

Turbines and motors made of DNA

The medium of life's genetic code is also a versatile structural material for building nanoscale machines.

From the cogs and wheels of well-oiled machines to the spinning flagella of single-celled swimmers, rotation is one of the most versatile forms of mechanical motion at almost any size scale. The rotating wheels of cars and conveyor belts drive linear motion. At the sub-cellular scale, rotation powers not just mechanical processes but chemical ones. ATP synthase, the enzyme that assembles molecules of adenosine triphosphate to fuel cellular processes, is based on a spinning central protein cylinder.

Researchers have long sought to mimic the molecular machinery of life to build their own miniature molecule assemblers and more, but they've been challenged by the small-scale physics. A submicron spinning rotor in water lacks the inertia to keep turning in one direction. Instead, it's pulled to a stop by viscous drag and batted around by the Brownian storm of random molecular movements. On top of the difficulty of just building the tiny machines, researchers need to engineer the physical mechanism of their operation, and it's not clear what the best one would be.

There have been some successes. Bernard Feringa, honored with a share of the 2016 Nobel Prize in Chemistry, designed the first one-way synthetic molecular rotor, powered by alternating pulses of heat and light. (See *PHYSICS TODAY*, December 2016, page 18.) David Leigh and colleagues at the University of Manchester have synthesized several rotors that, like biomolecules, are fueled chemically.¹ But so far, even state-of-the-art rotors have been impractically slow, taking minutes or hours to complete a single rotation.

Now two overlapping groups, both including Hendrik Dietz of the Technical University of Munich and his graduate student Anna-Katharina Pumm, have sped things up. They've designed two different rotors, both made with DNA origami, that rotate several times a sec-



FIGURE 1. ION FLOW through a nanopore drives the rotary motion of a 500-nm-long bundle of DNA, much like a miniature turbine, windmill, or water wheel. The ion flow is initiated either by a salt gradient—placing salt water on one side of the membrane and fresh water on the other side—or an electric potential difference. (Courtesy of Cees Dekker Lab/Scixel.)

ond: not quite as fast as their biological counterparts, but in the same ballpark. Although superficially similar—both rotor blades are bundles of DNA some 500 nm long—they operate in completely different ways. One, described in *Nature Physics*, works like a turbine that's pushed by the flow of the surrounding fluid.² The other, described in *Nature*, spins autonomously like a wireless electric motor, powered by an AC electric field applied to the whole system.³

Breaking symmetry

Biology uses proteins to create the intricate shapes and structures of its molecular machines. Although researchers are starting to decode the links between pro-

tein sequence, structure, and function (see *PHYSICS TODAY*, October 2021, page 14), they still have a long way to go before they can reliably design protein-based machines to order.

The advent of DNA origami is a testament to scientific creativity. In nature, DNA is an information-carrying material, not a structural one. But because of the ease of programming specific interactions—single strands of DNA stick easily to their complementary sequences, and almost not at all to any others—researchers have repurposed it to build things. (See *PHYSICS TODAY*, April 2012, page 20, and the Quick Study by Oleg Gang, *PHYSICS TODAY*, March 2021, page 58.)

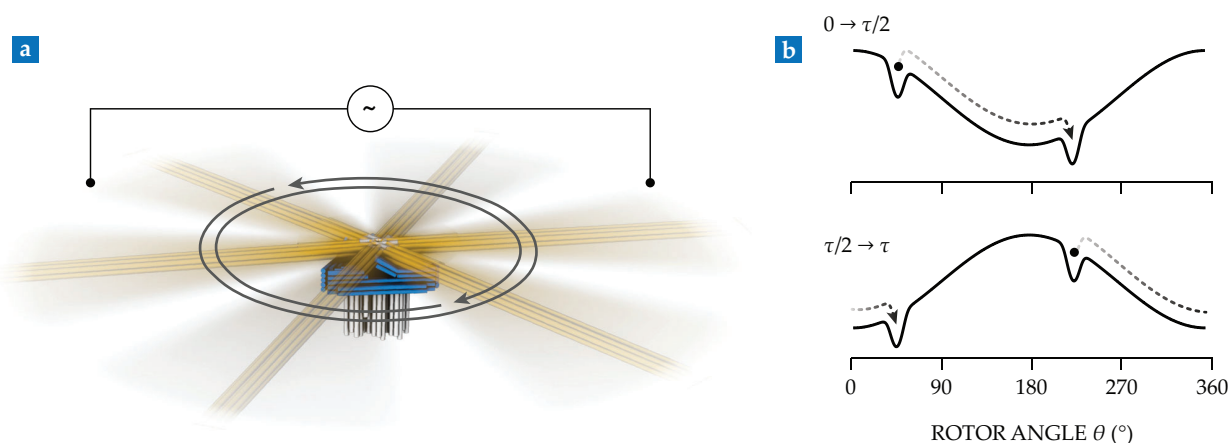


FIGURE 2. A WIRELESS ELECTRIC Brownian-ratchet motor **(a)** is made of three DNA-origami components: the rotor blade (yellow), dock (blue), and pedestal (white). An alternating applied electric field drives the blade's rotation in one direction or the other, depending on the motor's orientation. **(b)** Over the AC field's oscillation period τ , the energy landscape flip-flops between the two sine-wave configurations. The two small dips are created by the blade–dock interaction. The blade hops from one to the other, almost always in the same direction. (Adapted from ref. 3.)

