Karl Wittfogel (P. Ball *Nature* **564**, 186–188; 2018). This held that early agriculture-based empires such as Sumer in Mesopotamia rose through control of water, but tended to squander it — leaving them vulnerable to environmental degradation and outside attack.

More recent examples include the 'land rushes' that gripped Australia, New Zealand, South Africa and North America from 1650 to 1900. Barbier points out that these vast expansions of frontiers and economic gain were hugely dependent on claiming 'free' water. That practice lingers. Markets generally undervalue lakes, waterways and aquifers that are public goods. One impact of that, he notes, is a "use it or lose it" attitude, encouraging territoriality and, ultimately, water wars.

Barbier calls for an end to policy, markets and governance that underprice water and allow it to be used as if it were plentiful. Our innovations, he argues, are generally geared to expanding not reducing consumption.

He makes his points eloquently, offering a wellspring of facts and figures. I am impressed by the dozens of scholarly lists, tables and compendia, on history, current problems or tools for finding solutions to, for instance, types of water market that bring both benefits and perils. Those include river basins at risk from future conflicts; groundwater depletion now and in the near future; water grabbers and the grabbed-from; and many more.

But the book has three key gaps.

First, Barbier is so clear and thorough that I really hoped he would take on the paradox itself: our apparent inability to avert a human-driven existential threat. I hunted for a glimmer of a way forward, an until-now hidden path out of our political paralysis, or a psychological glitch that could be redirected. I searched for philosophers or social psychologists who could suggest ways of waking a sleeping world as the waters rise and fall. But on this key point, Barbier is silent.

Second, he almost entirely omits ongoing public opposition to most of his proposed measures — such as tackling the chronic underpricing of water — that is fuelled by factors such as aversion to taxes. Substantial hikes in water prices, water markets and governance involving greater private-sector dominance are anathema to many (M. Catley-Carlson *Nature* **505**, 288–289; 2014).

"Markets generally undervalue lakes, waterways and aquifers that are public goods."

Large companies and other players were chased out of water-asset management in the 2000s, criticized by a number of non-governmental organizations, the political left and unions. That grass-roots movement is part of a larger tide of resistance to globalization and multinational companies. It has affected the availability of investment capital, the direction of World Bank lending and significant strands of public opinion. Thus, in effect if not intent, Barbier prescribes an approach that is almost certain to lead to discord, making it problematic for governments. Also missing from his discussion are some of the less-than-wise corporate steps that have triggered successful protest.

Third, Barbier ignores the very real tension between some of his sensible suggestions and many countries' lack of economic, infrastructural and governmental capacity to implement them. He acknowledges the mismatch between water governance and institutions and our needs. If this is to be a book for the world, that obstacle course needs more attention (perhaps even a list of on-the-ground prerequisites for reform). And, although he covers desalination well, many other kinds of processing barely get a look-in: water reuse, waste-water reprocessing and the extraction of resources from industrial and domestic waste waters.

The Water Paradox is, however, jargon-free and readable, brilliantly detailing both problems and remedies. I hark back to Barbier's words on the fountains of Rome. To learn that 2017 was the first time in 2,000 years that these hydro-engineering marvels were turned off in response to drought provokes tears of sorrow and frustration. We know that it is happening. We do not act. That is the paradox. ■

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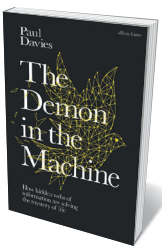
INFORMATION THEORY

Life versus entropy

Timo Hannay explores a study of life that takes up where Erwin Schrödinger left off.

Biology, long the domain of qualitative theories and experimental subjects that refuse to do the same thing twice, is now thoroughly data-driven. Propelled by the twentieth-century revolutions in molecular biology and computing, its emphasis has shifted from observing and describing to sequencing and calculating. In the process, biology has increasingly become like physics — a development that has caught the attention of quite a few physicists.

