Chapter 1

History of Nanotechnology

1.1 The Early History of Nanotechnology[1]

NOTE: This module was derived from the module *The Early History of Nanotechnology* by Devon Fanfair, Salil Desai, and Christopher Kelty, which was developed as part of a Rice University Class called Nanotechnology: Content and Context.

1.1.1 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.

1.1.2 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 1.1), 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).

[1] This content is available online at <http://cnx.org/content/m35280/1.1/>.

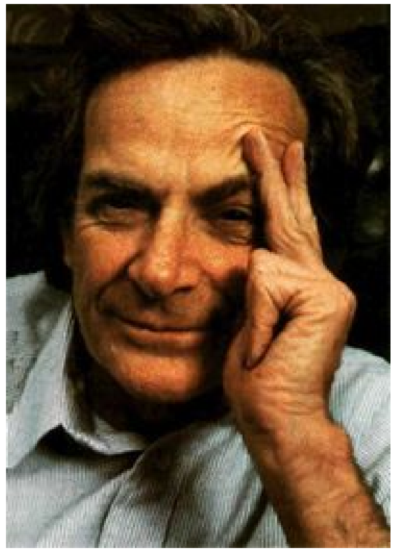

Figure 1.1: American physicist Richard Feynman (1918 - 1988).

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.

1.1.3 Eric Drexler: molecular manufacturing

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

In 1979, Eric Drexler (Figure 1.2) encountered Feynman's talk on atomic manipulation and "nanofactories." 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 1.2: 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 1.3).

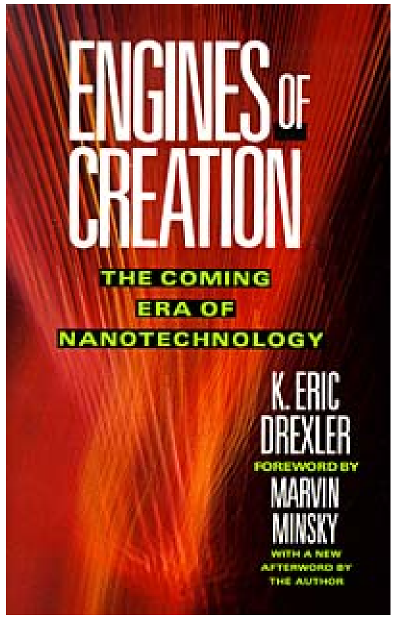

Figure 1.3: The cover of Eric Drexler's book *Engines of Creation: The Coming Era of Nanotechnology*.

1.1.4 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 1.4) 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 sensationally 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.

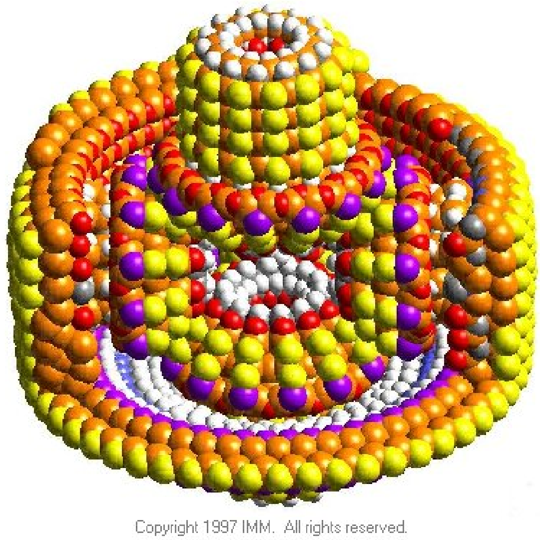

Figure 1.4: Drexler's "differential gear".

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 1.5).

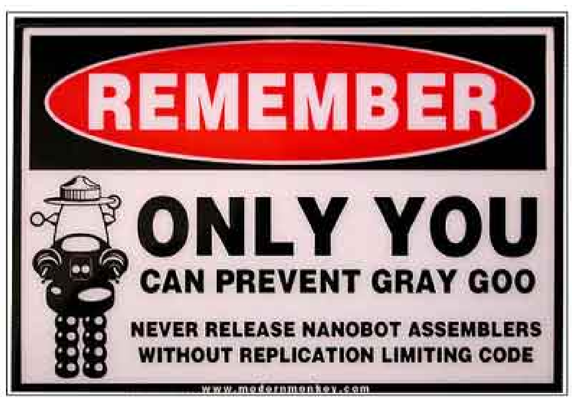

Figure 1.5: From Howard Lovy's Nanobot blog: http://nanobot.blogspot.com/

This book was highly influential as it brought nanotechnology to the mainstream scientific community for the first time. Though his theories of "gray goo" and molecular manufacturing were later criticized, there is no question that Drexler's work had a profound impact on the establishment of nanotechnology as a scientific field.

