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REVIEW

# NOT SO COOL

Eric D. Schneider and Dorion Sagan, *Into the Cool: Energy Flow, Thermodynamics, and Life*. Chicago and London: The University of Chicago Press, 2005. Pp. xviii + 362 US$30.00 HB

*By Craig Callendar*

To their dismay, children look like their parents. They are not perfect copies, and over many generations some features evaporate; but even over 50 generations features relevant to an anthropologist persist. Children perhaps can find some comfort in the fact that we are not alone: organisms in general maintain remarkably stable structures through time. In *What is Life?* Erwin Schrödinger famously predicted the existence of the gene, but he also asked how life manages such stability in the face of thermodynamics' prescription that systems spontaneously move to increase their entropy. How does life escape the randomising effects of the Second Law? Schrödinger, of course, recognised that there is no genuine conflict between life and thermodynamics. The Second Law applies only to closed, that is approximately energetically isolated, systems; yet living organisms are open. Although living creatures are not plugged into electrical sockets like your refrigerator, Schrödinger noted that organisms are dependent on the high quality energy of their environment. They maintain their structures at the expense of increased contributions of entropy (waste) to their environment. Life arises in the balance between the low entropy found in the environment and the entropy the organism itself throws off. Writing in the 1940s, Schrödinger could see the general form of the answer to his question, but he lacked the resources to explain why these stable structures arose in the first place.

Enter non-equilibrium thermodynamics (NET). This field has of late made substantial progress in our understanding of stable states in non-equilibrium contexts. Co-authored by an environmental scientist (Schneider) and a science writer (Sagan), *Into the Cool* introduces the reader to this wonderful subject. However, the book is not simply a popular exposition of new advances in science. Its main purpose is to propound a very bold claim: 'nature abhors a gradient'. This simple principle condenses what NET teaches us, but it can also be extended to new domains. 'The simple concept of collapsing gradients', they write, ''encapsulates the difficult science of thermodynamics, demystifies entropy . . . and illuminates how all complex structures and processes, including those of life, come naturally into being'' (p. 6). By 'all complex structures' the authors mean all: the origin of life, evolution, ecology, economics, and much, much more. *Into the Cool* is in many ways reminiscent of James Lovelock's *Gaia: A New Look at Life on Earth*. Also a book written for a popular audience, *Gaia* made a bold claim – that the Earth itself is alive – and argued that many disparate scientific claims could be explained in a unified manner by this general claim. Substitute NET for the Gaia hypothesis and one has a good sense of the present book.

To understand Schneider and Sagan's message, that 'nature abhors a gradient', it helps to have an example in mind. Consider the sublime physics of Rayleigh–Bénard convection. In the experiment done by Henri Bénard at the end of the 19th century, one heats a 1-mm layer of whale oil in a brass dish. This heating produces a sharp 80° temperature gradient between the steam from below at 100°C and the air from above at room temperature, i.e., 20°C. Whale oil at room temperature is a waxy substance, but at 46°C it turns into a viscous fluid. As the oil heats it dissipates the heat flow through conduction. Then, strikingly, a remarkable honeycomb structure appears. The $10^{20}$ molecules in the oil organise into coherent motion resulting in beautiful hexagonal 0.1 cm cells, dissipating heat now through convection. The Bénard cells are stable, lasting as long as the gradient, efficient and complex. They are an exemplification of Ilya Prigogine's insight that when open systems get into stationary states, they often organise themselves in ways to minimise entropy production. Complexity arises as a response to a gradient in an open system.

Supported by many similar examples, Schneider and Sagan elevate the idea that 'nature abhors a gradient' to the status of a law of nature. Parts I and II of the book deal with the physics. Time and again we see that physical systems take surprising turns in trying to compensate for being out of equilibrium. Parts III and

IV deal with the life sciences. Some of the more surprising turns, the authors argue, are the origin of life, evolution, regularities in ecology, human health and even economics. The central mechanisms of each of these fields, the authors claim, follow from their general principle that nature seeks to reduce gradients. Chemistry, cells, life, and so on, are all attempts by matter to efficiently dissipate energy due to various gradients, e.g., the temperature gradient due to the Sun. In short, the authors see Bénard cells everywhere they look.

