ence must adapt. The study of asteroids is therefore particularly exciting, as small planets provide the fulcrum for the growth of planetology, and for an evolution of geophysics in general. Complex and poorly understood solar system processes—such as impact cratering, accretion and catastrophic disruption, the evolution of volcanic structures, and the triggering of differentiation—may reveal themselves only in a study across the gamut of planets, from the least significant house-sized rock to the most stately terrestrial world. Like clockwork miniatures, asteroids demonstrate primary principles governing planetary evolution at an accessible scale, and thousands await discovery and exploration in near-Earth space alone.

References and Notes

1. For a typical asteroid with density $1.5 < \rho < 2.5$ g cm^{-3}, escape velocity (in meters per second) is about equal to asteroidal radius (in kilometers). If you can jump half a meter on Earth, you could leap off of an asteroid 5 km in diameter.
2. Rotational periods vary tremendously. Speedy Castalia revolves every 4 hours, Mathilde every 17 days. Non–principal-axis rotator Toutatis (see figure) has nothing that can be called a "day," forever showing different horizons. For further insights, see Scott Hudson's Web page, http://www.eecs.wsu.edu/~hudson/asteroids.html.
3. This "human ICBM" mode of transportation is ill-advised; D. J. Scheeres *et al.*, *Icarus* **121**, 67 (1996) demonstrated the complexity of trajectories proximal to Castalia.
4. For a video view of the Mathilde encounter, see http://hurlbut.jhuapl.edu/NEAR/Mathilde/images.html#ani.
5. J. Veverka *et al.*, *Science* **278**, 2109 (1997); D. K. Yeomans *et al.*, *ibid.*, p. 2106.
6. S. J. Ostro *et al.*, *Astron. J.* **102**, 1490 (1991). Visit the asteroid radar research home page at http://echo.jpl.nasa.gov.
7. R. S. Hudson and S. J. Ostro, *Science* **263**, 940 (1994).
8. ———, *ibid.* **270**, 84 (1995).
9. The upgraded Arecibo antenna will also be used to image the "back side" of Mathilde, which was not seen during the NEAR flyby.
10. P. C. Thomas *et al.*, *Science* **277**, 1492 (1997).

MATERIALS SCIENCE

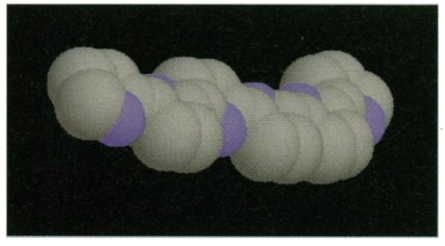
Conducting Polymers: From Novel Science to New Technology

J. Campbell Scott

On page 2103 of this issue, Lonergan describes a hybrid device in which an inorganic semiconductor and a conducting polymer are combined to create a diode, one of the fundamental building blocks of electronics (*1*). Polymers of the sort used by Lonergan, which become electrically conductive after being doped with electron donors or acceptors, have occupied an increasingly prominent place in physics, chemistry, and materials science since Shirakawa first reported his method for the polymerization of acetylene (*2*). Much research has since been motivated (and many grants funded) by the conviction that there is a huge potential for technological and commercial exploitation, yet the record reveals only a few truly successful products (*3*). What can we learn by examining the history of conducting polymers?

In addition to the technological possibilities, interest in polyacetylene was driven by scientific curiosity into the effect of broken symmetry in the *trans*-isomer form, which gives rise to highly nonlinear phenomena such as solitons (*4*). Experimental data in the early 1980s were eagerly scrutinized by theorists in search of tests of their calculations in nonlinear dynamics. Identification of polarons (single electronic charges, self-trapped by a structural distortion) and bipolarons (doubly charged) followed in short order (*5*). At the same time, synthetic chemists were exploring new materials and synthetic procedures to yield higher conductivity and environmental stability. The "holy grail" became an air-stable polymer with the conductivity of copper. In retrospect, it is hard to believe that serious consideration was given to the use of plastics to replace wiring, circuit board connections, motor windings, or solenoid coils.

