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Crowd Forcing: Random Movement of Bacteria Drives Gears

In the swimming motions of aerobic bacteria against asymmetric gears, apparent randomness can yield directed motion

The collective random motion of tiny bacteria can be harnessed to turn much larger mechanical gears in a preestablished direction, a new study demonstrates. The research, set to be published online this week by the *Proceedings of the National Academy of Sciences,* presents a new spin on the concept of the so-called Brownian ratchet, in which arbitrary fluctuations generate directed motion to power tiny mechanical systems.

The random and omnipresent movement of particles in a fluid, known as Brownian motion, presents on its face a tantalizing avenue to perpetual motion. In the classical, theoretical model of a Brownian ratchet, a paddle wheel is connected to a mechanical ratchet that constrains its rotation to one direction—say, clockwise. When the thermal fluctuations around the paddle wheel are sufficient to nudge it clockwise, the ratchet clicks over and a directed rotation of the system is achieved. But the pesky second law of thermodynamics intervenes, prohibiting the extraction of mechanical work from such fluctuations in equilibrium. In the thought experiment of the Brownian ratchet, the same equilibrium fluctuations that drive the paddle wheel also nudge about the brake on the ratchet mechanism, causing it to fail often enough to render it useless.

But that has not stopped researchers from pursuing the harvesting of directed motion from random motion, bowing to the laws of thermodynamics by introducing energy inputs that throw the system out of equilibrium. "So long as that system is out of equilibrium, if there is any flow of energy in the system at all, it is going to move," explains Dean Astumian, a University of Maine physicist who did not contribute to the new research. Several out-of-equilibrium setups have been devised, utilizing inputs such as alternating electric currents or magnetic fields, says Peter Hänggi, a physicist at the University of Augsburg in Germany who was also uninvolved in the study.

In the new implementation, researchers from Argonne National Laboratory, Princeton University and Northwestern University turn to a biological energy source: the common soil bacterium *Bacillus subtilis*. In the presence of oxygen and other nutrients, the tiny rod-shaped bacteria take to swimming about. Moving essentially randomly, *B. subtilis* bacteria provide what Hänggi describes as "a nonequilibrium source of random velocity kicks" to any obstacle in their way.

In a thin fluid layer along with the bacteria, the researchers placed just such an obstacle in the form of tiny gears—just 380 microns across—with slanted teeth so as to preferentially spin in one direction. (A micron is one millionth of a meter.)

In spinning ability, *B. subtilis* have an advantage over inanimate particles, says study co-author Bartosz Grzybowski, a Northwestern physical chemist: they tend to swim in swarms, like schools of fish. Even though the group's movement is essentially random, the bacteria's collective behavior allows them to leverage their collective heft to turn a gear, which in the experimental setup created by Grzybowski and his colleagues is as massive as millions of bacteria. "When you form swarms, the collective behavior has a collective gain in the amount of momentum they carry together," Grzybowski says. "They work in unison to push on this gear."

In the researchers' experiments, large swarms of bacteria, roughly 20 billion per cubic centimeter, turned the gears at a speed of about one to two revolutions per minute. The schools of *B. subtilis* were even able to turn a pair of directionally biased gears—one clockwise and one counterclockwise—whose teeth were enmeshed. What is more, Grzybowski's team could switch the motion of the gears on and off by controlling the flow of oxygen to the bacteria.

Astumian calls the new work "a fascinating implementation." At the same time, he is unsure that any applications using bacteria will be immediately forthcoming—for one thing, bacteria pollute their surroundings with waste and eventually die. "You go to the pet store and you see the hamsters, and they're all the time running around that wheel," Astumian says. "And I suppose that in principle you could attach it to a generator and power a small electric lightbulb. But so far that hamster-driven motion hasn't become a household appliance, and I think that this is probably similarly far from that."

A self-described theorist, Astumian is more interested in the ways that experiments such as the bacteria-powered gears further our understanding of physics at the smallest scales, where macroscopic analogies do not always hold. "It's all about building an intuition in an area where we don't have any," he says.

His colleague Hänggi calls the concept of using biological drivers for such Brownian-type ratchets or motors "a really nice idea, a nice experiment." Hänggi is optimistic that micromechanical motors could be powered by microorganisms—to sort healthy cells from diseased cells, for instance. But he is curious to see how the system responds to an opposing force—in the new experiment the gears spin freely. "It doesn't do work, really, against a load," Hänggi says, emphasizing that the new study is a starting point. "It's a first step," he says, "that gives you all kinds of ideas for engineering at the bio-level."