Caitlin Fellows
PH 382U
Intro Nanoscience and Nanotech
Fall 2022
Prof. Peter Moeck
Drexler vs Smalley Debate Final Essay

Before I read the C&EN article covering the debate between Drexler and Smalley I had already decided Drexler's concept of a molecular assembler wasn't scientifically sound. When I watched the example video of a desktop assembler (Lizard Fire Studios, 2006) I immediately noticed that there were structures shown that were depicted as smaller than atoms.

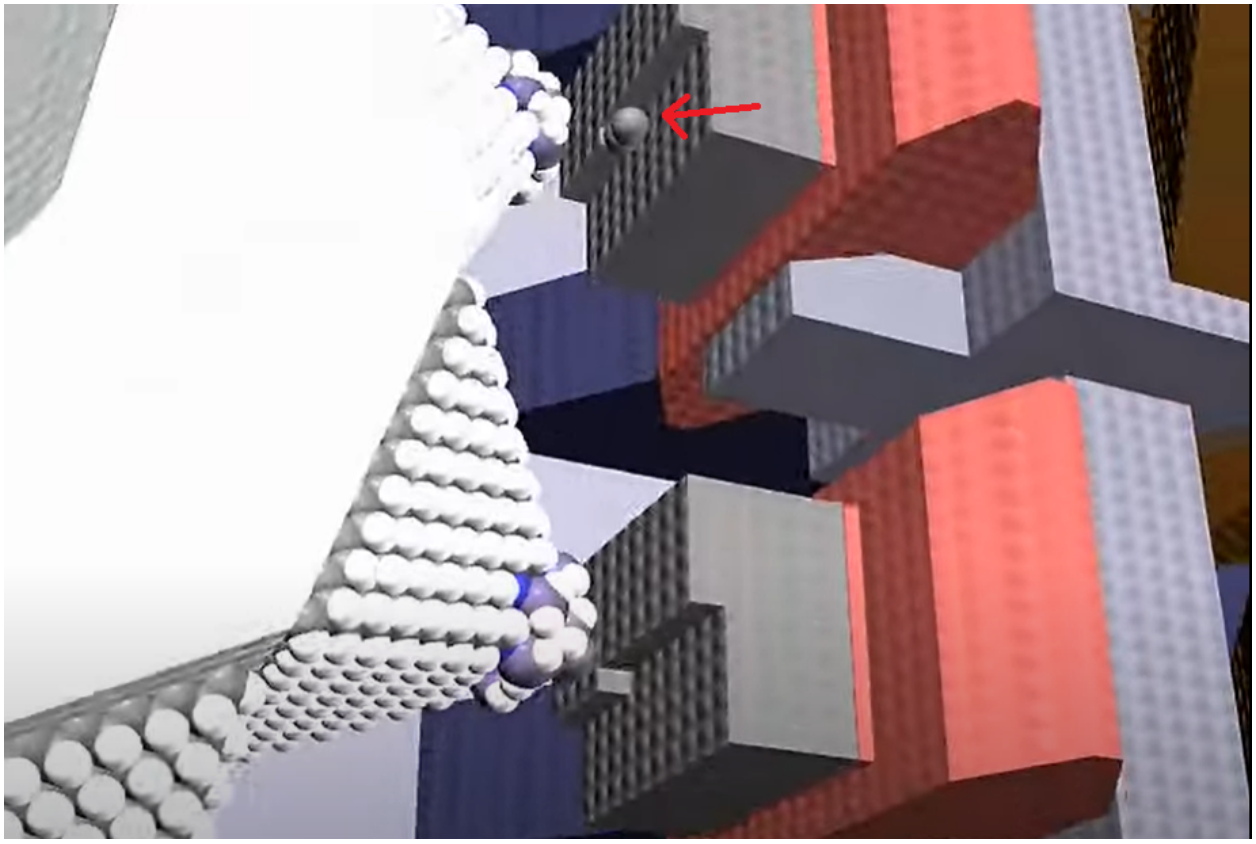

Figure 1. Nanofactory Animation (Lizard Fire Studios, 2006)

If the red arrow indicates two carbon atoms, then what on earth is the gray block it's being placed on?! It's clearly a structure with units that are smaller than an atom, and it has flat edges. How? What matter exists that is smaller than an atom? Yes, there are quarks, but quarks aren't used as mortar to fill in areas between atoms! Why go through the effort of rendering the molecular arms showing individual atoms, but not render the building blocks too? This lack of attention to detail shows that Drexler doesn't fully see the whole system as atomic in nature, but instead thinks of it more as a miniature factory. Also, all the atoms would be jittering around from thermal energy. They would fly off into the open space shown around the conveyor belt. If you wanted to keep a molecule on a "belt" then the belt would need to be a tunnel so that the

molecule wouldn't jostle away. One example in biology is an aquaporin, which is narrow and selective enough that only water is able to pass through, single file.

