THE EARLY HISTORY OF NANOTECHNOLOGY*

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Based on The Early History of Nanotechnology\footnote*{by Devon Fanfair, Salil Desai, and Christopher Kelty, which was developed as part of a Rice University Class called Nanotechnology: Content and Context.} by

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1 Introduction

Nanotechnology is an essentially modern scientific field that is constantly evolving as commercial and academic interest continues to increase and as new research is presented to the scientific community. The field's simplest roots can be traced, albeit arguably, to 1959 but its primary development occurred in both the eighties and the early nineties. In addition to specific scientific achievements such as the invention of the STM, this early history is most importantly reflected in the initial vision of molecular manufacturing as it is outlined in three important works. Overall, an understanding of development and the criticism of this vision is integral for comprehending the realities and potential of nanotechnology today.

2 Richard Feynman: there's plenty of room at the bottom

"But I am not afraid to consider the final question as to whether, ultimately—in the great future—we can arrange the atoms the way we want; the very atoms, all the way down!" -Richard Feynman, There's Plenty of Room at the Bottom

The first time the idea of nanotechnology was introduced was in 1959, when Richard Feynman (Figure 1), a physicist at Caltech, gave a talk entitled There's Plenty of Room at the Bottom. Though he never explicitly mentioned "nanotechnology," Feynman suggested that it will eventually be possible to precisely manipulate...
atoms and molecules. Moreover, in an even more radical proposition, he thought that, in principle, it was possible to create "nano-scale" machines, through a cascade of billions of factories. According to the physicist, these factories would be progressively smaller scaled versions of machine hands and tools. He proposed that these tiny "machine shops" would then eventually be able to create billions of tinier factories. In these speculations, he also suggested that there are various factors, which uniquely affect the nano-scale level. Specifically, he suggested that as the scale got smaller and smaller, gravity would become more negligible, while both van der Waals attraction and surface tension would become very important. In the end, Feynman's talk has been viewed as the first academic talk that dealt with a main tenet of nanotechnology, the direct manipulation of individual atoms (molecular manufacturing).

Figure 1: American physicist Richard Feynman (1918 - 1988).

Hence, long before STMs and atomic force microscopes were invented Feynman proposed these revolutionary ideas to his peers. As demonstrated in his quote (above), he chose to deal with a "final question" that wasn't fully realized till the eighties and nineties. Ultimately then, it was during these two decades, when the term "nanotechnology" was coined and researchers, starting with Eric Drexler, built up this field from the foundation that Feynman constructed in 1959. However, some such as Chris Toumey minimize the importance of Feynman in the establishment of the intellectual groundwork for nanotechnology. Instead, using evidence from its citation history, Toumey sees There's Plenty of Room at the Bottom as a "founding myth" that served only to directly influence Drexler rather than the other important scientists, who affected the future development of nanotechnology. Nevertheless, though the ultimate effect of Feynman's talk is debatable, it is certain that this work directly influenced Drexler's own research, which thus indirectly influenced nanotechnology as a whole.

3 Eric Drexler: molecular manufacturing

"The revolutionary Feynman vision launched the global nanotechnology race."-Eric Drexler

In 1979, Eric Drexler (Figure 2) encountered Feynman's talk on atomic manipulation and "nano-factories." The Caltech physicist's ideas inspired Drexler to put these concepts into motion by expanding Feynman's
vision of molecular manufacturing with contemporary developments in understanding protein function. From this moment, Drexler’s primary goal was to build upon the physicist’s revolutionary foundation. As a result, though the term was yet to be coined, the field of nanotechnology was created.

Figure 2: American engineer Kim Eric Drexler (1955- ).

In 1981, Drexler published his first article on the subject in the prestigious scientific journal, Proceedings of the National Academy of Sciences. Titled "Molecular engineering: An approach to the development of general capabilities for molecular manipulation," Drexler’s publication essentially expanded the idea of molecular manufacturing by integrating modern scientific ideas with Feynman’s concepts. Hence, he established his own vision of molecular manufacturing in this paper. Specifically, in his abstract, he discusses the possibility of molecular manufacturing as a process of fabricating objects with specific atomic specifications using designed protein molecules. He suggests that this would inevitably lead to the design of molecular machinery that would be able to position reactive groups with atomic precision. Thus, Drexler states that molecular manufacturing and the construction of "nano-machines" is a product of an analogous relationship "between features of natural macromolecules and components of existing machines." In addition, Drexler includes a table that outlines by function the molecular equivalents to macroscopic technologies. For example, he believed that bearings, which provide support for moving parts, are analogous to Sigma bonds. Overall, generating some interest in the scientific community, this publication presented Drexler’s initial vision of molecular manufacturing, which was ultimately influenced by Feynman’s talk. As a result, the field of nanotechnology continued to evolve, for Drexler took these concepts and expanded their potential in an accessible format through his now infamous book, Engines of Creation: The Coming Era of Nanotechnology (Figure 3).
4 Eric Drexler: engines of creation