Dietz, an expert in designing and characterizing sophisticated DNA nano-objects, got a grant in 2016 to work on DNA-origami motors. He started exploring different mechanisms of operation, including using an ion current through a nanopore to push a DNA rotor around in a circle like the blade of a windmill.

Cees Dekker, a biophysicist at Delft University of Technology in the Netherlands, had the same idea, and the *Nature Physics* paper is the result of his collaboration with Dietz, which included Dekker's postdoc Xin Shi. Together, they synthesized the rotor illustrated in figure 1: a long bundle of six DNA strands with a small protrusion that allows it to dock to a nanopore in a silicon nitride membrane. When an ion current (induced by either a salt gradient or an electrochemical potential) flows through the pore, the rotor starts to spin.

Curiously, the curvature that breaks chiral symmetry and enables one-way rotation is not inherent to the blade's structure. At equilibrium, a DNA bundle is a straight rod; it becomes curved only in the presence of ion flow. And there is no way to control or predict which way the symmetry is broken. Some rotors turn clockwise, some turn counterclockwise, and a few even spontaneously switch directions in the middle of an experiment.

Uncontrolled symmetry breaking wasn't the researchers' first idea for a rotor design. They tried for years to design a controllably curved blade. "But it never rotated," says Dietz. "So step by step, we stripped away all the complex-

ity until all that was left was the achiral rod. And then that one rotated!"

To understand why, they turned to Ramin Golestanian, a theoretical physicist at the Max Planck Institute for Dynamics and Self-Organization, and his student Jonas Isensee. "The electric field, the hydrodynamic friction, the elasticity of the bundle, and the flow field around the pore all conspire to break the symmetry," Golestanian explains. "It's a gift from the nonlinearities in the underlying physics, much the same as the Higgs mechanism in elementary-particle physics." (See *PHYSICS TODAY*, September 2012, page 14.)

With the success of their symmetry-breaking rotor, they returned to the quest to build a rotor with deliberately designed chirality. And in the months since they submitted their *Nature Physics* paper, they succeeded.⁴ The new rotor is still a straight rod, but the protrusion has three helical turbine blades wrapped around it. The chirality of the helix reliably controls the rotor direction.

Ratchet motor

To create the DNA motor described in the *Nature* paper, Dietz and his lab neighbor Friedrich Simmel looked into mechanisms of Brownian ratcheting. The Brownian storm is an inevitable feature of the nanoscale fluid environment, but there are ways to use it to one's advantage. If a time-dependent potential is applied in just the right way, it's more likely than not that the randomness will push a system in the desired direction.

The physics of Brownian ratchets

was worked out decades ago.⁵ (See the article by Dean Astumian and Peter Hänggi, *PHYSICS TODAY*, November 2002, page 33.) But when it came to designing a DNA implementation, Dietz says, "We spent a lot of time unsuccessfully with different driving modes, such as rapid laser heating and cooling. But one day it occurred to me that just shaking the system should lead to directional motion and that applying an AC electric field could be a way to power it."

As shown in figure 2a, the motor is made of three DNA-origami components: the rotor blade (yellow), the dock (blue), and the pedestal (white). The pedestal and dock are fixed to a glass surface, while the blade is free to rotate. Once again, Golestanian and Isensee helped elucidate the operating mechanism. The AC field doesn't drive the directed rotation itself, but it shakes the rotor back and forth between the two potentials shown in figure 2b. The blade–dock interaction creates the little potential dips shown at 45° and 225°, and the applied field superposes the flip-flopping sine wave on top of them. The asymmetry of the combination means that when the rotor hops from one dip to the other—aided by the Brownian storm—it almost always turns in the same direction.

The relative positions of the dips and sine wave depend on how the motor is oriented with respect to the field. In an ensemble of motors randomly scattered on a surface, all orientations are represented. So some motors, with the dips at 45° and 225°, turn counterclockwise;

some, with the dips at 135° and 315°, turn clockwise; and still others, with the dips at 0° and 180° or 90° and 270°, show no directed motion. But unlike the turbine, whose symmetry breaking is random, the direction of any given motor can be controlled by adjusting the direction of the field.

Full speed ahead

The *Nature* motor can perform work against a load: The researchers attached the DNA blade to a molecular torsion spring, and they showed that the motor's rotation winds up the spring and stores energy that can be released later. That capability hasn't been tested with the *Nature Physics* turbine—"That would be a fascinating avenue for future experiments," says Golestanian—but just drag-

ging the 500 nm DNA bundle through the surrounding liquid also takes work.

