[MOLECULAR-SCALE MOTORS]

FREE LUNCH (AT A COST)

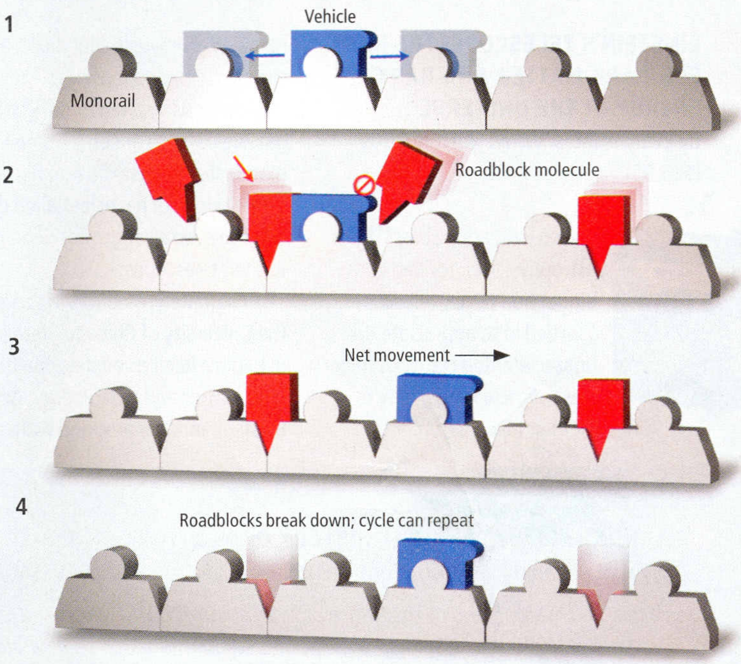
Molecules are never completely still. In the case of a liquid, the random movement is known as Brownian motion. Chemists are creating the first artificial Brownian ratchets, molecular-scale machines that harness Brownian motion rather than fight against it. David Leigh of the University of Edinburgh and his team, for example, are developing a monorail system that turns random steps into directed motion (*below*). Their invention might seem to be a perpetual motion machine, in violation of the laws of thermodynamics, or of the "no free lunch" rule. But any method of selecting Brownian motion must itself expend energy in the selection process, and this one is no exception: if the supplied energy ends, the motion stops.

1 VEHICLE MOVES RANDOMLY
A "vehicle" molecule can move in steps along a "monorail" immersed in a liquid. The engineless vehicle is subject to the fluid's Brownian motion, so it jumps back and forth each time it's hit by an unusually fast molecule from the liquid.

2 ROADBLOCKS COME INTO PLAY
Molecules in the liquid can also bind to the railing and act as roadblocks. But the vehicle is designed to be asymmetric, so that it prevents the roadblock molecules from binding directly in front of it.

3 RANDOM BECOMES DIRECTED
Now, when Brownian motion hits the vehicle, the roadblock behind it prevents it from backing up. The roadblocks thus increase the vehicle's chances of moving one step forward rather than one step backward.

4 SLATE IS CLEANED
The solution periodically breaks down the blocking molecules so that the vehicle molecule can keep moving ahead. Each of its steps is random and takes energy from Brownian motion. But breaking down the roadblocks costs energy, as required by the second law of thermodynamics.



that on the centimeter to millimeter scale the speed of a diode motor does not vary with its size, in agreement with theory. That result implies that such motors could be quite powerful on the scale of tens of microns, which is about the size of a human cell.

Thanks to the advances of computer chip technology, it is now possible to make diodes well below the scale of microns, and molecular diodes only two to three nanometers in length have long been synthesized chemically. It may thus become possible to make microscopic scalpels that consist of propulsion, steering and sensing components patterned onto tiny silicon chips. One can imagine driving diode-powered scalpels wirelessly and remotely with radio-frequency electric fields, which are not absorbed by the body. Ultimately, these microscalpels might be delivered with a very fine needle and piloted to their destination by remote control.

Scientists (and science-fiction writers) have contemplated nanomachines at least since 1959, when physicist Richard Feynman considered the limits of scale for machines and information storage systems in a forward-looking lecture entitled "Plenty of Room at the Bottom." He pointed out that the laws of physics are valid down to the length scale of molecules. There is, therefore, no reason, apart from the obvious challenges of making them, that one should be prohibited from constructing vehicles or even the factories to mass-produce nanomachines from atomically precise molecular parts.

In the intervening decades, Feynman's lecture has continued to inspire research in nanotechnology. Meanwhile the prevailing view of the living cell has shifted from a soup pot of enzymes carrying out metabolic reactions to a ticking Swiss watch of mechanically linked nanomotors. Thus, in many ways, cells are the molecular factories that Feynman envisioned.

Investigators have learned a good deal about how to make nonbiological motors inspired by those of biology, but there is still much to learn about the principles of catalyzed movement on this length scale. No doubt future work will find as yet unimagined ways to exploit such knowledge in biomedicine, energy conversion, chemical synthesis and other fields. ■

MORE TO EXPLORE

Life at Low Reynolds Number. E. M. Purcell in *American Journal of Physics,* Vol. 45, No. 1, pages 3–11; January 1977.

Molecules, Muscles and Machines: Universal Performance Characteristics of Motors. James H. Marden and Lee R. Allen in *Proceedings of the National Academy of Sciences USA,* Vol. 99, No. 7, pages 4161–4166; April 2, 2002.

Chemical Locomotion. Walter F. Paxton, Shakuntala Sundararajan, Thomas E. Mallouk and Ayusman Sen in *Angewandte Chemie International Edition,* Vol. 45, Issue 33, pages 5420–5429; August 18, 2006.

Can Man-Made Nanomachines Compete with Nature Biomotors? Joseph Wang in *ACS Nano,* Vol. 3, No. 1, pages 4–9; January 27, 2009.