1.1.5 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 1.6), 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.

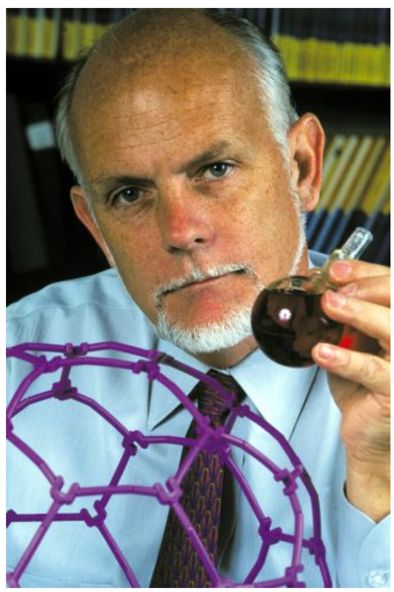

Figure 1.6: American chemist Richard E. Smalley (1943-2005), was awarded the Nobel Prize in Chemistry in 1996 for the discovery of a new form of carbon, buckminsterfullerene ("Buckyball").

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.

1.1.6 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 1.7). 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 1.8). 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 1.9), 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.

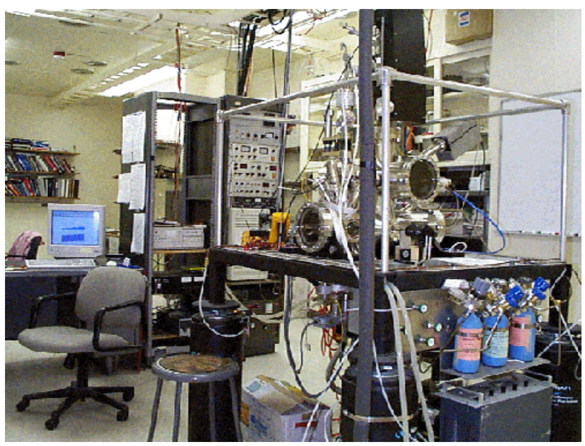

Figure 1.7: 1981-Invention of STM, Image From Steven Sibener, <http://sibener-group.uchicago.edu/facilities.html>.

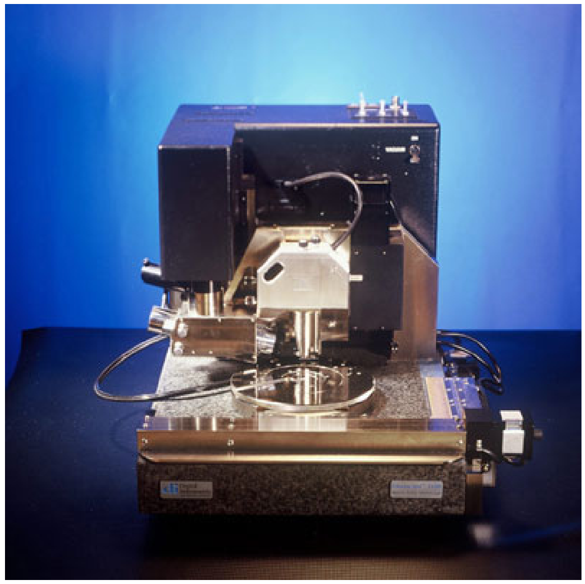

Figure 1.8: 1986-Invention of AFM, image from Mike Tiner, <http://www.cnm.utexas.edu/AFM.HTM>.

