Center for Responsible Nanotechnology

## SCENARIO #6: A Goal Postponed

The middle of the first decade of the millennium saw a slow shift toward acceptance of molecular manufacturing. Not only its proponents, but unaffiliated scientists as well, began to acknowledge that the idea of molecular machines building molecular machines might be worth pursuing. The supporters of the approach began to draw a cautious breath of relief. By 2007, at least one group (the Nanofactory Collaboration) was working toward atom-by-atom fabrication of diamond, a company with a history of successful lab research (Zyvex) was working toward atomically precise silicon shapes, and DNA technology was making great strides forward.

Few observers close to the field expected molecular manufacturing to be a victim of its own success. In hindsight, the irony was inescapable and almost predictable: each partial success and modest step forward siphoned off more and more interest from the ultimate goal of exponential nanoscale manufacturing using molecular tools.

It started with Zyvex LLC's announcement in 2011 that their Atomically Precise Manufacturing project had succeeded in building two-dimensional structures on a silicon surface with every atom exactly where it was planned to be. This was rightly seen as a major accomplishment: in precision and throughput, it went well beyond the 1994 laboratory demonstrations of the Aono group. Furthermore, Zyvex announced that three-dimensional structures, perhaps including layers of diverse materials, were in the works. Several spinoff technologies, including biomedical sensors and fast electronic circuits, were quickly pursued.

As early as 2006, the Rothemund technique of building DNA structures with small, easily-synthesized "staples" of DNA had succeeded in creating two-dimensional shapes that a high school student could design and construct. By 2012, advances in measurement and theory had led to reliable design rules for building three-dimensional shapes, and new techniques of post-assembly "locking" had enabled multi-level synthesis. Advances in a variety of nanoscale imaging and positioning techniques had led to systems that could literally pick up DNA structures and stick them together in any desired pattern. The maximum size of precision structures had broken the 1-micron barrier in 2011, the 10-micron barrier in 2013, and the 100-micron barrier -- large enough to see with the naked eye -- in 2017, though the larger structures were rather repetitive. By this time, Zyvex was building structures 100 microns square by 10 microns high, and starting to experiment with sacrificial materials to make free-standing kinematic structures (NEMS).

A complete survey of nanoscale fabrication technologies developed by 2018 would fill many pages. Suffice it to say that static structures containing billions of precisely-placed atoms were now almost commonplace. Sensors (including bio/med devices), electronics, photonics, plasmonics, and a variety of other practical fields were accelerated even faster than anyone had expected in 2005. Work on multi-physics simulation to deal with these structures had largely been successful by 2015, and by 2020 there was serious talk of pan-physics simulation: being able to predict any desired property or behavior of billion-atom structures.

In the midst of all this, the original goal of building fabrication systems at the nanoscale fell by the wayside. As early as 2007, officials at the U.S. National Nanotechnology Initiative (NNI) had started to quietly redefine the term "molecular nanotechnology" away from molecular manufacturing to mean simply building intricate molecular structures. By 2009, the redefinition had largely been successful; science writers commonly referred to Rothemund's work, for example, as molecular nanotechnology. Meanwhile, the NNI started on "molecular manufacturing" as well, and by 2011 that term had been associated with several then-current techniques including Zyvex's Atomically Precise Manufacturing. (Neither Zyvex nor Rothemund encouraged this, but they didn't have to.)

Although, by 2015, most scientists would acknowledge that molecular machines would someday build molecules -- indeed, Nadrian Seeman had built a DNA-building machine out of DNA in 2003 -- they typically would follow this with a comment to the effect that this was an uninteresting goal, since machines costing as little as $10,000 could build billion-atom structures in a week, and the price/performance was expected to continue to improve by a factor of four each year. At this rate, milligram structures costing as little as $1000 were expected as early as 2022.

Meanwhile, the Nanofactory Collaboration was making technical progress, but failing to gain mindshare. By 2012, they had managed to add carbon atoms to diamond with precise positioning. Microscopes precise enough to do this with high reliability became available around 2015. Despite this progress, funding did not appear, and it was not until 2018 that the first small chunk of diamond was built. In a vicious cycle, each delay reduced interest and funding, and lack of funding caused delays. By 2020, Collaboration participants had not yet achieved 1000-atom diamond shapes. Although, by this time, detailed recipes existed for building million-atom machines, and the Collaboration claimed that a few million dollars would build a diamond-based nanofactory in five years, broader opinion still held that it would take more than a decade and be relatively uninteresting, and the required funding was never forthcoming.

Several successful techniques for large-scale manufacturing of extremely large molecular structures had been firmly established in academia and industry by 2020, and fully one-third of all nanotechnologists were engaged in developing new uses for the structures. This was seen as a great success for molecular manufacturing. The leading-edge work was still done in the United States, with other nations struggling to gain their share of patentable applications. Thus, the focus worldwide was on these new "molecular manufacturing" techniques, and it was widely agreed that "molecular nanotechnology" was a great success after all.

In 2022, representatives of the Nanofactory Collaboration announced that new theoretical breakthroughs combined with ever more powerful tools had finally produced a complete blueprint for a system that would be capable of molecular manufacturing, in Drexler's original sense of the term. Just a few more years of privately funded work, they said, and the world would finally see genuine molecular manufacturing, not at $1000 per milligram, but $100 per kilogram -- cost-competitive with established large-scale manufacturing techniques such as metallurgy and nanotube composites. Most importantly, this would be *general-purpose* molecular manufacturing, far more powerful than existing techniques, and capable of extremely rapid, almost unbounded improvement. A few observers resurrected old fears of economic or geopolitical meltdown; the majority simply took an attitude of, "We've heard it all before, and we'll believe it when we see it."

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