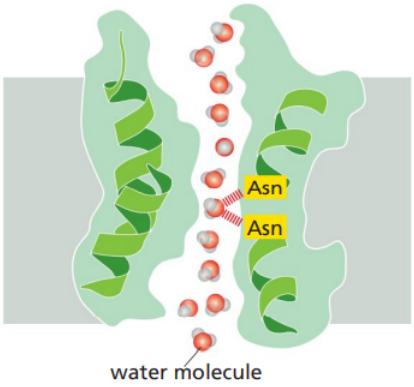

Figure 2. Aquaporin (Alberts et. al., 2015)

Next the article by Baum. He tried to depict both Drexler and Smalley as respectable scientists, listing their educations and credentials. However, saying Drexler received a PhD from MIT vastly oversimplifies the facts and is misleading. According to Drexler's wiki entry he was rejected by both the electrical engineering and computer science departments at MIT and was instead taken in by the MIT Media Lab, which is described as a research laboratory that grew out of MIT's School of Architecture (K. Eric Drexler, Wikipedia). The Media Lab's research is "not restricted to fixed academic disciplines, but draws from technology, media, science, art, and design" (MIT Media Lab, Wikipedia). Having a PhD from an unrelated architecture and design school doesn't confer the same level of prestige as a PhD from MIT's physics (or chemistry) department. Not to say that a PhD from an architecture school is completely invalid, if Drexler had received a PhD in designing public buildings, then that would be legitimate, but receiving a PhD not related to that department's scope is ridiculous. Baum implying that Drexler had a legitimate PhD is deceptive, and creates a false comparison between Smalley and Drexler. A college degree isn't required to be an expert in a certain field, but it can still be a pretty good indicator of someone's basic understanding of a subject.

Drexler starts his open letter by bragging about being the first to use the term nanotechnology, which I find pathetic and shows how self-important he is. Comparing his work to pre-sputnik and pre-Manhattan project work further reinforces how self-important he is. He believes Smalley is misrepresenting molecular manufacturing when referring to the assembler's "fingers", which is just the structure that moves the atoms from place to place, presumably with weak atomic forces that can easily be broken or denatured. As we saw from the video presented in class there are clearly arms or "fingers" that hold and move the cargo atoms about. However, that video was made in 2006 and this article was written in 2003. Giving Drexler the benefit of the doubt I tried to find more information. Sadly the producer Fire Lizard Studios no longer exists and John Burch, the other creator, doesn't come up when googled, though another website does reference him (Nanotech-now.com). Looking into Nanorex doesn't yield much either, just an old website from 2011 with 3D models of atoms arranged to look like gears.

I pivoted to find clues in the open letter Smalley originally wrote in Scientific American (2001). In Smalley's article "Of Chemistry, Love, and Nanobots" he points out the problem of

“fat” and “sticky” fingers. He accuses Drexler of stoking fear in the C&EN article yet he does it himself in the 2001 article. He even talks about gray goo. Why bring up topics that you don’t want in public discourse, and don’t even believe in. The only reason would be to sensationalize your article, which from a writing perspective is probably a good idea, but from a scientific perspective is deceptive and frankly unnecessary. Perhaps he just wanted to get a good review of his article. Another thing Smalley said was “suppose that each nanobot consisted of a billion atoms,” but if something consisted of a billion atoms then it wouldn’t be nano sized! Nanotechnology is defined as 1-100 nm, so if the average size of an atom is 0.1 nm then “nanotech” would be limited to 10-1000 atoms. A billion atoms would be roughly 1 mm in size! That’s the size of a gnat and I don’t think anyone would consider gnat-sized robots as nanobots. However, this only accounts for if the atoms were lined up end to end. Suppose the nanobot was a sphere, even then you could only have 3141 atoms and still be within the perimeters of nanotechnology. A billion atoms is extraordinarily large in biological terms. By comparison the largest human protein Titin is only 539,000 atoms and is ~1 μm (Wikipedia). It is unlikely that any structure could contain a billion atoms and remain smaller than 100 nm. The only possible example would be DNA in its densest form, a chromosome, but at that stage it is no more than compact data storage and isn’t functional.