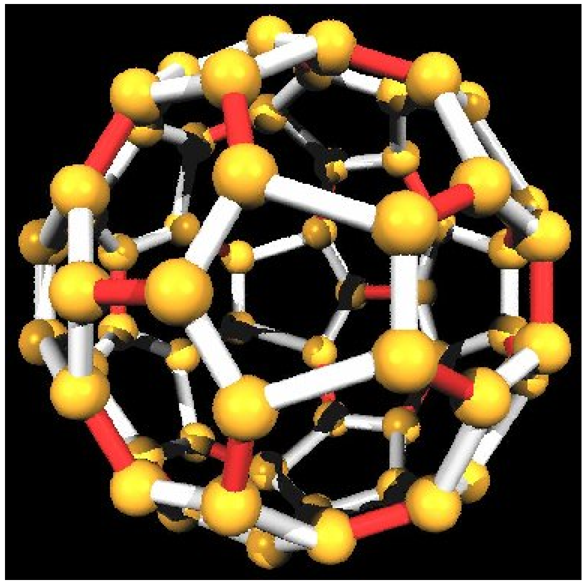

Figure 1.9: 1985-Buckyball discovered at Rice University. Image from Stephen Bond, <http://femto.cs.uiuc.edu/~sbond/reports/c60c60qm1/buckyball.jpg>.

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 1.10). 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.

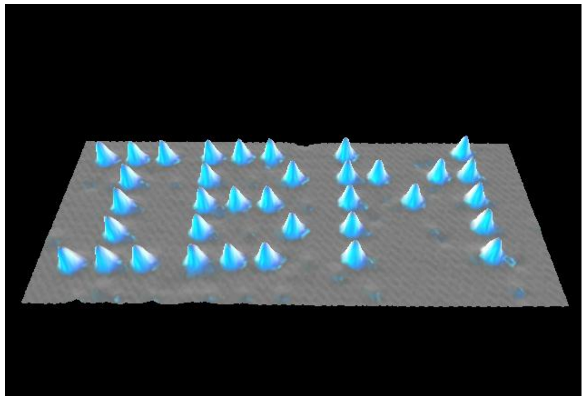

Figure 1.10: 1989-First atomic manipulation at IBM by Don Eigler. <http://www.almaden.ibm.com/vis/stm/atomo.html>.

1.1.7 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.17Though 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.

1.1.8 Bibliography

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- J. C. Miller, R. Serrato, J. M. Represas-Cardenas, and G. Kundahl, *The Handbook of Nanotechnology: Business, Policy, and Interllectual Property Law*, Wiley, NJ (2005).

1.2 Buckyballs: Their history and discovery[2]

NOTE: This module was developed as part of a Rice University Class called "Nanotechnology: Content and Context[3] " initially funded by the National Science Foundation under Grant No. EEC-0407237. It was conceived, researched, written and edited by students in the Fall 2005 version of the class, and reviewed by participating professors.

“This year’s Nobel Prize in Chemistry has implications for all the natural sciences. The seeds of the discovery were sowed by a desire to understand the behavior of carbon in red giant stars and interstellar gas clouds. The discovery of fullerenes has expanded our knowledge and changed our thinking in chemistry and physics. It has given us new hypotheses on the occurrence of carbon in the universe. It has also led us to discover small quantities of fullerenes in geological formations. Fullerenes are probably present in much larger amounts on earth than previously believed. It has been shown that most sooty flames contain small quantities of fullerenes. Think of this the next time you light a candle!”

-From the presentation speech for the Nobel Prize in Chemistry, 1996

1.2.1 Introduction

In 1996, the Royal Swedish Academy of Sciences awarded the Nobel Prize in Chemistry, the most prestigious award in the world for chemists, to Richard Smalley, Robert Curl, and Harold Kroto for their discovery of fullerenes. They discovered fullerenes (also called buckyballs) in 1985, but the special properties of the buckyballs took a few years to prove and categorize. Although by 1996 no practical applications of buckyballs had been produced, scientists appreciated the direction this discovery based in organic chemistry had led scientific research, as well as its specific contributions to various other fields. The accidental discovery of fullerenes also emphasizes the benefits and unexpected results which can arise when scientists with different backgrounds and research aims collaborate in the laboratory.

