non-equilibrium (sometimes called "irreversible") thermodynamics in the past quarter of a century has similarly been to find a language for discussing the thermodynamics of, say, muscle function, respiration, growth, replication and so on; but this work is of necessity formal and macroscopic. So there is bound to be great interest in an approach whose objectives

Fig. 1 Evolution of a single non-zero site under the replication rule $a_k = (a_{k-1} + a_{k+1}) \bmod 2$.

are "to abstract . . . general features of self-organising behaviour and perhaps to devise universal laws analogous to the laws of thermodynamics".

This arresting statement is one of the introductory sentences in "Statistical mechanics of cellular automata" (*Rev. mod. Phys.* **55**, 601-644; 1983) by Stephen Wolfram, now at the Institute of Advanced Study at Princeton, where he has settled after an unresolved dispute with the California Institute of Technology over proprietary rights in a computer program. A cellular automaton was intended by J. von Neumann (*The Theory of Self-reproducing Automata*, University of Illinois Press; 1966) to be what the name suggests — a way of realizing in the abstract literally machine-like entities that can replicate

themselves. More recently, cellular automata have become elements in computer simulations of autonomous replicating entities.

Here is Wolfram's way of setting up the simulation. Start with a linear array of points, each of which may or may not be occupied by an automaton. An occupied site is denoted by the digit 1, an empty site by 0. To simulate the transformation of this set of automata into the next generation, there must be a replication rule specifying the occupation numbers of the second-generation array in terms of their predecessors. Nothing interesting happens unless the k th site in the second-generation is determined by the earlier occupancy of the same site, and of its neighbours in the previous generation. One interesting rule is $a'_k = a_{k-1} + a_{k+1}$, where a'_k and a_k are the occupancies of the k th site in the second and first generations respectively. To ensure that the occupancy numbers have only the values 0 and 1, the addition is evaluated *modulo 2* (or by the remainder after dividing the sum by 2). In general, there are 2^8 possible rules, but Wolfram notes that only 32 of these satisfy the sensible requirements that a string of zeros should always yield zeros and that the effect of a replication rule on an array should be unaffected (except for a mirror reflection) by an inversion of the order.

Even with these restrictions, most replication rules yield nothing much of interest — generations quickly die out, or repeat themselves monotonously. But some yield weird and wonderful patterns on the video screen of the computer that simulates them. For example, Fig. 1 (in which solid squares represent ones and blanks, zeros) is the pattern of successive generations (horizontal rows) generated from an initial array with only one occupied site by the rule $a'_k = (a_{k-1} + a_{k+1}) \bmod 2$.

Now for a change of interpretation. Suppose that each horizontal row represents the state of a single system as, fancifully, it might if the zeros and ones were to represent the nucleotides A (or T) and G (or C) in a molecule of DNA. Specifically, Wolfram's argument goes, suppose that there are N elements in the array and, to avoid edge effects, impose periodic boundary conditions on the system. Then, it may turn out, a replication rule will generate an orderly pattern from a disordered state as the generations go by. Fig. 2, for example, is the pattern generated from a randomly chosen first generation by

the replication rule that $a'_k = 1$ except when $a_{k-1} = a_k = a_{k+1}$. Order out of disorder is obviously possible.

In general, Wolfram has shown that cellular automata can behave in four different ways. Some replication rules lead quickly to trivial outcomes. Repetitive cyclic behaviour is another possibility, with some cycles so long that they are hardly recognizable as such. An array of 71 lattice

Fig. 2 Evolution over 30 generations of a random initial state under the replication rule $a'_k = 1$ except when $a_{k-1} = a_k = a_{k+1}$. points replicating according to the rule of Fig. 1 will lapse into a cycle that repeats itself only after $2^{35}-1$ generations.) Then some replication rules appear to generate what is technically called chaos while, finally, others generate complicated structures that appear to evolve systematically as time goes on.

Where will all this lead? First, the analytical mathematics of cellular automata promises to be absorbing. More practically, there are close analogies with non-linear differential equations (of the kinds that generate soliton and chaotic solutions). The usefulness of this model in the study of lattice order-disorder problems remains to be explored. Wolfram himself seems especially interested in cellular automata as universal computing machines.

The connection with the thermodynamics of living things is at this stage only crude but nevertheless significant: for the cellular automata that generate orderly structures from initially disordered states, there is obviously a decrease of entropy at the outset followed by a condition in which the entropy is distinctly different from the maximum. In one sense, this is no great surprise, for a replication rule that screens out disorder may be supposed to incorporate some kind of Maxwell's demon. The result, however, is a model by which the non-equilibrium thermodynamics of replicating systems may eventually be tackled on a microscopic scale.

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