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A Special Issue on Diatom Nanotechnology

Until only very recent times, diatomists and nanotechnologists could be said to constitute what C. P. Snow called "The Two Cultures".[1] Diatomists studied their unicellular organisms from a "classical" biological perspective in order to make sense of the daunting species diversity by tracing diatom genealogy over millions of years or by applying the results to dating and ecological characterization of deposits. On the other hand, the more recent development of synthetic nanotechnology has, to a large degree, been driven by the nearly insatiable global demand for ever smaller structures for electronic, optical, chemical, or biomedical devices (e.g., memory chips, tiny sensors, or—at the brink of science fantasy—nanorobots). It would have been logical to suppose that the phrase "ne'er the twain shall meet" would continue to apply to the apparently disparate research areas of diatom biology and synthetic nanotechnology.

When advanced imaging tools like scanning electron and transmission electron microscopes became available, diatomists were confronted with a structural complexity even more bewildering and awe-inspiring than had been revealed by the light microscope. In addition, the cellular engines driving the unique silicification process of these organisms—like the silica deposition vesicle—became accessible to investigation. To interpret the images, diatomists had to develop at least an intuitive feeling for engineered structures and become more familiar with concepts like shear or elastic moduli. At the same time, the spectacular images that began to appear in the diatom literature could not fail to draw the attention of a more technologically inclined fraternity of researchers. This was epitomized by a fairly hefty publication[2]—probably the first formal podium for both diatomists and "engineers"—which focused mainly on the architectural analogies between diatoms and man-made structures but also included a concise introduction[3] to the silica deposition process in diatoms.

New venues are needed in the present times to explore nonconventional interdisciplinary synergies between the fields of diatom biology and nanotechnology. The biannual North American Diatom Symposium has acquired a reputation for nonconventional approaches to diatom-related scientific and technical issues. Indeed, Evelyn Gaiser, the organizer of the recent NADS 2003 conference, embraced the embryonic idea of adding a workshop on Diatoms and Nanotechnology to the NADS 2003 portfolio. Proposals for contributions came in rapidly and the workshop agenda was quickly filled. The symposium, which was held October 22–26, 2003, was preceded by a bit of press activity[4,5] and an invited article.[6] Biological and nanotechnological sessions were deliberately alternated during the workshop to allow for intermixing of the two cultures. Contributors on both sides sat through each type of session so that lively interdisciplinary discussions could occur. While the success of such a cross-disciplinary workshop will ultimately be measured by the collaborations that are spawned, the realization that similar interdisciplinary discussions could be applied to a host of biomineralizing microorganisms other than diatoms has led to plans for a Symposium on Biomineralization for Nanotechnology.

In addition to a workshop setting and format, we had to confront the question of where to formally publish the diverse and interesting research presented by the contributors. The Two Cultures phenomenon was again encountered (e.g., the board of a more traditional, diatomist-oriented journal considered the subject too "far out" for coverage). We then reasoned that, while general diatomists may not be tinkerers by nature, sophisticated tinkerers like nanotechnologists would be enthralled with the potential for utilizing natural microorganisms to generate enormous numbers of nanoparticulate assemblies with intricate three-dimensional shapes and fine (meso-to-nanoscale) features. The Editor-in-Chief of the *Journal of Nanoscience & Nanotechnology (JNN)*, Dr. Hari Singh Nalwa, enthusiastically endorsed our proposal for this special issue as one that would be tutorial and horizon-widening for both diatomists and nanotechnologists, while providing an in-depth survey of diatom nanoscience. Thus, the Two Cultures that have come ever closer together in the past decade present some of their work here. We personally have become increasingly aware of the breadth of the field covered under the heading diatom nanotechnology. From the classic "diatomological" subjects like taxonomy and morphology via genetics and molecular research to mathematical modeling, structural analysis, and morphology-preserving chemical transformations, a great variety of disciplines are

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involved with exciting opportunities for cross-fertilization. Because of this diversity, we have tried to make the contributions accessible also to nonspecialists in the particular subject covered, with every paper reviewed by both diatomists and nanotechnologists. In our view, the central theme of diatom nanotechnology has quickly outgrown its original (and now unjustified) science fiction context and has emerged as a legitimate and growing field of scholarly research. The contributions to this special edition of *JNN* fall into the following general categories:

(1) Reviews of diatom microscopy, structure, and phylogeny
(a)"Comments on Recent Progress Towards Reconstructing the Diatom Phylogeny," by Alverson and Theriot (A review of the progress made to date in determining the phylogeny of diatoms is given.)
(b) "Crystal Palaces—Diatoms for Engineers," by Sterrenburg (A review of the historical parallels between microscopic imaging and evaluation of diatom frustule structure is given.)
(c) "A Guide to the Diatom Literature for Diatom Nanotechnologists," by Gordon et al. (A list of diatom-related literature, courses, collections, and other sources of information is supplied.)