I also want to comment on how Smalley is concerned about the public image of nanotechnology. People worrying about nanobots possibly taking over the world, or at the very least dramatically changing it, is a common belief of what nanotechnology is capable of, and anyone outside of a physics or chemistry career would have no reason to doubt that it’s plausible. This is dangerous. I myself read Michael Crichton’s Prey when it came out in 2002 and was enchanted with the idea of what nanotechnology could accomplish. I was in highschool at the time and these public views of nanotechnology significantly shaped my life and career decisions. I also read Radial Evolution by Joel Garreau. I was 17 at the time and I’m ashamed to say that I was a bright-eyed, naive teenager and I decided that a career in nano-biotechnolgy was what I wanted to do. I wanted to accomplish the impossible and push the limits of science. I wanted to make little robots that could target diseased cells and administer drugs exclusively where needed. I wanted to be a genetic engineer. I wanted to splice together DNA to achieve the unimaginable. I wanted to exploit the principles of biology to subvert death and disease. I wanted to find out how far life could be transformed.

I went to Stevens Institute of Technology for biomedical engineering. Despite my dreams of being a mad scientist that made the impossible possible, the reality was that the curriculum was just mundane mechanical engineering. To my dismay there weren't any biology classes either. I looked instead to see what nanotech classes were available, but the only ones offered were a few graduate-only level classes and they focused exclusively on carbon nanotubes and their production. Where were the nanobiotech classes? Did they not exist? How could an entire field of study just not exist?! Did I just plan my whole life on a fallacy? After 2 years I couldn’t take it anymore. I left college in 2008 due to severe depression. I was lost and without a purpose for many years after that. I couldn’t bear that I would never accomplish the dream I had envisioned. I still feel a deep loss from this, and have regretted my decisions for the past decade. I wish that science fiction hadn’t been labeled as science future, and that I might have made significantly different decisions based on that knowledge. Perhaps I could have studied Biology instead and pursued a career in research.

I was thrilled to learn about the nano biomarkers during the first couple of classes. Seeing real life applications of biology on a nano-scale renewed my hope that I could still accomplish my dreams. For the first time ever, I felt excited about a class. It was difficult to contain my tears while on zoom. And even though I lack extensive physics and chemistry knowledge, I still found all of the science fascinating and exciting. Thank you from the bottom of my heart. Knowing that there are possibilities still out there is encouraging.

But all of this is a very long tangent away from finding evidence of what Drexler believes and if his machines have “fingers”. In his 1991 paper “Molecular directions in nanotechnology” he discusses moving atoms around with atomic force microscopes. His molecular tip array would be reversed from normal, so the substrate is on the cantilever and the tip is on the flat surface. A normal setup is shown in Figure 3, and Drexler’s reversed setup is in Figure 4.

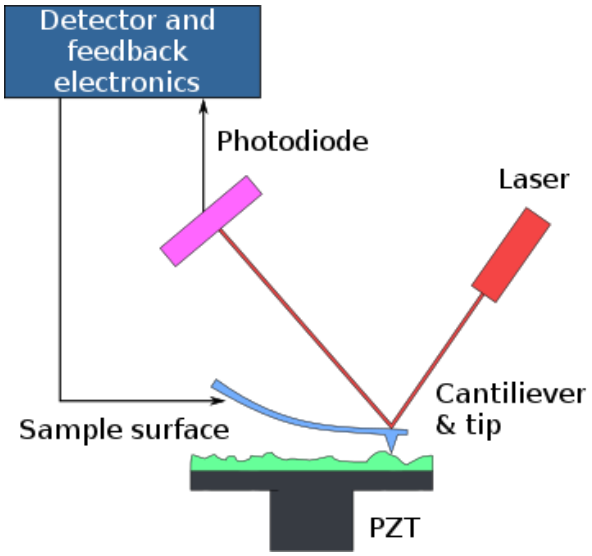

Figure 3. Normal AFM Setup (Wikipedia, 2022)

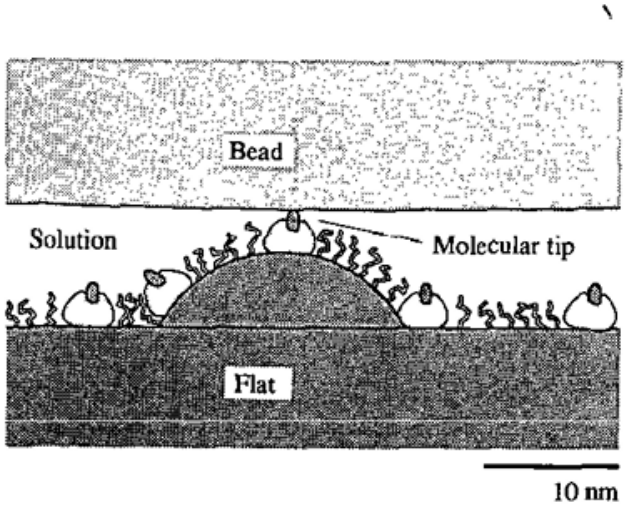

Figure 4. Reversed Setup (Drexler, 1991)