Nevertheless this period was an extremely productive time, owing to the synergy of scientists with backgrounds as diverse as field theory, solid-state physics, and physical and synthetic chemistry. A milestone was reached in the development of conducting polymers when it was recognized that they could be synthesized by electrochemical polymerization, then subsequently dedoped and redoped by electrochemical methods (*6*). Thus, properties such as electrical conductivity and optical absorption could be manipulated in ways that are not possible with conventional semiconductors and metals. This distinction has led to the introduction, or at least the trial, of conjugated polymers in new technological niches, and it is this feature that Lonergan exploits (*1*).



Conjugated conductor. Space-filling model of a polypyrrole chain. Carbon atoms are white; nitrogen atoms are blue.

One of the earliest commercialization attempts was in batteries (*3*), on the basis of electrochemical energy storage characteristics combined with a perceived weight advantage. However, because of breakthroughs in other battery materials such as lithium ion and metal hydride, and because volumetric capacity turned out to be more important than weight, conducting polymer batteries were not successful and have been withdrawn from the market. Electrolytic capacitors, introduced in 1992, have been more successful. Here, conducting polymers permit an all-solid-state device and obviate the problem of containing a liquid electrolyte by gelation or encapsulation.

Another unique and advantageous property of conjugated polymers lies in the processing and compatibility that one associates with plastics. The earliest examples—polyacetylene, polyphenylene, polythiophene, and polypyrrole (see figure)—were not very tractable, but considerable synthetic effort to add side-chain substituents has resulted in materials that are quite soluble in common organic solvents, and even (as with derivatives of polythiophene and polyaniline) in water. Thus, the materials engineer has at hand processes for casting thin conducting layers on a wide variety of substrates, or for blending the conducting polymer with structural polymers in films and fibers.

The resulting range of applications accounts for the majority of today's production of conducting polymers. Antistatic blends of conducting polyaniline or polypyrrole in textile fibers prevent the buildup of charge and the resultant damaging discharge. Camouflage fabrics can be treated to prevent radar reflection. A major manufacturer of photographic film coats the base layer with a transparent conductive layer of polyethylenedioxythiophene in order to make the sheet easier to handle during deposition of the optically active dyes, and to alleviate some of

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the safety concerns associated with sparks and solvent vapors. An area that has emerged in the last several years combines film casting processability with electrochemical properties to make coatings of conducting polymers that are found to limit the corrosion of ferrous metals. If these preliminary and unexpected laboratory findings can be translated to a viable technology, the potential market applications are enormous.

The conductivity, permeability, and electrochemical activity of conducting polymers leads to their use as chemical sensors, and their compatibility with other organic materials may extend this usefulness to biological sensors. This is an area of extensive current research and incipient commercialization ["electronic noses" (*7*)] and one where Lonergan's work may potentially have the greatest impact. His hybrid device, combining an organic semiconductor with an electrochemically dopable polymer, forms a Schottky barrier junction whose electrical characteristics are exquisitely sensitive to the doping level of the polymer and therefore to the presence of reactive analyte species in contact with it. The cleverly embedded gold grid provides a means for controlling the baseline dopant level and thus perhaps the specificity and sensitivity of response.

Other applications of conjugated polymers are in various stages of research or technology transfer: nerve replacement for muscle stimulation, electroluminescence for (very) flat panel displays, and seed layers for electroless plating on printed circuit boards. There are also examples, like the batteries cited earlier, that showed great initial promise but have fallen, at least for the time being, by the wayside: nonlinear optics for use in fiber-optic switches and routers; photorefractive polymers for optical computing and holographic data storage; *pn* junctions, formed by donor and acceptor doping to make diode rectifiers; and electrochromic displays. The jury is still out on field-effect transistors for use in inexpensive smart cards.

All these examples illustrate the lesson that is to be learned: The successful commercialization of conjugated polymers has come (and presumably will continue to come) in applications that exploit additional unique properties. The lesson can be equally well applied to any new material. There is no economic advantage to the simple displacement of an entrenched manufacturing base. Rather, it pays to remember: One cannot spin-coat a transparent layer of copper from aqueous solution onto acres of celluloid film; nor can one change the Fermi level of silicon by immersing it in a solution of oxidant.