(2) Morphological evolution during diatom frustule formation
(a) "Valve Morphogenesis in the Diatom Genus *Pleurosigma W. Smith* (Bacillariophyceae)—Nature's Alternative Sandwich," by Sterrenburg, Tiffany, and del Castillo (A description is given of the evolution of the nonloculate valve structure of the frustule of the diatom genus *Pleurosigma W. Smith*)
(b) "Nanostructures in Diatom Frustules: Functional Morphology of Calvocopulae in Cocconeidacean Monoraphid Taxa," by De Stefano and De Stefano (A review of the morphological characteristics and functional roles of nanostructures involved in the linkages between silica components in diatom frustules is given.)
(c) "Diatom Auxospore Scales and Early Stages in Diatom Frustule Morphogenesis: Their Potential for Use in Nanotechnology," by Tiffany (A description is given of the early-stage structural evolution of fine-scale diatom frustule components.)

(3) Application of advanced biological techniques to understand and control diatom frustule formation
(a) "The Prospects of Manipulating Diatom Silica Nanostructures," by Hildebrand (Genetic and non-genetic approaches that may ultimately be used to control the shapes and features of frustules generated by diatoms are described.)
(b) "Diatomics: Toward Diatom Functional Genomics," by Monsant et al. (The different techniques that may be used to evaluate gene and protein function in diatoms are discussed.)
(c) "Biosynthesis of Silicon-Germanium Oxide Nanocomposites by the Marine Diatom *Nitzschia frustulum*," by Rorrer et al. (A two-stage cultivation process is described for the incorporation of germanium into the diatom cell to yield nanostructured Ge–Si oxides.)
(d) "Approaches for Functional Characterization of Diatom Silicic Acid Transporters," by Thamatrakoln and Hildebrand (The current understanding of silicon transport in diatoms with a focus on silicic acid transporters is reviewed.)

(4) Simulations of diatom frustule morphology and morphological evolution
(a) "Nature's Batik: A Computer Evolution Model of Diatom Valve Morphogenesis," by Bentley, Cox, and Bentley (A computer simulation is presented that describes the structural evolution of diatom frustules.)
(b) "Geometry and Topology of Diatom Shape and Surface Morphogenesis. Potential Applications in Nanotechnology," by Pappas (Mathematical modeling is used to describe diatom frustule structures.)

(5) Novel uses of diatom-derived biomolecules or frustule templates or diatom-inspired chemical processing to generate new nanostructures or nanodevices
(a) "Ceramic Nanoparticle Assemblies with Tailored Shapes and Tailored Chemistries via Biosculpting and Shape-preserving Inorganic Conversion," by Dickerson et al. (Diatom-derived peptides are used to biosculpt synthetic silica nanoparticle structures that can then be converted into new chemistries while preserving the biosculpted shape.)
(b) "Zeolitisation of Diatoms," by Anderson et al. (Approaches are described for utilizing diatom frustules as templates for zeolitization processes.)
(c) "Controlled Silica Synthesis Inspired by Diatom Silicon Biomineralization," by Vrieling et al. (The syntheses of mesoporous silicas with micro-to-nanoscale features through the use of bio-analogous reactants and reaction conditions are described.)
(d) "A Comparison of Diatoms, Exfoliated Graphite, Single Wall Nanotubes, Multiwall Nanotubes, and Silica for the Synthesis of the Nanomagnet Mn_{12}," by Manning et al. (The use of diatom frustules and other templates for controlling the syntheses of magnetic nanostructures is described.)

(6) Analyses of the mechanical behavior of diatom frustules
(a) "The Evolution of Advanced Mechanical Defenses and Potential Technological Applications of Diatom Shells," by Hamm (Correlations between mechanical requirements, structure, and mechanical properties of diatom frustules are discussed.)
(b) "Investigation of Mechanical Properties of Diatom Frustules using Nanoindentation," by Subhash et al. (Nanoindentation tests are used

to evaluate the mechanical properties of diatom frustules.)