I fail to see how reversing the orientations of the surfaces changes the function of the microscope. The cantilever would still bob up and down as it’s pulled across the surface,

deflecting the laser beam at different angles. He could be implying that the simple act of squishing the bead against the molecular tip is enough to bond atoms, but that seems ridiculous. I didn't feel that this publication was descriptive, or logical enough to follow. Instead I tried to find his publication, "Nanosystems: Molecular Machinery Manufacturing and Computation". The book wasn't available digitally from the library and I'm not going to give money to Drexler to buy the book on Amazon. Thankfully MIT keeps records of their students' doctoral thesis, and Drexler's was essentially the first version of his book.

His thesis is almost 500 pages so suffice it to say I skimmed to find the relevant parts. He explained how positioning mechanisms are "familiar in the engineering of industrial robots," and that he thought "with the availability of nanometer-scale digital logic systems, motors, gears, bearings, and so forth, similar designs are feasible" (Drexler, doctoral thesis p. 445). Figure 5 shows how he planned to bring reactive moieties together using belts.

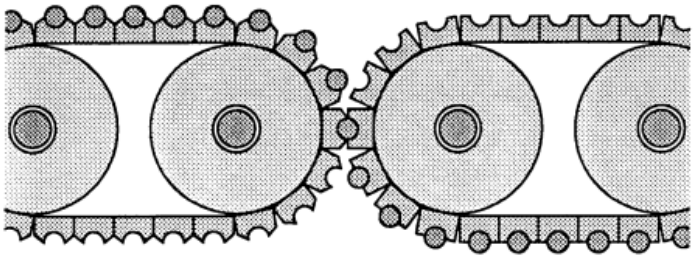

Figure 5. Reactive moieties brought together, aligned, and compressed (p. 442)

He suggested using molecular tips arrays, but did at least recognize that a possible problem would be maintaining positional accuracy when thermal energy was present. He proposed three solutions: the use of rigid structures or "a stiff arm design," alignment of tools immediately before application, or operating at reduced temperatures (p. 445). Figure 6 shows the array used with AFM.

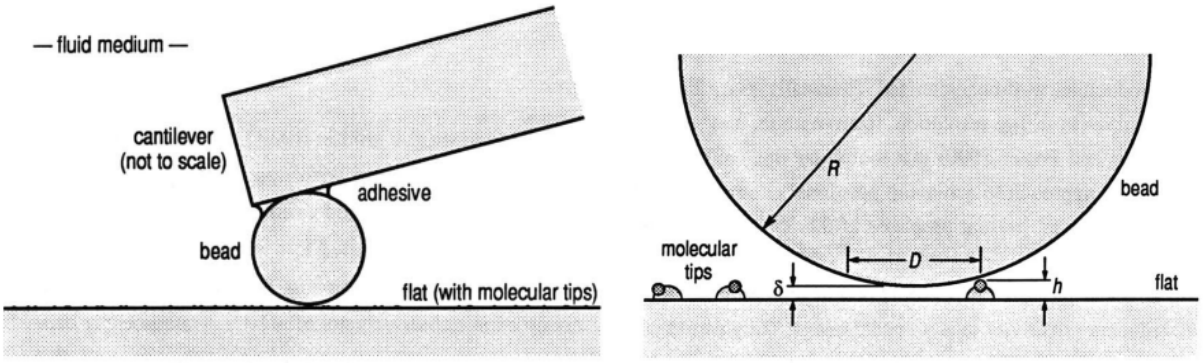

Figure 6 Molecular tip array using an atomic force microscope

He also proposed the use of ligands and proteins for the tips due to their structural strength. Again I fail to see him explain how compounds would be built from this procedure. He talks about protein binding, but proteins and ligands binding and unbinding doesn't build structures. It seems like he lays out the beginning pieces that are based in science, but fails to

explain that jump to assembly. He discusses imaging, but again imaging is not building structures. He seems to dance around the topic of moving and compiling atoms, but never actually explains anything. I will admit that there were no diagrams of moving arms as are shown in the assembler video. So quite possibly he genuinely thinks that his design lacks “fat” or “sticky” fingers. Arguably the molecular tips would be sticky fingers though.