1.2.2 What are Buckyballs?

Before going into detail about the actual buckyball, we should discuss the element that makes its structure possible, carbon. Carbon is the sixth element on the periodic table, and has been found to be at least a partial constituent in over 90 per cent of all chemicals known to man. Indeed, its electron-bonding properties grant it a versatility specific to carbon, allowing it to be so widely functionalized, and more importantly, the reason for life on Earth. Anything that is living is necessarily chemically based on Carbon atoms, and for this reason, substances containing carbon are called organic compounds, and the study of them is called organic chemistry.

Though carbon is involved in chemistry with all sorts of other elements and compounds, it can also exist in pure carbon states such as graphite and diamond. Graphite and diamond are two different allotropes of carbon. An allotrope is a specific physical arrangement of atoms of an element. So although diamond and graphite are both pure carbon, because the crystalline structure of each is significantly different, their chemical and physical properties (as well as value) are very different.

[2]This content is available online at <http://cnx.org/content/m14355/1.1/>.
[3]http://frazer.rice.edu/nanotech

Above: diamond Below: carbon. Notice how the structure of the two allotropes vary, even though they are both made of the same carbon atoms (black)

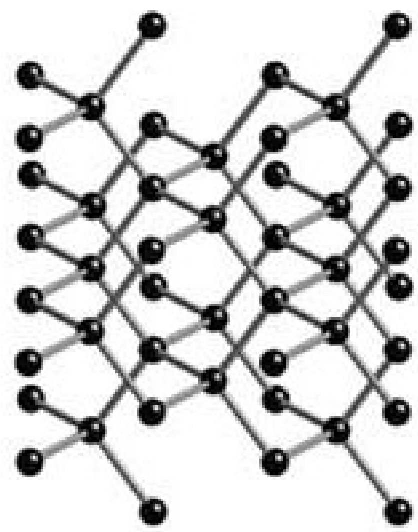

Figure 1.11: Images from The Austrailian Academy of Science[4]

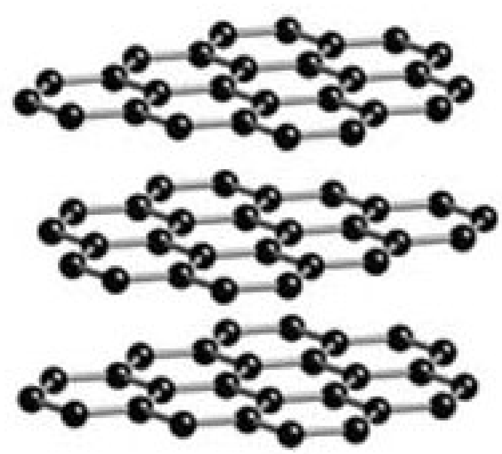

Figure 1.12

Diamond and graphite are not the only known allotropes pf carbon, chaoit and carbon(VI), discovered in 1968 and 1972, respectively, have also been found. Even more recently, the Buckminsterfullerenes, the subject of this module, were discovered at Rice by Smalley, Kroto,and Curl. Buckminsterfullerenes is actually a class of allotropes

[4] http://www.science.org.au/nova/024/024print.htm

Above: C540 Below: C60 Both of these are different allotropes of carbon. C60 is the most common and the most popularized of the Buckminsterfullerenes. Not shown is the second most common Buckyball, C70[5]
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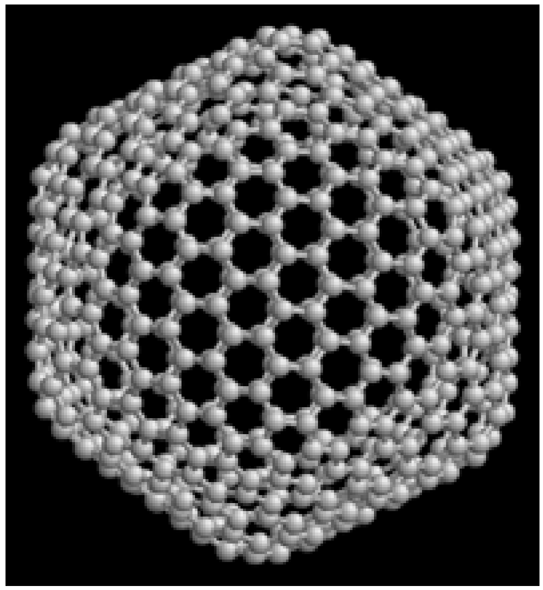

