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GUEST EDITORIAL

Molecular Machines

Consult a dictionary or two on the meanings of the word "machine" and you quickly learn a thing or two about the English language.[1] Like many words in this complex language, "machine" can assume quite a variety of meanings relating to different contexts and settings. And so a "machine" to those of us who are a bit egocentric or politically aware might be construed as "one who can do only what he is told" or "an organized group of persons whose members appear to be under the control of one or more leaders". We have all heard of party machines, and we can all think of someone who behaves like a machine. In yet another context, a "machine" can be viewed as simply ourselves—namely, "the human body"—or, indeed, a functional unit, e.g., the heart or kidneys, contained within such a body. More often than not, however, when we hear the word "machine", we think of a system or device, along with its power source and auxiliary equipment, e.g., an automobile, a lawnmower, a food blender, a hairdryer, or even an electronic computer, to mention but a few machines that are part and parcel of our everyday lives. They all more or less fit the description of "any system, usually of rigid bodies formed and connected to alter, transmit, and direct applied forces in a predetermined manner to accomplish a specific objective such as the performance of useful work".

The key words that surface from these formal definitions are organization, the power source (fuel), and work of a repetitive—often, it would seem to be implied of a cyclic—nature. And so it comes as little or no surprise that the word "machine" is often supplanted in our way of speaking about something that imparts or produces motion by that other well-known synonym, "motor", which the dictionary tells us is "a device that converts any form of energy into mechanical energy"; i.e., the definition is just a shade narrower than that which we associate with a "machine". Once again, we need look no further than within ourselves to find motors "pertaining to or designating nerves carrying impulses from the nerve centers to the muscles". Medical doctors refer to "motor coordination" when discussing the health of our nervous systems.

This exercise in etymology is all well and good, except that it would insinuate that "machines" and "motors" are to be found by and large in our macroscopic world with perhaps some modest intrusion down to the microscopic level. This view was certainly a generally held one until Richard Feynman came along and challenged us all to think about the possibilities of—and the opportunities provided by—manufacturing nanoscale machines and motors. It was on December 29, 1959, at Caltech in his famous talk[2] entitled "There's Plenty of Room at the Bottom" to the American Physical Society when he entered the realm of speculating about making machines out of molecules. Toward this end, he was to issue this challenge to the chemist:

> "Ultimately, we can do chemical synthesis.... The chemist does a mysterious thing when he wants to make a molecule. He sees that it has got that ring, so he mixes this and that, and he takes it, and he fiddles around. And, at the end of a difficult process, he usually does succeed in synthesizing what he wants."

And with molecular machinery as a meaningful and increasingly respectable goal, this challenge is one that a few chemists have been responding to with more and more fervor, particularly during the past 15 years or so. They had to wait—as often is the case in science—until the time was ripe. There is no doubt that our abilities to design and construct artificial molecular-level machines has been aided and abetted by a number of major breakthroughs and paradigm shifts in physics, chemistry, and biology. They include (1) the rapid development of a range of different probe microscopies[3] following the award of the Nobel Prize in Physics to Binnig and Rohrer in 1986; (2) the realization that supramolecular assistance to covalent synthesis provides a means by which interlocked molecules (catenanes and rotaxanes) can be self-assembled with comparative ease after the pioneering work of Pederson, Cram, and Lehn on the nature of the noncovalent bond[4] led to their being awarded the 1987 Nobel Prize in Chemistry; (3) the elucidation of the mechanisms of action of some of key biological systems,[5,6] such as those involved in photosynthesis (Deisenhofer, Huber, and Michel recognized by the 1988 Nobel Prize in Chemistry) and in ATP synthesis (leading to the 1997 Nobel Prize in Chemistry to Boyer, Skou, and Walker); (4) tremendous progress in unraveling the mechanisms of the homogeneous and heterogeneous thermal and photoinduced electron-transfer reactions[7] provided by Marcus, who was awarded the Nobel Prize in Chemistry in 1992; and (5) the growing realization that the top-down (physical) approach to miniaturization in the electronics industry has intrinsic limitations and the increasing confidence that it might be replaced profitably by a bottom-up (chemical) approach.[8]

This special issue of *Accounts of Chemical Research* presents the reader with a collage on molecular machines and motors—as well as some closely related topics—from a wide range of different perspectives (mainly chemical but also physical) that cover their design and synthesis

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and, in a few instances, their organization and fabrication, prior to their being put through their paces, often in solution but sometimes also in (solid-state) devices. Clearly, the collage can give no more than a flavor for what is out in the marketplace currently. I must emphasize that it is my opinion that we are only looking at a collage with all its abrupt features on view: the detailed picture has yet to emerge. These are early days for a field that is re-inventing itself and re-defining its substance and scope by the month, if not the week. It is my feeling that the art and science (not to mention engineering) of building molecular machinery is about to receive an enormous fillip from the relentless drive toward nanoscience and nanotechnology that now characterizes our times. The fabrication and construction processes that must necessarily surround the production of *working* machines and motors from molecules and supermolecules is going to thrive in a remarkable way from goal-driven projects involving synthetic and physical chemists, physicists, computational and materials scientists, and engineers of all persuasions. The future lies in us all working together as one. And just one more thought—chemistry will be greatly enriched in its own right as both an academic and a scientific discipline.

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J. Fraser Stoddart

University of California, Los Angeles

Guest Editor

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