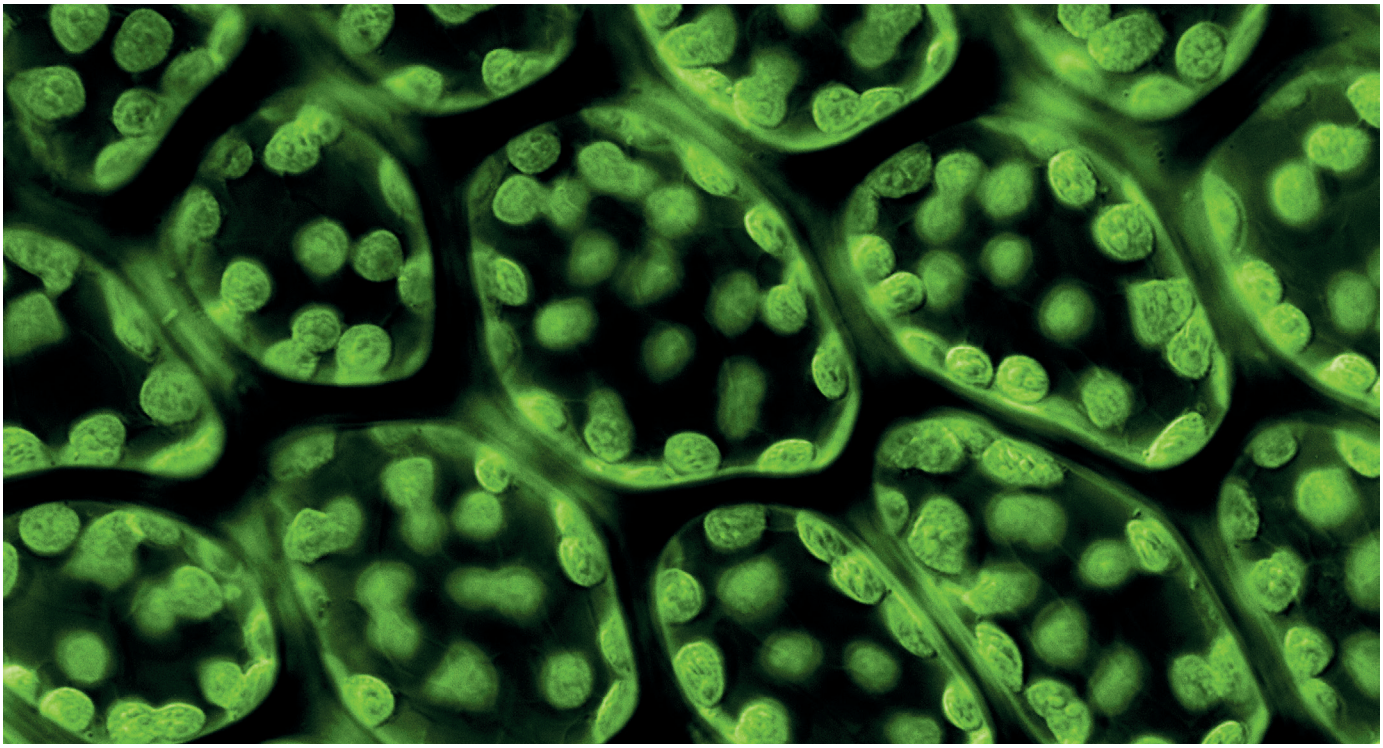
One such boundary-transcending thinker is the cosmologist and writer Paul Davies. His latest book, *The Demon in the Machine*, presents a case that information is central not just to doing biology, but to understanding life itself. He follows in esteemed footsteps. In 1943, the Austrian physicist Erwin Schrödinger delivered a landmark series of public lectures at Trinity College Dublin. Published the following year as *What Is Life?*, it explained many principles of molecular genetics — a decade before the structure of DNA was discovered (see P. Ball *Nature* **560**, 548–550; 2018).



The Demon in the Machine: How Hidden Webs of Information Are Finally Solving the Mystery of Life
PAUL DAVIES
Allen Lane (2019)

As a quantum theorist, Schrödinger was particularly struck by the observation that atoms, although profoundly unpredictable, can form highly ordered systems. Furthermore, those systems persist for long periods and even replicate, thus seeming to evade the second law of thermodynamics, which states that total entropy, or disorder, can only increase.

