Head Lines – Playing with Nature's "Ultimate Toy Box", or Why the Best Things Come in Small Packages

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What might be the uses of an electric motor far smaller than a human cell? Or an equally small nonpolluting energy conversion machine, that takes cheap, plentiful materials and converts them into energy storage devices? Or a tiny "cement mixer" that takes particles of chalk dust and manufactures from them superstrong bricks?

Sounds like I've taken too many trips to Santa Fe? Well, probably, but the machines just described aren't fantasies — they've existed for millions of years. Your life depends every instant on the operation of molecular-sized motors for everything from cellular transport to flagellar motion; all the food you eat is a direct or indirect result of photosynthesis; and the almost unbreakable shell of the abalone results from its ability to perform microscopic masonry that would put any human contractor to shame. Nature, through evolution and biology, has performed engineering feats that until recently we could only dream of, or at best crudely imitate.

Wouldn't it be nice, though, if we could match those feats?

Surprisingly, we're now on the verge of doing so. Recognizing the tremendous potential this holds for the future, the University of Arizona Physics Department started in the mid-90's, when many Physics Departments were looking elsewhere, to build a sizable and powerful group of experimentalists and theorists who are poised to place us in the forefront of exciting developments in this area over the next decade.

We all know that the rapid advance of technology in recent decades has been fueled by miniaturization. But we're talking now about an entirely new level. In the near future, the ultimate limits set by nature (i.e., the atomic scale) will be approached. Already, atomically thin conductors and mechanical components (e.g., levers and rods) have been created in the laboratory, as have single-electron transistors. Understanding the electrical and mechanical properties of such components—and how to integrate them to make circuits or machines—is a major challenge.

The prophet who foretold this very recent explosion of activity was — not surprisingly — Richard Feynman. Back in 1959, in what is now recognized as one of the most prescient scientific lectures of the 20th century, Feynman anticipated much of what is grabbing scientific headlines today. In his lecture, entitled "There's Plenty of Room at the Bottom", Feynman observed that biology had learned to make fantastically versatile and efficient devices on extremely small scales. So, why shouldn't humans do the same? No physical laws, Feynman pointed out, prevent one from using an electron beam to write the information contained in the contents of the entire Enyclopedia Britannica on an area the size of the period at the end of this sentence. Nothing we know forbids the existence of computers operating through minitiarized wires, with transistors and other components shrunk to the size of a hundred or so atoms. In fact, nothing prevents direct manipulation of atoms and molecules (remember, this was 1959). Feynman's main point was that none of these visions violated any known laws of physics, unlike the perpetual motion machines and anti-gravity shields that remain popular to this day.

Much of what Feynman talked about is now happening, outrageous as it may have seemed forty or even thirty years ago. That the day has arrived is evidenced by the naming of new disciplines — "nanoscience" and "nanotechnology".

A nanometer is one-billionth of a meter — roughly the length of ten atoms placed side by side. A typical human cell is about a thousand nanometers in diameter. A DNA molecule has a width of 2-3 nanometers; a human hair has a cross-sectional diameter of 100,000 nanometers. We're talking small here.

What has spurred this incipient revolution is the ability, realized over the past two decades, to "see" and manipulate individual atoms and molecules, as Feynman predicted. By constructing molecules, or materials, one atom at a time, there's potential to control to great precision their structural, electrical, mechanical, and optical properties. These "designer" materials have the potential to give rise to a vast array of new and powerful vaccines and medicines; or to "smart" matter (e.g., pigments that take on the characteristics of their surroundings, leading perhaps to optically invisible planes; or materials that sense weather conditions and alter their permeability to temperature and humidity in response); and who knows what else. We now have the tools that allow us to play with what Horst Stormer at Columbia calls the "ultimate toy box of nature" — atoms and molecules. And we're just beginning.

I won't describe in detail the many nanoscience-related research activities in our department (and don't have space to discuss the numerous nanoscience activities occurring elsewhere in the University). But just to give you a flavor (and also because I can't resist), here are a few.

The research group of Prof. Charles Stafford has been at the forefront of theoretical work on metallic and semiconducting nanostuctures. They were the first to show that the correlated electrical and mechanical properties of metal nanowires can be explained using a single quantum model. Their current research focuses on several related topics, including the essential role of defects in quantum transport through metal nanowires (with Dr. Jérôme Bürki); the cohesion, stability, and dynamics of metallic nanostructures (using quantum chaos techniques, with graduate student Chang-hua Zhang); quantum interactions between nanoscale components (a quantum circuit designer's version of the two-slit experiment), essential to integration in complex architectures (with undergraduate Jeremie Korta); electron-electron interactions and the nonequilibrium carrier distribution in nanostructures with a driving voltage (with graduate student Steven Bildstein); and the dynamics of quantum systems with dissipation, from nuclei to qubits (an interdisciplinary project with Prof. Bruce Barrett and graduate student David Cardamone).