"Molecular Assemblers will bring a revolution without parallel since the development of ribosomes, the primitive assemblers in the cell. The resulting nanotechnology can help life spread beyond Earth - a step without parallel since life spread beyond the seas; it can let our minds renew and remake our bodies - a step without any parallel at all." - Eric Drexler in *Engines of Creation*

In this book, Drexler is credited as being the first person to use the word nanotechnology to describe engineering on the billionth of a meter scale. Though the term was used by Norio Taniguchi in 1974, Taniguchi’s use of the word referred to nanotechnology in a different context. Published in 1986, *Engines of Creation* served to present Drexler’s vision of molecular manufacturing that he outlined in his 1981 paper. Essentially, Drexler presented, albeit simplistically, that if atoms are viewed as small marbles, then molecules are a tight collection of these marbles that "snap" together, depending on their chemical properties. When snapped together in the right way, these molecules could represent normal-scaled tools such as motors and gears. Drexler suggested that these "atomic" tools and machines would operate just as their larger counterparts do. The moving parts of the nano-machine (e.g., Figure 4) would be formed by many atoms that are held together by their own atomic bonds. Ultimately, in *Engines of Creation*, Drexler envisioned that these would then be used as "assemblers" that could put together atoms into a desired shape. Applying this simplistic vision of molecular manufacturing, Drexler, in theory, presented that coal can be turned into diamond and computer chips can be created from sand. These processes would occur by using these fabricated atomic tools to reorganize the atoms that make up these materials. Most importantly, from these principles, he sensationaly proclaimed in his book that nanotechnology, through the molecular manufacturing of "universal assemblers," would revolutionize everything from biological science to space travel (see quote above). Thus, with both his 1981 publication and his 1986 book, Drexler presented nanotechnology as a scientific field that solely revolved around his own expanded vision of Feynman’s molecular manufacturing.
In addition, *Engines of Creation* also cautions about the possible dangers that accompany this kind of technology. Primarily, Drexler warns of the "gray goo," an amalgamation of self-replicating nanobots that would consume everything in the universe in order to survive (see Figure 5).

![Figure 5: From Howard Lovy's Nanobot blog: http://nanobot.blogspot.com/](http://cnx.org/content/m35280/1.1/)
there is no question that Drexler's work had a profound impact on the establishment of nanotechnology as a scientific field.

5 The Aftermath of Engines of Creation: Impact and Criticism

Directly after the publication of this book, Drexler founded the Foresight Institute, whose stated goal is to "ensure the beneficial implementation of nanotechnology." Drexler used this "institute" as a way to present his vision of molecular manufacturing that he vividly illustrated in Engines of Creation. Thus, this "institute" was used to further propagate research, through his influential yet highly controversial depiction of nanotechnology and its future.

As a result, due to the publicity generated by both Drexler's work and institute, scientists from all over the world began to have a vested interest in the field of nanotechnology. Rice University chemist, Richard Smalley (Figure 6), for example, specifically said that he was a "fan of Eric" and that Engines of Creation influenced him to pursue nanotechnology. Moreover, he even gave Drexler's book to the top decision-makers at Rice University. Though criticizing Drexler and his work in future years, Smalley, like other scientists, were intrigued by this book and proceeded to do research in this new and evolving field.

Figure 6: American chemist Richard E. Smalley (1943-2005), was awarded the Nobel Prize in Chemistry in 1996 for the discovery of a new form of carbon, buckminsterfullerene ("Buckyball").

Drexler’s vision of molecular manufacturing and assemblers has become, on one hand, a scientific goal, through the Foresight Institute, and, on the other, a controversial issue. Some scientists have criticized Drexler’s visions as impossible and harmful. Richard Smalley has led this movement against Drexler’s almost sensationalist vision of molecular manufacturing. In their open debate in 2003, Smalley writes almost scathingly, "you cannot make precise chemistry occur as desired between two molecular objects with simple mechanical motion along a few degrees of freedom in the assembler-fixed frame of reference." Furthermore, he also chastises Drexler for his "gray goo scenario" saying, "you and the people around you have scared our children—while our future in the real world will be challenging and there are real risks, there will be no such
monster as the self-replicating mechanical nanobot of your dreams." In contrast to Drexler’s radical vision, Smalley realistically argued that nanotechnology could be used on a much more practical and attainable level. As a result, due to the onset of academic criticism from scientists such as Richard Smalley, nanotechnology evolved from Drexler’s vision of molecular manufacturing to a broad field that encompassed both practical manufacturing and non-manufacturing activities. Chemistry, materials science, and molecular engineering were now all included in this science.

