# Biology and Materials?

## Part II

Mark Alper, Guest Editor

The October issue of the *MRS Bulletin* focused on two areas of research in biomolecular materials; biomineralization and protein fibers. In addition, the development of a new carbohydrate-based material with a variety of novel properties was discussed.

In this issue, we turn to two other types of materials based on biological systems: (1) polymers and other materials produced through enzyme-catalyzed biosynthetic reactions and (2) protein and lipid complexes based on biological membrane structures. In each case, as in the October issue, a discussion of how Nature produces and uses these materials is followed by reports describing manipulations of these systems to enhance their properties for nonbiological applications.

In the October issue, Kaplan and Cappello discussed in detail the synthesis of proteins. They described how living organisms expend a very large fraction of their energy producing these polymers to grow and repair damage to their bodies. (The other major fraction of their energy is dedicated to maintenance of brain function). Synthesis of carbohydrates, lipids, and other materials, however, is achieved through a somewhat more complex process. The organism outlines a pathway that consists of a sequence of reactions; each reaction converts a substrate—the product of the preceding reaction—to a product which is the substrate for the next reaction. The net result of the action of the pathway is the conversion of a nutrient to a useful material, often of far different chemical structure.

Each step of a pathway is catalyzed by an enzyme that is specific for its substrate and for the reaction. Enzyme catalysis proceeds at a rate up to 16 orders of magnitude greater than the uncatalyzed rate. Most enzymes are proteins and are produced through the protein synthesis machinery described by Kaplan last month. Each enzyme binds its particular substrate, chemically converts it to product, and releases it.

Doi describes a family of polyesters produced by bacteria. These are environmentally degradable thermoplastics with a wide range of potential applications. The bacteria carry three genes for the process, each gene coding for an enzyme involved in the three-step pathway converting a common metabolic intermediate (itself produced from sugar through a ten-step pathway) to the polymer. The genes have been cloned and studied in great detail.

Morrow discusses his work in using purified enzymes in reactions *outside* the organism to produce novel polymers. By virtue of the substrate and reaction specificity of the enzymes, their use allows the synthesis of optically active and therefore highly stereoregular polymers. Enzyme use outside the organism provides an increased level of control and flexibility of the reaction, but requires considerable work in designing appropriate reaction conditions.

Hilvert takes the system one step further. The specificity of enzymes is an advantage in that it rigorously controls the structure of the reaction product. It is, however, a disadvantage in limiting the flexibility of the system. One would like to use variants of the natural substrate to allow the enzyme to produce variants of the product. These would have novel structures and therefore novel properties. Enzymes that are highly specific for their substrate cannot recognize altered substrates and catalyze reactions converting them to altered products. Hilvert describes the genetic engineering technique of "site-directed mutagenesis," which allows the rational redesign of an enzyme to allow it to catalyze a reaction leading to a new product with new and, with luck, interesting properties. He goes on to discuss the newer techniques that allow the substitution of non-natural amino acids in the enzyme, providing greater flexibility in modifying its structure. Finally, he discusses the production of catalytic antibodies, proteins with enzyme activity that can be generated for catalysis of targeted reactions, whether they occur in nature or not.

Callstrom and Bednarski's article in the October issue is also relevant here. Once enzymes have been selected for use in materials synthesis, their inherent instability must be addressed. One application of the new carbohydrate-based polymer described in that article is its unique ability to stabilize enzymes at high temperature, in organic solvents, and in distilled water without buffer.

Membranes surround and contain virtually all biological structures. They self-assemble from lipid and protein substituents and form barriers between the surrounded structure and its environment. The lipid components form the thin film structure of the membrane in which the proteins are embedded. These proteins perform a variety of biological functions. After briefly discussing the features of naturally occurring membrane systems, Hampp et al. describe their efforts to use these materials in optoelectronic applications. They present work with bacteriorhodopsin (BR), a light-driven protein pump that moves and concentrates protons across the bacterial cell membrane. Using site-directed mutagenesis, the group has been able to modify the properties of BR and use it in holographic pattern recognition. They compare the effectiveness of this modified biological material to that of the more conventional liquid crystals and photorefractive crystals now in use.

Finally, Charych and Bednarski examine a variety of films whose structures mimic, to varying degrees, the self-assembling nature of biological membranes. By modifying the functional groups attached to the outer surface of these films, they are able to control surface properties and approach questions of tribology, including lubrication and adhesion, and also the development of a variety of sensors and coatings.

Although virtually all biological materials fall into one or another of the four major classes addressed in these two issues of the *Bulletin*, space limitations allowed us to focus on only a few of the types of materials in these classes. Not discussed, for example, are organisms that produce ferritin, an antiferromagnetic iron storage protein, or others that produce clusters of semiconducting materials, protein adhesives, or complex carbohydrate lubricants. Also not discussed are proteins such as myosin, kynesin, and

dynein which act as biomolecular motors, moving and positioning other molecules to their required locations in the cell. Further, a wide variety of molecules, including enzymes, act as "smart" materials, modulating their activity in response to a variety of external, environmental factors. They sense these factors individually, and respond on the basis of the weighted sum of the individual interactions.