Prof. Sumit Mazumdar, in collaboration with others both within and outside of the University of Arizona, is planning to conduct a program to develop, through combined experimental/theoretical studies, nanostructured two-dimensional organic materials for photonic (i.e., as opposed to electronic) devices. He and his group are also working on "tuning" (by varying the molecular components) the (effective) dimensionality of certain organic superconductors.

Prof. Srinivas Manne's lab uses atomic force microscopy (AFM) in liquid environments to measure intermolecular forces and to image interfacial ordering at molecular scales. When a liquid contacts a solid surface, the ordered lattice of the solid imparts partial order to a thin interfacial layer of molecules in the adjoining liquid. This phenomenon plays a crucial role in a surprising number of technological and biogenic processes–e.g., crystal growth, biomineralization, boundary layer lubrication, surface catalysis, and mesoscopic materials synthesis. Undertanding of these processes — still poor at best — requires a specifically molecular approach. Measurement of molecular forces, and the interfacial structures to which they give rise, is the first essential step.

The effect of the substrate structure on interfacial ordering serves as the unifying theme for Prof. Manne's investigations into the nucleation of solid phases (crystal growth) and the self-assembly of liquid-crystalline phases (surfactant micelles). Temperature-driven phase transitions in such "soft matter" are explored using a home-built temperature stage that operates over the entire aqueous range (0-100°C). In addition to these scientific goals, Prof. Manne also is active in an interdepartmental program (in collaboration with the Chemistry and the Materials Science & Engineering departments) to exploit self-assembly, microcontact printing and AFM-based lithography to create molecular devices such as thin film transistors and organic light-emitting diodes.

Prof. Koen Visscher's biological physics lab has a broad interest in the different aspects of protein synthesis, but part of his current research focuses on using "optical tweezers" (devices that use light to manipulate objects smaller than biological cells) to ultimately record the forces (piconewton-scale) and displacements (nanometer-scale) produced by individual ribosomes, which are cellular structures on which proteins are assembled. Such single-molecule experiments provide new data that are unattainable with conventional methods. The ribosome itself is nature's version of a type of nanoscopic device that might be considered the "Holy Grail" of nanotechnology. It is a self-assembled, programmable molecular machine that is capable of piecing together monomers, which can fold to make stable and functional products. By studying in detail the mechanism of protein synthesis, important lessons can be learned for designing functionally equivalent man-made devices. What did nature do right? Is the natural ribosome an optimal design? What room is there for improvement? Can (modified) ribosomes be used in hybrid devices or should we start from scratch? Prof. Visscher's experiments provide the basic and crucial steps required to answer such questions.

Research on nanoscale phenomena in Prof. Ray Goldstein's group focuses also on biological physics problems, particularly on two aspects of bacterial structure and function. The first concerns the elasticity and fluid dynamics of helical flagella. Bacteria swim through their fluid environment by rotating helical flagella with rotary motors embedded in the cell body. Reversals of these motors during the course of chemotaxis create torques that lead to chiral reversals of the flagella, so that a left-handed helix converts to a right-handed helix through a process of front propagation. Prof. Goldstein's group has proposed the first dynamical model of this phenomenon that accounts for a wide range of experimental observations on the structure and dynamics of these chirality transitions — and may provide new insights into the construction of subcellular sized electric (or fluidic!) motors.

A second area of investigation is the physics of the bacterial cell wall, a cross-linked chiral polymer network. Experimental observations by Prof. Neil Mendelson (Dept. of Molecular and Cellular Biology) have shown remarkable twisting and coiling instabilities of cellular assemblages likely due to stresses in the cell walls, and Prof. Goldstein's group has studied models for this behavior. In collaboration with Prof. Mendelson, they also measured the cell wall stiffness directly with optical trapping methods.

The Dean of Science, Joaquin Ruiz, has the vision of creating a College-wide "Nanoscience Center", to be a focal point for collaborative efforts involving Physics, Chemistry, the various Biology departments, and others within the College (and perhaps a few outside, like the Optical Sciences Center). We're very excited about this, and look forward to joining with our fellow scientists in the College to turn this vision into reality. Our mutual goal, which is entirely within our reach, is to make the University of Arizona an outstanding and highly visible example of a research and teaching center for what will certainly become a focal point of early 21$^{\mathrm{st}}$-century science and technology.

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