6 Important successes in nanotechnology

In addition to the criticism of Drexler’s vision of molecular manufacturing, three important developments that were independent of Drexler’s paper helped turn nanotechnology into this broad field, today. First, the scanning tunneling microscope (STM) was invented by Binnig and Rohrer in 1981 (Figure 7). With this technology, individual atoms could be clearly identified for the first time. Despite its limitations (only conducting materials), this breakthrough was essential for the development of the field of nanotechnology because what had been previously concepts were now within view and testable. Some of these limitations in microscopy were eliminated through the 1986 invention of the atomic force microscope (AFM) (Figure 8). Using contact to create an image, this microscope could image non-conducting materials such as organic molecules. This invention was integral for the study of carbon Buckyball (Figure 9), discovered at Rice University. Ultimately, with these two achievements, nanotechnology could develop through the scientific method rather than through the conceptual and thus untestable visions of Drexler.

Figure 7: 1981-Invention of STM, Image From Steven Sieben, <http://sibener-group.uchicago.edu/facilities.html>.
Figure 8: 1986-Invention of AFM, image from Mike Tiner, <http://www.cnm.utexas.edu/AFM.HTM>.

Figure 9: 1985-Buckyball discovered at Rice University. Image from Stephen Bond, <http://femto.cs.uiuc.edu/~sbond/reports/c60c60qm1/buckyball.jpg>. 
This overall trend created by advancements in microscopy is illustrated through Don Eigler's revolutionary "stunt" at IBM. Here, he manipulated individual Xenon atoms on a Nickel surface to form the letters "IBM" (Figure 10). With the microscopy technology that was invented in the early to mid-eighties, Eigler and his research team advanced the field of nanotechnology by seeking to simply manipulate atoms. Thus, while Drexler was conceiving sensationalized possibilities of "universal assemblers," Eigler focused his nanotech research on the realistic and attainable level that Smalley presented in his argument with Drexler. From this "stunt," nanotech research followed Eigler's path and therefore strayed away from Drexler's original vision. Because nanotechnology was viewed at this level, the field soon encompassed both practical manufacturing and non-manufacturing activities as Drexler's ideas were put aside.


7 Conclusion

While nanotechnology came into existence through Feynman's and then Drexler's vision of molecular manufacturing, the field has evolved in the 21st century to largely include research in chemistry and materials science as well as molecular engineering. As evidenced by Smalley's debate, this evolution is partly a response to the criticism of Drexler's views in both Engines of Creation and the Foresight Institute. Thus, in regards to the development of nanotechnology in the present, Drexler's vision can be viewed as an indirect influence through the sheer interest and subsequent criticism that he created in the field. As Toumey argues, Drexler and therefore Feynman did not have a direct role in the three most important breakthroughs in nanotechnology, the invention of the STM, the invention of the AFM, and the first manipulation of atoms. Instead, Drexler, through Molecular Manufacturing and Engines of Creation, brought scientists from all over the world to the brand new field. Consequently, criticism for Drexler's vision was established by researchers such as Dr. Smalley. Through this reevaluation and the parallel breakthroughs in microscope technology, nanotechnology as a scientific field was established in a way that diverged from Drexler's original vision of molecular manufacturing. This divergence is illustrated through the contrasting goals of the government's National Nanotechnology Initiative and Drexler's Foresight Institute. As a result, a thorough grasp of this early history is integral to understanding the development and definition of both the realities and potential of nanotechnology, today. Whereas Drexler created interest in the field but also sensationally outlined a nanotech revolution, researchers around the world have brought the nanotechnology that Drexler first envisioned to a more realistic and attainable level. All in all, today, the goal for nanotech research is not to
immediately create billions of assemblers that will revolutionize our world but rather to explore the manufacturing and non-manufacturing aspects of nanotechnology, through a combination of chemistry, materials science, and molecular engineering. Though places such as Drexler’s Foresight Institute remain, academic institutions such as Rice University stay away from Drexler’s sensationalized vision of nanotechnology as molecular manufacturing. This divergence is epitomized by the contrasting goals of the U.S government’s National Nanotechnology Initiative and the Foresight Institute.

8 Bibliography