References and Notes

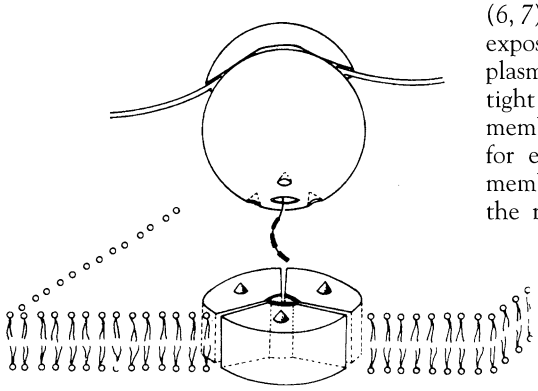
1. M. C. Lonergan, *Science* **278**, 2103 (1997).
2. T. Ito, H. Shirakawa, S. Ikeda, *J. Polym. Sci. Polym. Lett. Ed.* **12**, 11 (1974); C. K. Chiang *et al.*, *J. Chem. Phys.* **69**, 5098 (1978).
3. J. S. Miller, *Adv. Mater.* **5**, 587 (1993).
4. W. P. Su, J. R. Schrieffer, A. J. Heeger, *Phys. Rev. Lett.* **42**, 1698 (1979); *Phys. Rev. B* **22**, 2099 (1980).
5. For an extensive review of the field as it stood in the mid-1980s, see *Handbook of Conducting Polymers*, T. J. Skotheim, Ed. (Dekker, New York, 1986), vols. 1 and 2.
6. A. Dall'Olio, Y. Dascola, V. Varacca, V. Bocchi, *C. R. Acad. Sci. Ser. C* **267**, 433 (1968); A. F. Diaz, K. K. Kanazawa, G. P. Gardini, *J. Chem. Soc. Chem. Commun.* **1979**, 635 (1979).
7. H. V. Shurmer and J. W. Gardner, *Sens. Actuat. B* **8**, 1 (1992).

PROTEIN SYNTHESIS

A Ribosome at the End of the Tunnel

Ted Powers and Peter Walter

In all eukaryotic cells, proteins are sorted and delivered to final destinations inside and outside the cell. Those that are to be exported or inserted into membranes are first directed into a network of membrane tubes called the endoplasmic reticulum (ER). For many proteins, this process occurs early, while they are being created. In these cases the ribosomes together with their growing protein chains bind to pores in the ER membrane, forming the characteristic studded appearance of the rough ER seen under the electron microscope. The major constituent of the ER pore, or translocon, is the heterotrimeric Sec61 protein complex (*1*, *2*). The challenge at hand is to understand how the ribosome binds to the translocon and what happens during protein movement through the translocon and into the ER. On page 2123 in this issue, Beckmann *et al.* (*3*) rise to this challenge by describing the cryo–electron microscopic (EM) structure of the toroidal Sec61 complex bound to the ribosome.



Twenty-two years ahead of its time. "Hypothetical model for the formation of a transient tunnel through which the nascent chain would be transferred," as originally proposed by Blobel and Dobberstein (*4*, p. 848). [Reprinted from (*4*) with permission Rockefeller Press]

The idea that an aqueous, protein-conducting channel exists in the ER membrane was one of the original tenets of the signal hypothesis proposed in 1975 (see figure) (*4*) and has gained steady experimental support in recent years. Electrophysiological studies demonstrated that large ion-conducting channels appeared when ER-attached ribosomes were treated with puromycin, an antibiotic that causes release of nascent protein chains from the ribosome (*5*). Subsequent studies with fluorescence probes incorporated into the nascent chain showed directly that the translocating chain traverses the membrane through an aqueous environment (*6*, *7*). Moreover, the nascent chain was not exposed to small ions present in the cytoplasm, indicating that the ribosome forms a tight seal with the cytoplasmic face of the ER membrane. Now we know that sometimes—for example, during synthesis of integral membrane proteins—the tight seal between the ribosome and the membrane may be transiently broken to facilitate the lateral opening of the translocon. This brief opening would allow transmembrane segments of the protein access to the hydrophobic interior of the lipid bilayer, as well as provide entry for internal cytosolic domains into the cytosol during membrane protein integration (*8*). Thus, the ribosome-translocon interface must be both dynamic and tightly regulated.

In parallel studies, the components of the translocation pore have been identified (*9*). The basic translocon is astonishingly simple, composed principally of the heterotrimeric Sec61 complex. This complex is highly conserved; the Sec61α, Sec61β, and Sec61γ subunits from mammals are related to the yeast Sec61, Sbh1, and Sss1 proteins, respectively. Moreover, convincing homologs can be

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