**Acknowledgments**

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**Mark D. Alper**

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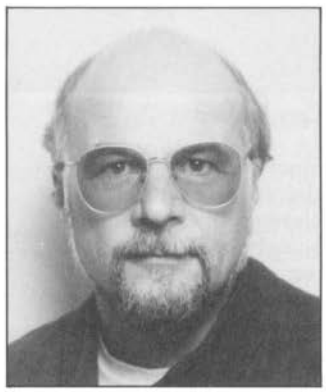

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**Mark D. Bednarski** is a professor in the Chemistry Department at the University of California–Berkeley, and a staff scientist at Lawrence Berkeley Laboratory. He received his PhD degree in chemistry at Yale University in 1987 and was a postdoctoral associate at Harvard University. Bednarski's research group is investigating the synthesis of biocompatible materials and the construction of cell-surface mimics in order to understand the process of biological adhesion. Bednarski has received the American Cancer Society Jr. Faculty Research Award, the National Institute of Health First Award, the Proctor and Gamble University Exploratory Research Program, the Chevron Research and Technology Award, and the Eli Lilly Young Investigator Award.

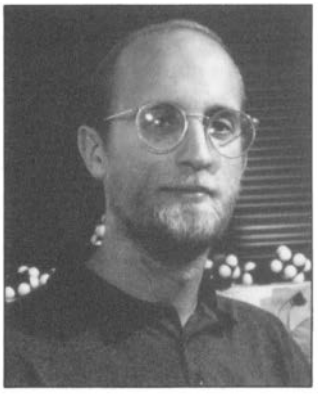
**Christoph Bräuchle** received his PhD degree in 1978 from the University of Munich, after studying chemistry and physics at the Technical University of Berlin and the University of Tubingen. He then spent a year as a postdoctoral worker with IBM Research Laboratory in San Jose, California, and finished his habilitation in 1982. Bräuchle joined the University of Munich in 1984 as an associate professor, and was made full professor in 1988. His research activities include laser spectroscopy and laser chemistry.

**Yoshiharu Doi**

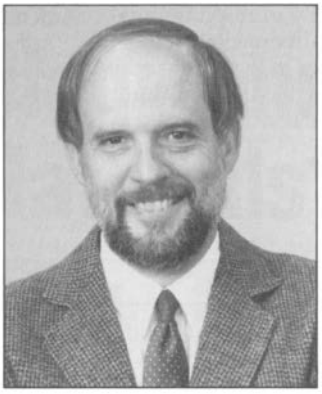
**Norbert Hampp**

**Deborah H. Charych** is a postdoctoral research fellow at the Center for Advanced Materials at Lawrence Berkeley Laboratory, where she is working on the development of polydiacetylene Langmuir-Blodgett films as biosensors, and on the tribological properties of ultrathin organic films. Charych received her BS degree in chemistry from Carnegie-Mellon University in 1986. She received her PhD degree from the University of California–Berkeley in 1992 under Marcin Majda, working on two-dimensional charge transport along organic monolayer films.

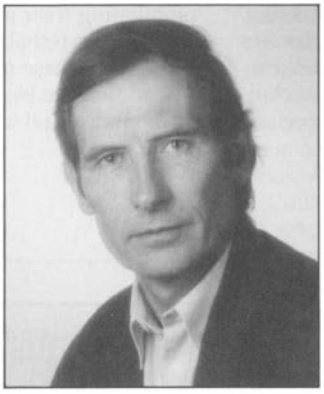
**Yoshiharu Doi,** head of the Polymer Chemistry Laboratory, RIKEN (The Institute of Physical and Chemical Research), Japan, obtained his doctoral degree in 1975 from the Tokyo Institute of Tech-



Donald Hilvert



Cary J. Morrow



Dieter Oesterhelt

nology, and was an associate professor at the Institute from 1984 to 1992. Doi has researched in the fields of both applied microbiology (biosynthesis and properties of microbial polyhydroxyalkanoates) and polymer chemistry (living coordination polymerization and block copolymer synthesis). He has published 160 papers, 50 review articles, and five books.

**Norbert Hampp** studied pharmacy and physics at the University of Munich and, in 1986, completed his PhD degree with M.H. Zenk on plant tissue cultivation and genetics. That year he received a postdoctoral BMFT grant for biosensor research. Since 1987, he has been at the University of Munich where his research activities focus on technical applications of bacteriorhodopsin and biosensor technology. Hampp belongs to several national and international scientific societies.

**Donald Hilvert** is an associate professor in the Departments of Chemistry and Molecular Biology at the Scripps Research Institute. He received his PhD degree in chemistry from Columbia University and was an NIH postdoctoral fellow at Rockefeller for two years before joining Scripps. Hilvert's research interests include the development, study, and optimization of novel biocatalysts, particularly semisynthetic enzymes and catalytic antibodies. His work has been honored by a number of awards, including a faculty research award from the American Cancer Society, an Alfred P. Sloan Fellowship, and a Cope Scholar Award from the American Chemical Society.

**Cary J. Morrow** is a professor of chemistry at the University of New Mexico (UNM) and current chairman of the Department of Chemistry. His research focuses on applying enzymes to problems in organic chemistry, preparing and analyzing stereochemically enriched materials, enabling enzymes to make polymers and to use polymers as substrates, and preparing, analyzing, and using optically active polymers. Morrow received his BS degree from Davidson College and his PhD degree from Tulane University. He was a postdoctoral research associate at the University of California–Berkeley for two years before joining the UNM faculty.

**Dieter Oesterhelt,** director of the Max-Planck-Institut of Biochemistry in Martinsried, Germany, and honorary professor of biochemistry at the University of Munich, pursues research in the bioenergetics and molecular biology of photoreceptors, membranes, and enzymes. Working under Feodor Lynen on the multi-enzyme complex of fatty acid synthetase (active centers, crystallization), Oesterhelt received his PhD in biochemistry from the University of Munich. During a sabbatical at the University of California, he discovered retinal in the purple membrane of halobacteria, after which the function of the retinal protein bacteriorhodopsin as a light-driven proton pump was postulated. Oesterhelt was also a professor of biochemistry at Wurzburg prior to joining the Max-Planck-Institut. □