Figure 1.13: The Icosahedral Fullerene C540

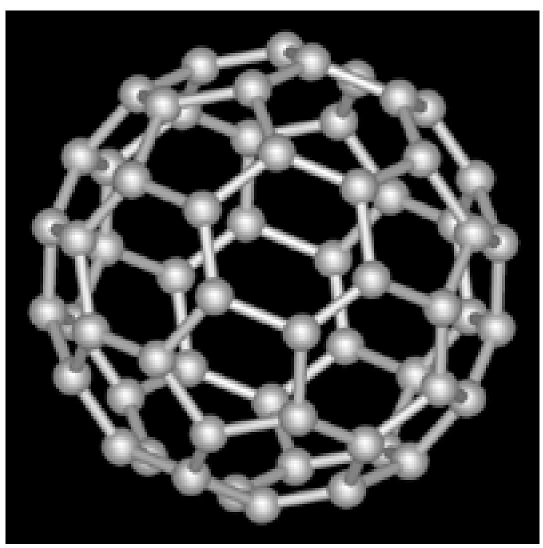

Figure 1.14

[5]http://en.wikipedia.org/wiki/Buckyball

In fact, scientists have now discovered hundreds of buckyballs of different sizes, all with the trademark spherical-like shape. To differentiate them, each allotrope is denoted as C (for carbon) with the number of carbon atoms in the subscript (i.e. C80). Technically, the geometrical shapes that these buckyballs share are actually known as geodesics, or rather, polyhedrons that approximate spheres. Specifically, the commonly depicted C60 buckyball is a truncated icosahedron. A more satisfactory representation of it can be had in a soccer ball, with which it shares the exact same shape. It is made up of 12 pentagons, each surrounded by 5 hexagons (20 in all).

1.2.3 The Discovery

British chemist Harold W. Kroto at the University of Sussex was studying strange chains of carbon atoms found in space through microwave spectroscopy, a science that studies the absorption spectra of stellar particles billions of kilometers away to identify what compounds are found in space. This is possible because every element radiates a specific frequency of light that is unique to that element, which can observed using radiotelescopes. The elements can then be identified because a fundamental rule of matter stating that the intrinsic properties of elements apply throughout the universe, which means that the elements will emit the same frequency regardless of where they are found in the universe. Kroto took spectroscopic readings near carbon-rich red giants, or old stars with very large radii and relatively low surface temperatures, and compared them to spectrum lines of well-characterized substances. He identified the dust to be made of long alternating chains of carbon and nitrogen atoms known as cynopolyynes, which are also found in interstellar clouds. However Kroto believed that the chains were formed in the stellar atmospheres of red giants and not in interstellar clouds, but he had to study the particles more closely.

At the same time, Richard Smalley was doing research on cluster chemistry, at Rice University in Houston, Texas. “Clusters” are aggregates of atoms or molecules, between microscopic and macroscopic sizes, that exist briefly. Smalley had been studying clusters of metal atoms with the help of Robert Curl, using an apparatus Smalley had in his laboratory. This laser-supersonic cluster beam apparatus had the ability to vaporize nearly any known material into plasma using a laser, which is a highly concentrated beam of light with extremely high energy.

Through an acquaintance with Curl, Kroto contacted Smalley and discussed the possibility of using his apparatus to recreate the high-heat conditions of a red giant’s atmosphere in order to study the clusters of carbon produced, which might give Kroto insight as to the formation of the carbon chains. Smalley conceded and Kroto arrived in Smalley’s laboratory in Rice University on September 1, 1985 whom began working on the experiment along with graduate students J.R. Heath and S.C. O’Brien.

