When will artificial molecular machines start working for us?

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Physicist Richard Feynman in his famous 1959 talk, "Plenty of Room at the Bottom," described the precise control at the atomic level promised by molecular machines of the future. More than 50 years later, synthetic molecular switches are a dime a dozen, but synthetically designed molecular machines are few and far between.

Northwestern University chemists recently teamed up with a University of Maine physicist to explore the question, "Can artificial molecular machines deliver on their promise?" Their provocative analysis provides a roadmap outlining future challenges that must be met before full realization of the extraordinary promise of synthetic molecular machines can be achieved.

The tutorial review will be published Nov. 25 by the journal *Chemical Society Reviews*.

The senior authors are Sir Fraser Stoddart, Board of Trustees Professor of Chemistry, and Bartosz A. Grzybowski, the K. Burgess Professor of Physical Chemistry, both in Northwestern's Weinberg College of Arts and Sciences, and Dean Astumian, professor of physics at the University of Maine. (Grzybowski is also professor of chemical and biological engineering in the McCormick School of Engineering and Applied Science.)

One might ask, what is the difference between a switch and a machine at the level of a molecule? It all comes down to the molecule doing work.

"A simplistic analogy of an artificial molecular switch is the piston in a car engine while idling," explains Ali Coskun, lead author of the paper and a postdoctoral fellow in Stoddart's laboratory. "The piston continually switches between up and down, but the car doesn't go anywhere. Until the pistons are connected to a crankshaft that, in turn, makes the car's wheels turn, the switching of the pistons only wastes energy without doing useful work."

Astumian points out that this analogy only takes us part of the way to understanding molecular machines. "All nanometer-scale machines are subject to continual bombardment by the molecules in their environment giving rise to what is called 'thermal noise,'" he cautions. "Attempts to mimic macroscopic approaches to achieve precisely controlled machines by minimizing the effects of thermal noise have not been notably successful."

Scientists currently are focused on a chemical approach where thermal noise is exploited for constructive purposes. Thermal "activation" is almost certainly at the heart of the mechanisms by which biomolecular machines in our cells carry out the essential tasks of metabolism. "At the nanometer scale of single molecules, harnessing energy is as much about preventing unwanted, backward motion as it is about causing forward motion," Astumian says.

In order to fulfill their great promise, artificial molecular machines need to operate at all scales. A single molecular switch interfaced to its environment can do useful work only on its own tiny scale, perhaps by assembling small molecules into chemical products of great complexity. But what about performing tasks in the macroscopic world?

To achieve this goal, "there is a need to organize the molecular switches spatially and temporally, just as in nature," Stoddart explains. He suggests that "metal-organic frameworks may hold the key to this particular challenge on account of their robust yet highly integrated architectures."

What is really encouraging is the remarkable energy-conversion efficiency of artificial molecular machines to perform useful work that can be greater than 75 percent. This efficiency is quite spectacular when compared to the efficiency of typical car engines, which convert only 20 to 30 percent of the chemical energy of gasoline into mechanical work, or even of the most efficient diesel engines with efficiencies of 50 percent.

"The reason for this high efficiency is that chemical energy can be converted directly into mechanical work, without having to be first converted into heat," Grzybowski says. "The possible uses of artificial molecular machines raise expectations expressed in the fact that the first person to create a nanoscale robotic arm, which shows precise positional control of matter at the nanoscale, can claim Feynman's Grand Prize of $250,000."

More information: The title of the paper is "Great Expectations: Can Artificial Molecular Machines Deliver on Their Promise?" In addition to Stoddart, Grzybowski, Coskun and Astumian, the other co-author of the paper is Michal Banaszak from Adam Mickiewicz University, Poland.

Provided by Northwestern University