



# Potential Roles for Diatomists in Nanotechnology

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Diatoms produce diverse three-dimensional structures that, due to their exponential rate of growth, may be of use in the manufacture of components for nanotechnology as an alternative to present linear lithographic techniques. Vapor replacement of the silicon permits the conversion of diatom silica valves and other structures to metal/ceramics, with no loss of structure. The literature on diatom nanotechnology is reviewed, along with suggestions on how diatomists might enhance this emerging technology. There is a need for a systematics based catalog of parts (via genomics technologies), improved diatom culture techniques, better understanding of the mechanisms of diatom morphogenesis and motility, and genetic manipulation, mutagenesis, and selection, as via the chemostat-like compustat. Given the self-motility of raphid diatoms, they could form the basis for industrially useful nanobots.

**Keywords:** Diatom Nanotechnology, Silica, Careers in Science, Diatomist.

## 1. INTRODUCTION

In 1988, one of us (R.G.) was probably the world's only professor of botany and radiology and received an invitation to an IEEE (Institute of Electrical and Electronics Engineers) meeting in New Orleans. A two-page paper for the microscopic imaging session was presented, reporting on work on diatoms with a then recent postdoc in R.G.'s lab, Baltazar Aguda, but adding an engineer's slant. The following is the abstract from that paper:

"Diatom shells are intricate structures made by single algal cells with a spacing between parts of about 0.1  $\mu\text{m}$ . They appear to be formed by instabilities in diffusion-limited precipitation of amorphous, colloidal silica. The patterns are apparently modified by surface diffusion during their formation. They present a possible means of microfabrication of intricate structures."<sup>30</sup>

This was expanded 11 years later, when we addressed more specifically a nanotechnology audience,<sup>78</sup> a paper that has already been cited at least 10 times.<sup>11, 20, 36, 58, 59, 64, 73, 87, 88, 108</sup>

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One might wonder why people in nanotechnology would bother with diatoms, since they are made of silica, rather than elemental silicon, the staple of the electronics industry. We wondered too, and then a remarkable paper arrived by Kenneth H. Sandhage and his colleagues.<sup>87</sup> Inspired by Ref. [78], they added one major step: replacement of all the silicon atoms with magnesium atoms. This was done by placing diatom shells (*Aulacoseira* obtained from diatomaceous earth) in a magnesium gas at 900 °C for 4 h. The structure was preserved during this process, much like the (not necessarily slow<sup>13</sup>) process of fossilization. Here, the  $\text{SiO}_2$  was being replaced by MgO:

"...the silica could also be converted into a wide variety of other ceramics or ceramic/metal composites with desired electronic, optical, thermal, or chemical properties... it seems likely that future genetic engineering could yield frustules with tailored, non-natural shapes and features."<sup>78, 87</sup>

An advantage of diatoms is that they allow direct fabrication of three-dimensional structures, instead of the layer by layer manipulation common in present day nanotechnology, which is based primarily on the lithographic methods used to make microelectronics.<sup>65</sup> Furthermore,

diatoms reproduce and so can outperform any factory production method via exponential growth of their numbers.<sup>87</sup> Diatom parts could also be used as molds.<sup>4</sup> The diatom valve is flexible, without being brittle,<sup>7</sup> and it will be interesting to measure its strength, in silica and substituted materials, using micromanipulation techniques,<sup>38, 39, 42, 83</sup> or to calculate it, which would be a challenge to finite element methods.<sup>18</sup> The manipulation of diatom valves, either via changes in their architecture or the degree of silicification (which has been found to vary in nature within a single species) has the potential to radically alter these structural properties. The degree of versatility in design and composition coupled with our ability to perform such manipulations may allow the study of diatoms to take center stage in nanotechnology and biotechnology. Below are listed just a few of the many opportunities for diatomists to apply their skills:

1. Nanotechnologists need a catalog of parts that diatoms make that might be useful and which species of diatoms make them. Parts include pores of many shapes, costae, raphes, whole valves, girdle bands, strutted processes, rimoportulae, labiate processes, setae, spines, hollow spines, etc. Some parts come prefit together, such as marginal spines in certain colonial diatoms.
2. Culture of diatoms with interesting parts may have to be standardized and scaled up. In particular, we may have to learn how to prevent diatom malformations, common in culture,<sup>19</sup> from occurring (except when they are exactly what we want).
3. Quantitative control of silicification, by making silica the limiting nutrient,<sup>24</sup> gives us a degree of control of the morphogenetic process.
4. Inclusions of salt crystals<sup>32</sup> and manipulation (or poisoning, as with germanium or aluminum<sup>100</sup>) of the physicochemical conditions in the silicalemma should also provide altered valve geometries.<sup>101</sup>
5. Since the molecular biology of diatoms (reviewed in Ref. [20]) is now well under way,<sup>47, 86</sup> including genetic transformation,<sup>3, 16, 21, 106</sup> we may find means of genetically manipulating diatoms to produce silica parts with desired characteristics.
6. Further control of the morphogenetic process may be achieved by imposing evolutionary selection via devices such as the proposed compustat,<sup>26</sup> a visual analog of the chemostat in which culling or not is based on visual match to a desired shape or pattern,<sup>15</sup> or via selection by physical forces.<sup>31</sup> Such manipulation, especially with variations produced by mutagenesis,<sup>97</sup> has the potential to create diatoms capable of making novel parts. This idea has been debated<sup>9</sup> but not yet tested.
7. Silica starvation synchrony<sup>75</sup> could be used to mass produce parts whose silicification is stopped early, such as nascent valves not yet released from their silicalemmae. For example, pennate diatoms form transient combs<sup>89</sup> of possible use in comb drives.<sup>105</sup>
8. Auxospores<sup>37, 98</sup> and resting spores<sup>76</sup> may provide unique diatom parts, and we need to master how to bring on these life cycle stages and diatom sex for recombination.<sup>20</sup>
9. Separation techniques such as flow cytometry<sup>68</sup> need to be developed for the isolation and purification of specific diatom parts.<sup>5, 22, 35, 85</sup>
10. Given that many diatoms decrease in size through succeeding generations,<sup>55, 81, 82</sup> we may have to either focus on those few species that somehow avoid this or sort diatoms or components by size, which might also be achieved by flow cytometry.
11. Diatom paleontologists<sup>95</sup> may be able to extend the parts list and challenge us to recover lost morphogenetic capabilities by selective breeding and mutagenesis of extant species for “throwbacks”.
12. Much may be learned by the further analysis of just how diatoms create silica structures, i.e., how to bridge the gap from the genome to morphogenesis.<sup>14, 70</sup> This field has advanced from simple precipitation models (albeit with instabilities in diffusion limited precipitation)<sup>34, 90, 91</sup> to the role of the cytoskeleton,<sup>77</sup> to the molecular analysis of silica transport and “prepatterned” organic molecules,<sup>6, 23, 46, 48, 57–62, 67, 72, 84, 93, 103, 107</sup> whose place in the overall spatiotemporal morphogenesis of diatom valves and other parts is far from understood.<sup>99</sup> These molecules are already in use to produce holograms.<sup>6</sup>
13. The optical properties of diatom shells have yet to be explored, except for speculations that the valve and spines form an antenna for visible light (Ryan W. Drum, personal communication) (but cf. Ref. [96]). With metal/ceramic substitutions<sup>87</sup> the refractive index would change, altering optical characteristics. Perhaps diatom shells and parts could become components in optical computing.<sup>54</sup> The remarkable regularity of striation in some genera makes the valves act as small diffraction gratings.<sup>94</sup> This idea was also raised in an apparently unsuccessful grant application (reviewed a decade ago by R.G.) but is certainly worth pursuing.
14. Diatom adhesion to surfaces is strong, a major factor in biofouling.<sup>51</sup> These glues,<sup>43</sup> deposited by us, or diatoms directed by us to specific locations, might prove useful in bonding nanotechnology components.
15. With the advent of low-cost, high throughput DNA sequencing, it may now be time to launch a diatom genome project focused on diatom nanotechnology objectives. Selection of appropriate diatoms should be based on morphological and phylogenetic<sup>56</sup> criteria and, due to cost, may depend to some extent on genome size.<sup>20</sup> In addition, expressed sequence

tag technology,<sup>1</sup> which has been successfully applied to the study of many groups of organisms including nematodes<sup>79</sup> and protists,<sup>63</sup> offers a low cost alternative to full genome sequencing, allowing the surveying of expressed genes from a larger number of different diatoms (cf. Ref. [70]).

16. The application of diatoms to nanotechnology provides an opportunity for rationally choosing a model organism or two, rather than locking in on someone's favorite beast, which may be evolutionarily specialized (as happened with *Drosophila*, *Xenopus*, and zebrafish). One diatom, the morphologically simple *Thalassiosira pseudonana*, has been sequenced at the US Department of Energy's Joint Genome Institute in California.<sup>44, 45, 92</sup>
17. If diatoms are to be used for microencapsulation of drugs,<sup>87</sup> then we have to worry about biocompatibility or silicosis,<sup>40, 50</sup> unless we first convert diatoms to other materials<sup>87</sup> or coat them with immunocompatible materials.
18. If we succeed in morphologically and/or genetically modifying diatoms, given that they are at the bottom of many food chains or webs, attention will have to be paid to the accidental release of altered diatoms into the environment.<sup>53</sup> The ubiquity of some species presents the possibility of worldwide impact, which we should evaluate before it happens. This is part of the general problem of the ethics of nanotechnology.<sup>69</sup> Could diatoms become "the specter of self-replicating nanobots gone amok"?<sup>2</sup>

Finally, motile diatoms can lift 1000× their own weight<sup>33, 42</sup> via a still puzzling raphe motility mechanism<sup>14</sup> that appears to be over 99% energy efficient.<sup>25</sup> Some diatoms move for a while and then adhere tightly to surfaces.<sup>102</sup> If we understood their chemotactic,<sup>10</sup> phototactic,<sup>74</sup> and adhesion<sup>104</sup> behavior better, we might be able to get diatoms to move into specified positions, say on micropatterned substrates,<sup>8</sup> and then in place convert them into organized arrays of nanotechnology components. Considering that some colonies of unlinked diatoms form tubes,<sup>12, 80</sup> a form of emergent behavior,<sup>17, 28, 49, 52, 71</sup> self-assembly of larger arrays or structures from many diatoms, might be possible.

Some engineers are trying to grow computers the way embryos grow.<sup>29, 66</sup> Diatoms give us a handle on morphogenesis at the finer, subcellular level (cf. Refs. [27] and [41]). There is much work ahead, but there is no reason that diatomists could not take the lead, teaming up with the engineers who are trying to grow nanotechnology.

We are preparing an article for *Trends in Biotechnology* reviewing developments in diatom nanotechnology since the 17th NADS meeting October, 2003, which will include discussion of the first DNA sequencing of a diatom.<sup>109</sup>

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## References and Notes

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