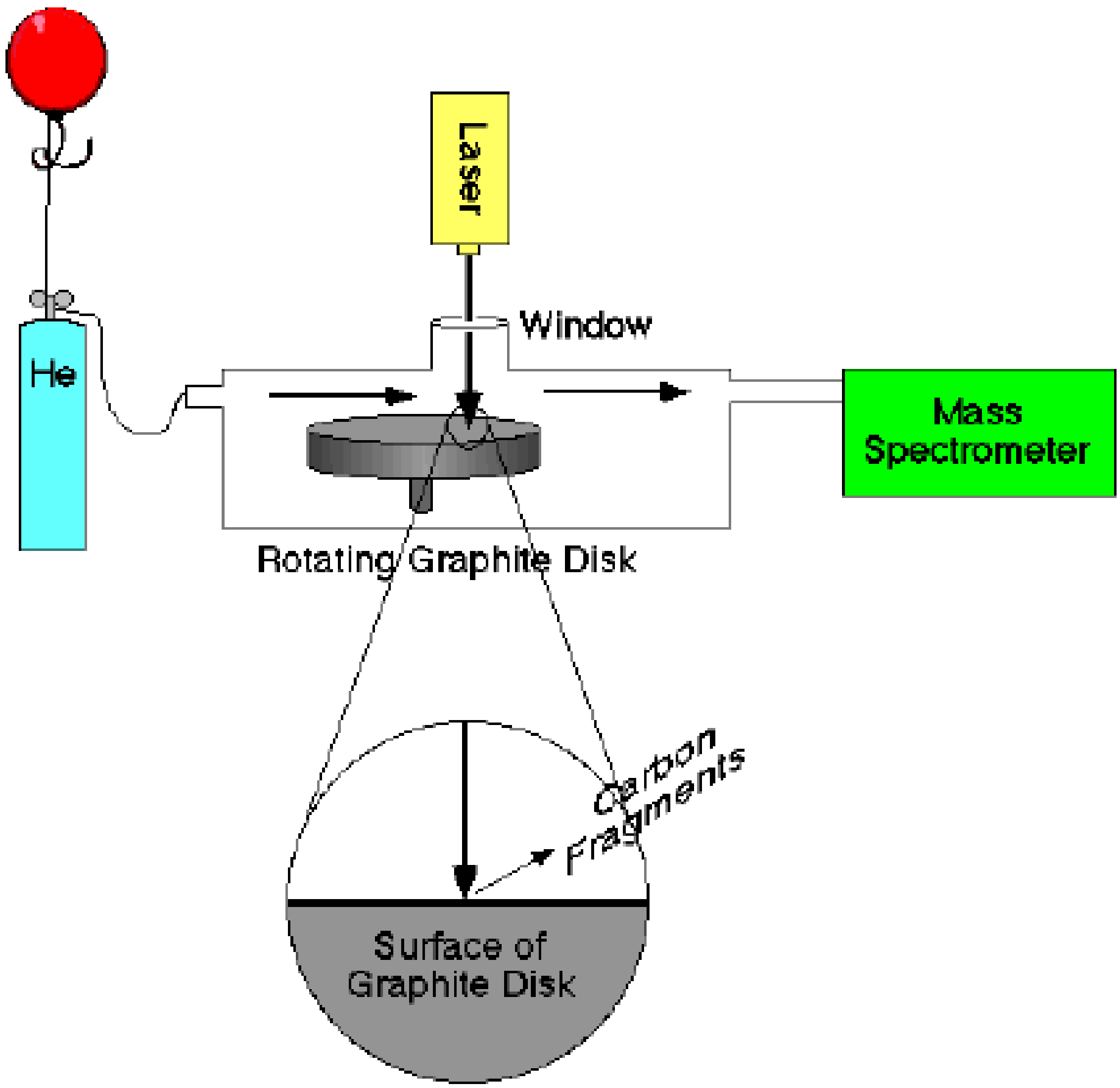

Figure 1.15: Smalley's apparatus[6]

Smalley's apparatus, shown above, fires a high energy laser beam at a rotating disk of graphite in a helium-filled vacuum chamber. Helium is used because it is an inert gas and therefore does not react with the gaseous carbon. The intense heating of the surface of the graphite breaks the C—C bonds because of the intense energy. Once vaporized, the carbon atoms cool and condense in the high-pressure helium gas, colliding and forming new bond arrangements. Immediately upon cooling several degrees above absolute zero in a chamber, the carbon leads to a mass spectrometer for further analysis.

