Life's Ratchet: How Molecular Machines Extract Order from Chaos

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The Maxwell demon is in the details

Life's Ratchet
How Molecular Machines Extract Order from Chaos

Peter M. Hoffmann
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Reviewed by R. Dean Astumian

In the microscopic world, molecular machines carry out tasks, including transport, pumping, and assembly, that are associated with machines in the macroscopic world. In the past those remarkable molecules have been found only in living systems, but recent advances in chemistry have made it possible to take the first, halting steps toward synthetic molecular machines.

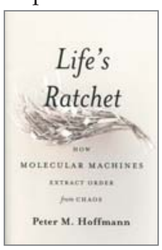
In *Life's Ratchet: How Molecular Machines Extract Order from Chaos*, Peter Hoffmann offers a fascinating glimpse into recent research on molecular-machines, research that lies at the intersection of biology, chemistry, and physics. He explains the unexpected ways that machine-like functions are accomplished by molecules and discusses conceptual similarities between how molecular machines operate and the mechanisms by which biological organisms evolve.

The book starts out with the early Greek natural philosophers and the beginnings of the tension between deterministic and statistical explanations of matter. It covers the development of probability theory as a mathematical discipline. That theory is at the heart of recent descriptions of molecular machines according to which thermally driven molecular motion combines aspects of deterministic mechanics with ineluctable probabilistic fluctuations due to the thermal environment.

An overarching motif of the book is a comparison between evolution and the Brownian motion of molecular machines. Evolution works by locking in only those random changes to a species that confer a competitive advantage; Brownian-motor mechanisms use chemical energy to lock in the fluctuations—driven by random thermal noise—that move the molecular machine forward. A key idea is the interplay between chance, due to ineluctable thermal noise, and necessity, as described by the deterministic laws of classical physics.

Unfortunately, in chapter 3 Hoffmann makes a serious, but perhaps understandable, error in discussing the second law of thermodynamics. He offers a straw man by restating the second law as follows: "There can be no process whose only result is to convert high-entropy (randomly distributed) energy into low-entropy (simply distributed, or concentrated) energy" (page 78).

The primary literature is replete with similar formulations of the second law, but the statement above is not correct. Many processes result only in the conversion of random energy into ordered energy. Take as a simple example a small particle suspended in water. If the particle (say a micron in diameter) is denser than the surrounding water, gravity will on average pull it down toward the bottom of the container. In any short time interval, however, there is a reasonable chance that, because of thermal noise, the particle will move up. During that time, the only thing happening is that random thermal energy from the water is converted into "concentrated" potential energy in the particle. As the author points out later in chapter 5, precise statements of the second law focus not on single events but on the impossibility of cyclic or repeatable processes that convert random energy into concentrated energy.



The instant we recognize that processes converting high-entropy energy into low-entropy energy in fact happen all the time in single molecules, just less frequently than the microscopically reverse processes, we are led to the possibility that a molecular machine could work by capturing the relatively rare free-energy-increasing fluctuations. And that is where the thought experiments of Maxwell's demon and Smoluchowski's trapdoor come in. An individual particle fluctuates up and down, though on average it moves down. If the fluctuations could be observed by an external being—a demon—who traps the upward fluctuations, the particle could be caused to move continually upward against gravity and thereby store energy. One-way devices such as a trapdoor, or the ratchet and pawl famously discussed by Richard Feynman, could accomplish the same goal, but without the need for intervention by an intelligent being.

Of course, no one-way devices can operate at the molecular scale without input energy, nor are there real demons to control molecular events. However, the work of a Maxwell's demon can be accomplished by allosteric interactions. That well-known macromolecular phenomenon is a way by which the binding between a ligand and a molecular machine is controlled by the state of the machine. Allosteric interaction with a single ligand provides a mechanism for a switch and hence for regulation of molecular processes, but it does not provide a mechanism for powering a machine—unless the ligand can be catalytically converted to a different form as, for example, in adenosine triphosphate hydrolysis. When allosteric interactions discriminate between reactant and product, energy released by the nonequilibrium chemical reaction can be used to power the machine. An important take-home message is that in coupling a chemical reaction to drive motion, molecular recognition is more important than the mechanics of the machine's conformational changes.

Overall, *Life's Ratchet* does an excellent job of conveying the tension between mechanical descriptions of molecular machines, in which input energy causes "forward" motion, and the chemical perspective, in which input energy prevents "backward" motion and in which forward motion is caused by thermal noise. Although written primarily for a lay audience, with not a single equation in the text, I highly recommend this book to scientists in the fields of biophysics and nanoscience as a readable introduction to a broad variety of topics in those areas.

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Time Reborn
From the Crisis in Physics to the Future of the Universe

Lee Smolin
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Lee Smolin is a very good popularizer of science, a provocative thinker, and a