Indeed, both rotor blades were longer, and therefore slower, than they'd likely be in any future molecular-machinery application. They needed to be as long as they were so the researchers could attach fluorescent molecules to the ends of the blades and watch the rotation in real time. The resulting speeds, up to 20 rotations per second for the turbine and four rotations per second for the motor, were slower than those of biomolecular rotors by a factor of 10–100. But shortening the blades would probably make them faster.

Research on synthetic molecular machines is still in the exploratory stages, but researchers have ambitious dreams. On the wish list of what might be possible: docking rotors to biological mem-

branes instead of synthetic ones, finding a way to reverse the turbine action to pump ion currents instead of being driven by them, and using the rotors to mechanically assemble molecules like ATP synthase does. Dietz says, "It feels like with one more missing piece, we could make something really useful, straight out of science fiction."

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References

1. See, for example, S. Borsley et al., *Nature* **604**, 80 (2022).
2. X. Shi et al., *Nat. Phys.* **18**, 1105 (2022).
3. A.-K. Pumm et al., *Nature* **607**, 492 (2022).
4. X. Shi et al., <https://arxiv.org/abs/2206.06612>.
5. M. O. Magnasco, *Phys. Rev. Lett.* **71**, 1477 (1993).

Giant meteorites could be responsible for Earth's continents

The isotopic composition of ancient Australian rocks may answer a long-standing question about early Earth.

The Pilbara craton, in the Pilbara region of Western Australia, is the best-preserved remnant of Earth's ancient continental crust (see figure 1a).

It formed during the Archean eon 4 billion to 2.5 billion years ago. At that time, Earth is believed to have had a water-covered primordial crust that was more

or less a single, continuous shell around the mantle. Eventually, the primordial crust transformed into continental crust, which was later joined by its thinner and denser cousin, oceanic crust.

Most present-day oceanic crust is at most 200 million years old, and its for-

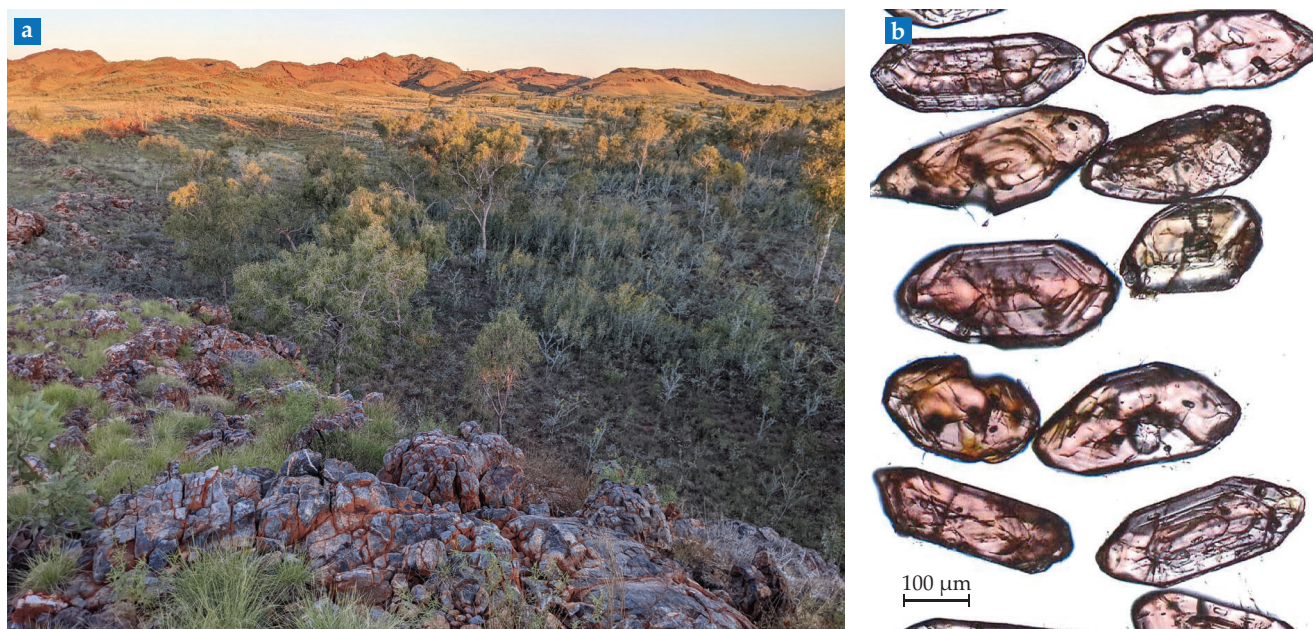


FIGURE 1. THE PILBARA REGION of Western Australia hosts the best-preserved fragment of Earth's ancient continental crust. **(a)** The Pilbara craton formed as far back as 3.6 billion years ago, around the same time as most of today's landmass. It is one of a handful of locations where geological processes between the rocks' formation and the present day haven't erased mineral markers of their origins. **(b)** Zircon grains extracted from Pilbara rocks are particularly useful measures of the craton's past because their composition reveals their age and the conditions at the time of their formation. (Images courtesy of Chris Kirkland.)