(c) "Frustules to Fragments, Diatoms to Dust: How Degradation of Microfossil Shape and Microstructures can Teach us How Ice Sheets Work," by Scherer et al. (Analyses of the mechanical degradation of diatom-rich sediments are used to better understand large-scale glacial processes.)

(d) "Diatom Bionanotribology—Biological Surfaces in Relative Motion: Their Design, Friction, Adhesion, Lubrication, and Wear," by Gebeshuber et al. (Comments and suggestions on issues in tribology as related to diatoms are presented.)

(7) Future interdisciplinary research

(a) "Potential Roles for Diatomists in Nanotechnology," by Gordon and Parkinson (Critical roles to be played by diatomists in the development of biological routes to nanostructures are discussed.)

(b) "Engineering and Medical Applications of Diatoms," by Wee et al. (Suggestions are provided for using diatom frustules in membranes, as magnetized structures, and as nanopowders.)

An interesting result of the workshop, apparent in the papers in this issue, is that diatom nanotechnologists are having to confront fundamental, outstanding problems of biology in order to get on with their work. The following are among the basic questions to be resolved: What are the relationships between the diatom genotype and the phenotype (i.e., can we bridge the gap between genome and morphogenesis) that would allow for control of 3D shape and pattern by genetic engineering? What are the limits for evolution of an organism; that is, how far can we push diatoms in our efforts to get them to make what we want? Thus, we may find that an industrial problem, driven by the desire to invent new things and cash in on them, may end up contributing directly and substantially to some basic problems in science.

We offer this special issue in the hope that it may find interest among diatomists and nanotechnologists both. Even for the general diatomist, the nanostructural aspects of the diatoms' shells may well be essential. For instance, in the search for reliable characters to be used in systematics and taxonomy, an engineering approach may shed light on whether particular structural aspects are of biotic—and thus genomic—origin or, rather, abiotic and determined by purely physical constraints. Or what morphological aspects can be interpreted from the engineering point of view as evolutionary structural advantages? On the other hand, engineers may become more aware of the fact that diatoms are not mere structural preforms but tiny specks of life subject to all the vagaries and pressures of nature. Different biological routes may originate in the same physicochemical laws, and, conversely, different physicochemical conditions can result in a single biological solution that copes with all.

As has become evident, diatoms are among the most diverse and spectacular nanostructure-generating organisms. Perhaps their nanotechnological applications will become comparably diverse in our lifetime!

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References and Notes

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ABOUT THE GUEST EDITORS

Richard Gordon did his B.Sc. at University of Chicago in Mathematics in 1963 and his Ph.D. at the University of Oregon in Chemical Physics in 1967 under the mentorship of Terrell L. Hill. His wide ranging career as a theoretical biologist has taken him from membrane transport to embryology, with contributions to the theory of evolution, the evolution of perception, and the use of condoms to prevent spread of the AIDS epidemic. He discovered the ART algorithm for computed tomography in electron microscopy, which led to a career in medical imaging and his position as Professor of Radiology at the University of Manitoba. Here he teaches graduate students in engineering, physics and computer science as they engage in research on the detection of early breast cancer, how embryos build themselves, and diatom motility and morphogenesis. He is also involved in rebuilding the libraries of Afghanistan.

After 40 years' consultancy to research centres and hi-tech industries in the fields of medical instrumentation, aviation, defense, power generation and environmental sciences, **Frithjof Sterrenburg** now has more time to devote to another life-long interest, the study of diatoms. He is a Research Associate of the National Natural History Museum in Leiden, The Netherlands.

Ken H. Sandhage (B.S. Metallurgy with Highest Distinction, Purdue University, 1981; Ph.D., Ceramics, Massachusetts Institute of Technology, 1987) is a Professor of Materials Science and Engineering at the Georgia Institute of Technology. Sandhage and his students have invented, developed, and patented several reaction-based processes for converting ceramic-bearing preforms into new compositions while preserving the shapes and fine features of such preforms (i.e., near net-shape processing). Recent work by the Sandhage group on the shape-preserving chemical conversion of bioclastic structures (e.g., diatom frustules) and biosculpted structures (e.g., interwoven silica fibers via collaboration with the Biotechnology Group at the Air Force Research Laboratory) opens the door to a wide variety of biologically mass-produced and chemically tailored 3-D micro-to-nanoscale structures for biomedical, optical, electronic, sensing, and other applications.