My search for what Drexler believes was vague and inconclusive, so I turned back to the C&EN debate article. Drexler brags that he has 20 years of publishing within the nanoscience field. However this doesn’t automatically mean he is knowledgeable, it just means he’s good at writing. I could write 20 years worth of my dreams, but that doesn’t make me an expert in the psychology of dreams, just simply an expert in being convincing for 20 years. Drexler states that he has always pursued to “guide the chemical synthesis of complex structures by mechanically positioning reactive molecules, not by manipulating individual atoms” (Baum, 2003). Based on what I gathered from his doctoral thesis the molecular tips were to be ligands, not individual atoms so perhaps this is what he is referring to. He believes that as long as two reactive moieties are close to each other then they will react, which is true of enzyme/ligand interactions, however not all compounds are reactive with one another just based on proximity.

Concerning the future of nanotechnology and the fear of reducing the world to gray goo or having nanobots take over, any technological advancement can be used maliciously, that is not unique to nanotechnology, but warning of impossible futures is negligent. It’s fine that Drexler expects some oversight of research, that is warranted, but screaming to the heavens that the world is ending is unproductive.

Smalley points out that he is glad that Drexler doesn’t believe in moving individual atoms with molecular fingers. I think it’s amazing that Drexler was even able to admit this. I think Smalley starts off his argument well, speaking in straightforward concepts, and trying to find common ground with Drexler. But then Smalley takes a hard turn into more accusatory language concerning the specifics of enzyme chemistry and production. I think this just upsets Drexler and puts him on the defensive. Smalley hammers away with questions, and then finishes his letter with a sarcastic remark.

Clearly Drexler took offense because he immediately goes back to points he’s already made instead of addressing Smalley’s questions. It’s almost as if Smalley led him up the cliff of belief and right as Drexler was at the precipice, looking down at the truth, he vehemently reversed course and disengaged. Instead of facing the truth and changing his mind, which implies that he was wrong to begin with, he derails the conversation. Drexler is clearly hypersensitive to criticism and doubt from others, so he becomes avoidant and effectively withdraws from the debate.

Smalley makes a good point in his reply letter that the chemistry to build a molecular assembler simply can’t be achieved by “mushing two molecular objects together” and that to manipulate a molecule you would need a molecular chaperone (Baum, 2003). This is precisely how proteins are made and shaped in the endoplasmic reticulum! Chaperones help guide proteins as they are created and can either aid in folding or keep a protein unfolded, depending on what type of chaperone it is. The positional control Drexler is looking for is already done in biology!

All in all I’d say Smalley won the debate just based on scientific facts. Though to truly win a debate he would have had to convince Drexler of his ideas, so in this way he lost. If he had

remained encouraging and plied Drexler with more flattery (which was clearly effective), perhaps he could have tricked Drexler into finally agreeing with him. You catch more flies with honey than vinegar. If Smalley had better people skills then maybe he could have finally ended this debate over nanotechnology.

Works Cited:

Alberts, B., Johnson, A., Lewis, J., Morgan, D., Raff, M., Roberts, K. & Walter, P. (2015) *Molecular Biology of the Cell.* Garland Science. ISBN 978-0-8153-4464-3

Atomic force microscopy. (2022, December). In *Wikipedia*. https://en.wikipedia.org/wiki/Atomic_force_microscopy

Baum, R. (2003, December 1). *Drexler and Smalley make the case for and against 'molecular assemblers'*. Chemical & Engineering News: Cover story - nanotechnology. Vol.81 (48), p.37-42, https://doi-org.proxy.lib.pdx.edu/10.1021/cen-v081n048.p037

Drexler, K. E. (1991). Molecular Machinery and Manufacturing with Applications to Computation [Doctoral dissertation]. Massachusetts Institute of Technology.

Fire Lizard Studios. [Sidewinder77]. (2006, July 30). *Nanofactory Animation* [Video]. YouTube. https://www.youtube.com/watch?v=zqyZ9bFl_qg&t=8s&ab_channel=Sidewinder77

John Burch search result: https://www.nanotech-now.com/Art_Gallery/John-Burch.htm

K. Eric Drexler. (2022, December). In *Wikipedia*. https://en.wikipedia.org/wiki/K._Eric_Drexler

MIT Media Lab. (2022, December). In *Wikipedia*. https://en.wikipedia.org/wiki/MIT_Media_Lab

Nanorex search result: https://chem.beloit.edu/classes/nanotech/nanorex/index.html

Smalley, Richard E. (2001, September). *Of Chemistry, Love and Nanobots.* Scientific American, vol. 285, no. 3, pp. 76–77, https://doi.org/10.1038/scientificamerican0901-76.