Life’s Ratchet:
How Molecular Machines Extract Order from Chaos
by Peter M Hoffmann

reviewed by Sonya Bahar

Among the torrent of recent books popularizing current topics in science, Peter M Hoffmann’s Life’s Ratchet: How Molecular Machines Extract Order from Chaos stands as a singular achievement. Writing in a style that ranges from folksy to poetic, Hoffmann introduces the reader to a wide variety of exciting ideas without compromising scientific accuracy. The book, illustrated with a series of charming hand-drawn sketches, could easily be enjoyed by a bright high school student or adult layperson. But Hoffmann, a physicist and materials scientist at Wayne State University, has achieved something else quite rare and significant: he has written a popular book that is also a refreshing and inspiring read for a working scientist (like this reviewer).

The underlying theme of Life’s Ratchet is how random thermodynamic fluctuations at the molecular level (what Hoffmann calls the “molecular storm”) are harnessed by molecular machines—biomolecules such as molecular motors, enzymes, and DNA—to generate the “purposeful motion” that characterizes living cells. In his first chapter (“The life force”), Hoffmann sets out the terms of the problem by revisiting 17th- and 18th-century arguments over vitalism versus mechanism: is there a fundamental life force, or are living creatures, as Julien Offray de La Mettrie suggested, simply extraordinarily complicated machines? Describing the work of Hermann von Helmholtz and others, who demonstrated energy conservation in living organisms, Hoffmann traces the decline of the vitalist tradition, but also illustrates the mounting evidence that a pure “clockwork” model of biology is likewise insufficient.

In the second chapter (“Chance and necessity”), Hoffmann sketches the origins of probability theory (gambling among the French nobility), and then discusses how statistics and probability were gradually applied to biological problems, beginning with John Graunt’s 17th-century studies of London’s mortality rolls. Hoffmann then addresses more recent arguments over the ubiquity (or not) of probability and randomness in biology, in the work of Jacques Monod, Erwin Schrödinger, and others.

Hoffmann next provides a beautifully clear exposition of the key ideas of thermodynamics in his third chapter, “The entropy of a late-night robber”. Hoffmann turns a frightening anecdote of having been robbed at gunpoint during his grad school days into a transparently clear way of explaining energy conservation: “The robber gained ten dollars, and I lost ten dollars. Is it possible, in the same transaction, for me to lose eight dollars and the robber to gain ten dollars? No. Money does not appear out of nowhere.” He then continues the
example to illustrate the loss of mechanical energy to heat: “Imagine that the robber stole a thousand pennies instead of a ten-dollar bill. After a while, one thousand people could potentially each have a penny of my money. It would be highly unlikely that my pennies would be spontaneously reunited, as this would require one thousand people (probably unacquainted) to go to the same merchant at the same time to spend their pennies” (page 73). After introducing the idea of entropy and the Second Law of Thermodynamics, Hoffmann uses examples at the atomic level to explore the relation between free energy and entropy. The formation of a snowflake illustrates the key idea, often (deliberately?) misunderstood by creationists, that entropy can decrease locally, and thus order can increase locally, without violating the Second Law of Thermodynamics.

Moving into the meat of his argument, Hoffmann introduces nanoscience (Chapter 4, “On a very small scale”). Building on examples from his own research using atomic force microscopy (AFM) to probe the structure of biomolecules, he drives home the utter uniqueness of the nanoscale. “Life must begin at the nanoscale,” he writes. “This is where complexity beyond simple atoms begins to emerge, and where energy readily transforms from one form to another. It is here where chance and necessity meet” (page 91). The reason for this remarkable confluence: the exchange of energy among various forms (thermal, chemical, electrical, mechanical) takes place with particular ease at the nanoscale, where these forms of energy have similar magnitudes.

In the next three chapters (“Maxwell’s Demon and Feynman’s Ratchet,” “The mystery of life,” and “Twist and route”), Hoffmann weaves the preceding themes together to show the extraordinary results of this confluence of energy scales. He explains how molecules can harness random thermal fluctuations of the “molecular storm” to drive directed motion across an asymmetric energy landscape. But there is no free lunch: biomolecules must use up energy as they ratchet themselves along. Hoffmann then guides the reader through examples of how specific molecular machines accomplish this feat: kinesin walking on a microtubule, ribosomes translating RNA into proteins, the synthesis of ATP molecules in the mitochondria, topoisomerase preventing DNA from turning into a hopeless tangle while it is being replicated. Hoffmann has succeeded in introducing a suite of fundamental ideas, and also in presenting a unique and vivid perspective on the balance of chance and necessity. I finished this section of the book more struck by the confluence of energies at the nanoscale than I had ever been before (and I am a biophysicist!) and also inspired with new examples I can use to introduce ideas of molecular structure and thermodynamics to my first-year-level university students.

In the final chapters of Life’s Ratchet, Hoffmann explores the evolution of molecular machines. Deftly debunking a creationist canard (“how can molecular complexity arise simply from randomness?”), Hoffmann explains that, like the action of molecular motors, evolution itself is driven by a balance of randomness (in this case, genetic mutations rather than thermal fluctuations) and determinism (arising from the constraints of physics and chemistry, and imposed by the action of natural selection). While the molecular storm allows molecules to ratchet themselves up an asymmetric energy landscape, genetic “noise” provided by mutations allows evolution to ratchet life toward a plethora of new forms. The idea of an essential tension between chance and necessity has been explored before, by other authors, but I have never seen it so clearly drawn as here—and drawn, moreover, at various scales. There is something unique about the nanoscale, it is true; but there is also
something uniquely beautiful about a universe where the same delicate balance operates at a range of scales: the flicker of molecular motion and the slow unspooling of geological time. Hoffmann has done a marvelous job of presenting this beautiful complexity.

**About the Author**

Sonya Bahar is Professor of Biophysics and Director of the Center for Neurodynamics at the University of Missouri at St Louis.

**Author’s Address**

Sonya Bahar  
Department of Physics and Astronomy  
University of Missouri at St Louis  
One University Boulevard  
St Louis MO 63121  
bahars@umsl.edu