This classic account serves as Davies's starting point. As a cosmologist, however, his principal question arises from a consideration not of the irreducibly small, but of the incomparably large. If life exists elsewhere in the Universe, Davies wonders, how can we recognize it? Searches for signs of liquid water, organic chemistry or certain atmospheric gases (such as oxygen, carbon dioxide or methane) make sense given the



JOHN DURHAM/SPL

Chloroplasts inside moss cells. These organelles conduct photosynthesis, a process that relies on quantum effects.

characteristics of the one ecosystem we know, but to accept these as the essence of life seems to him (and me) desperately narrow-minded.

Davies claims that life's defining characteristics are better understood in terms of information. This is not as absurd as it may seem. Energy is abstract, yet we have little trouble accepting it as a causal factor. Indeed, energy and information are closely related through entropy.

Davies explains this connection by referring to Maxwell's demon. Victorian physicist James Clerk Maxwell's celebrated thought experiment features a hypothetical miniature beast perching at an aperture between two containers of gas, where it allows only certain molecules to pass, depending on their kinetic energy. The demon can thus create a temperature gradient between the containers: a reduction in overall entropy, apparently breaking the second law of thermodynamics. The resolution to this paradox seems to lie in the fact that the demon must gather information about the properties of each molecule, and for this it requires a recording device, such as a brain or a miniature notebook. When its storage space eventually runs out, the information must be deleted, a process that necessarily produces an increase in total entropy.

From this perspective, living systems can be seen as composed of countless such 'demons' (proteins and other cellular machinery) that maintain local order by pumping disorder (often in the form of heat) into their surroundings. Davies adroitly brings Schrödinger's account up to date by way of Claude Shannon's information theory, Turing machines (universal computers), von Neumann machines (self-replicating universal constructors), molecular biology, epigenetics, information-integration theories of consciousness and quantum biology (which concerns quantum effects in processes from photosynthesis to insect coloration and bird navigation).

Such disparate threads might seem like unpromising material from which to weave a coherent narrative. But Davies does so admirably, with only occasional forays into areas that feel slightly out of place. One such is the brief account of his work on cancer, which he sees less as an example of broken cellular machinery and more as a regression to an earlier evolutionary state, when single-celled organisms responded to adverse conditions by replicating.

> ***"We are already beginning to treat computers as companions; might we eventually come to see them as living creatures?"***

What practical difference does it make to see life as informational? We don't yet know, but can speculate. For one thing, if the essential characteristics of life are entropic, extraterrestrial searches based on chemistry could be misguided. It might be more useful to look for phenomena such as 'anti-accretion' — in which matter is regularly transferred from a planet's surface into space. Earth has experienced this since the 1950s, when the one-way traffic in asteroids and meteorites plunging into the globe was finally counteracted by the launch of the first artificial satellites. Arguably, such situations are not merely consistent with the presence of life, but almost impossible to explain in any other way.

Moreover, a definition of life that depends on its informational characteristics rather than its carbon-based substrate could force a reappraisal of our attitudes towards artificial systems embodied in computers. We are already beginning to treat these as companions; might we eventually come to see them as living creatures rather than mere imitations? With apologies to Charles Darwin, there is grandeur in this view of life.

As well as having eclectic interests, Davies is iconoclastic and opinionated. Although certainly no believer in a vital force distinct from physics or chemistry, he has little time for reductionism, believing that life cannot be fully explained in terms of lower-level laws (such as the second law of thermodynamics), even in principle. In a final nod to Schrödinger — who believed that a proper understanding of life might reveal "other laws of physics hitherto unknown" — Davies closes by arguing that biology might yet contain deep lessons for physics. This is highly speculative and, in my (biologist's) view, probably wrong. But this is not a criticism. On the contrary, if only more of us were wrong in such thought-provoking ways, we might more readily uncover the truth. ■

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