The problem with their hypothesis, like the problem with the Gaia hypothesis (the reader may recall), is that when left vague one sees it confirmed everywhere, but when provided with rigorous content, it seems false. Nowhere in the book is the main claim developed in any technical or even conceptual detail. Understood in full generality, however, it's hard to imagine something happening that *couldn't* be put in the form of a gradient reduction. Bénard convection is due to a temperature gradient, whirlpools to gradients in gravitational potential energy, the rise of new species to "underutilised gradients and habitats" (p. 241), Taylor vortices and hurricanes to pressure gradients, and arbitrage in finance due to price gradients. What are the constraints on the theory? It seems the gradients don't even have to be measured by a thermodynamic parameter.

By contrast, if we sharpen the claim it's probably false. By 'non-equilibrium thermodynamics' let's agree to mean roughly the theory described in a book like *Beyond Classical Thermodynamics* by Hans Christian Öttinger. If understood as the assertion that the central features of these fields *follow* from NET, I don't believe this has been established or even rendered plausible. No attempt has been made to (say) apply Onsager's, Crooks' or Jarzynski's fluctuation theorems to the various fields or to apply the complicated physics of Prigogine to capital. The hypothesis seems particularly overblown when extended to systems whose variables aren't even thermodynamic.

What provides the hypothesis its air of plausibility are two related claims that are true. First, there are deep analogies between the various subjects, often expressed in a common mathematical structure. Treating traffic flow, gene flow, and monetary flow with the master's equations originally designed for the statistical mechanics of gas molecules has often been successful. But the authors want to go further. The similarities are not merely analogies for them (see p. 282 on economics). Second, in some cases biological and even economic systems are non-equilibrium thermodynamic systems. The systems are macroscopic and as such admit a thermodynamic description. From this fact, one may infer many useful generalisations in the biological and economic sciences. Indeed, NET has enjoyed demonstrable success in understanding biological motors in the cell.

That said, it doesn't follow that NET *explains* life or economics. It follows no more than it follows from pointing out that organisms or economic systems are primarily carbon systems that carbon science explains life and economics. NET may be necessary for life and economic markets, but it doesn't seem sufficient. This point was already seen, ironically, by Schrödinger. Schrödinger tiptoed to the edge of saying that NET explains life, but backed away:

> But F. Simon has very pertinently pointed out to me that my simple thermodynamical considerations cannot account for our having to feed on matter 'in the extremely well ordered state of more or less complicated organic compounds' rather than on charcoal or diamond pulp. He is right.

Because we're thermodynamic organisms and far from equilibrium, physics says that we need low-entropy intake. That much is right. But Simon points out that thermodynamics doesn't provide further discrimination about what the form of low-entropy intake must be, yet there are generalisations about this in biology. In accepting Simon's point, Schrödinger is seeing that some biological facts don't follow from thermodynamics.

NET may encroach on the possibilities available to biology and economics, just as chemistry does, and there are examples of this happening already. But at this stage of the game, there is no reason to imagine that it has the unprecedented explanatory benefits Schneider and Sagan believe it does. NET enjoys enough genuine success, both theoretical and experimental, that it doesn't need such a boost.

Apart from the merits of the main claim, the book also has some flaws in both style and content that bear mentioning. The authors seek drama and will embellish where they cannot find it. Newton's equations, for instance, are linked to Platonism, Pythagoreanism and the afterlife, and Newton is described as "a kind of English scientific Jesus – able to access the eternal mind of God and show that he did his divine handiwork" (p. 37). The writing in this passage is cringe inducing (though not more so than the description of NET as a fattened veal calf with 'jittery legs' emerging from the isolated box of classical thermodynamics (p. 81)). But the content may also induce winces. Throughout NET is portrayed as revolutionary, advertised as a 'new science' that "emerges to replace its esteemed foundation", "classical equilibrium thermodynamics" (p. 71). Equilibrium thermodynamics describes a "boring" (p. 5), pessimistic and literally lifeless world. While it's true that NET has advanced significantly and that equilibrium theory perhaps suffers from an 'image' problem due to its longstanding association with deterioration, I worry that the physics novice will come away with the wrong impression. NET is not yet a single theory (which the authors acknowledge) but a collection of disparate theories and techniques. These theories and techniques are not only compatible with the equilibrium theory, but in virtually all cases they require the truth and methods of equilibrium theory. And historically, there was work in the subject from early on. It's not an accident that one of the most important equations in the field is called the Boltzmann Equation.

It is a pleasant change to read a popular science book extolling the neglected virtues of non-equilibrium physics instead of the quantum and relativistic enigmas. NET is a truly exciting field, filled with beautiful surprises. Unfortunately, less than rigorous argument and hyperbolic writing sometimes obscure the fascinating science in this book.

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