A mass spectrometer uses an atom or molecule's weight and electric charge to separate it from other molecules. This is done by ionizing the molecules, which is done by bombarding the molecules with high energy electrons which then knocks off electrons. If an electron is removed from an otherwise neutral molecule,

[6] http://www.chem.wisc.edu/~newtrad/CurrRef/BDGTopic/BDGFigs/2_1SmalApp.gif

then the molecule becomes a positively charged ion or cation. The charged particles are then accelerated by passing through electric plates and then filtered through a slit. A stream of charged particles exits the slit and is then deflected by a magnetic field into a curved path. Because all the particles have a charge of +1, the magnetic field exerts the same amount of force on them, however, the more massive ions are deflected less, and thus a separation occurs. By adjusting the strength of the accelerating electric plates or the deflecting magnetic field, a specific mass can be selected to enter the receptor on the end. After adjusting the experiment, it became greatly evident that the most dominant molecule measured was 720 amu (atomic mass units). By dividing this number by the mass of a single carbon atom (12 amu), it was deduced that the molecule was comprised of 60 carbon atoms (720 / 12 = 60).

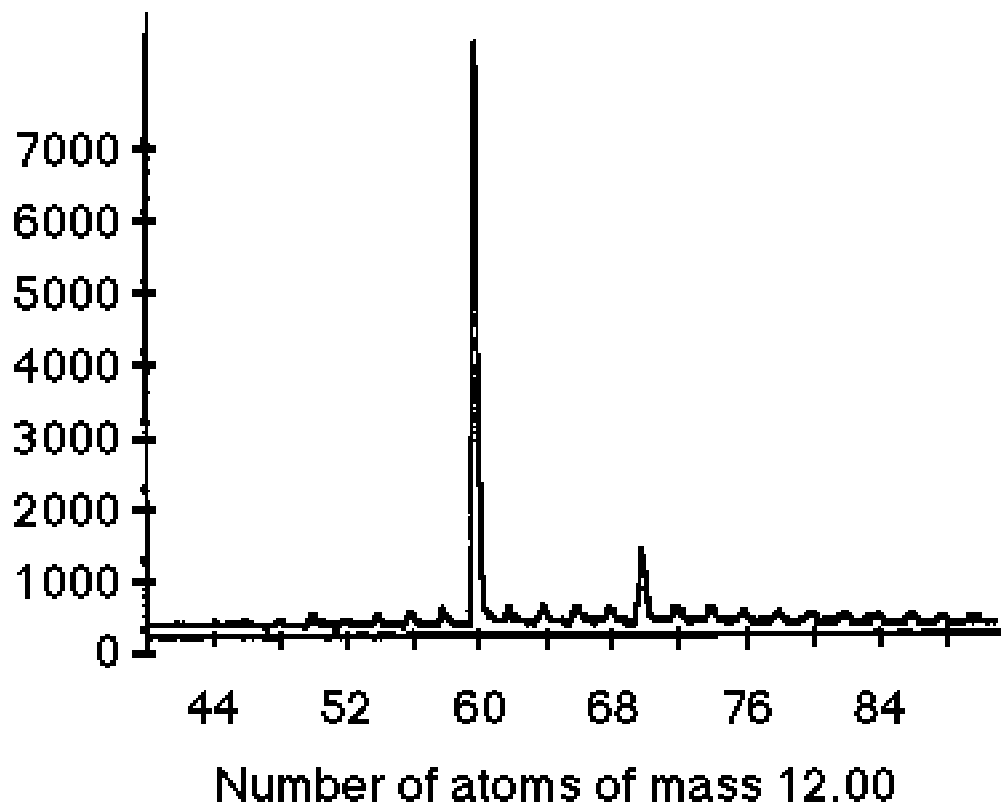

Figure 1.16: University of Wisconsin[7]

The next task was to develop a model for the structure of C60, this new allotrope of carbon. Because it was overwhelmingly dominant, Smalley reasoned the molecule had to be the very stable. The preferred geometry for stable molecule would reasonably be spherical, because this would mean that all bonding capabilities for carbon would be satisfied. If it were a chain or sheet like graphite, the carbon atoms could still bond at the ends, but if it were circular all ends would meet. Another hint as to the arrangement of the molecule was that there must be a high degree of symmetry for a molecule as stable as C60. Constructing a model that satisfied these requirements was fairly difficult and the group of scientists experimented with several models before coming to a conclusion. As a last resort, Smalley made a paper model by cutting out

[7]http://www.chem.wisc.edu/~newtrad/CurrRef/BDGTopic/BDGFigs/2_1SmalApp.gif

paper pentagons and hexagons in which he tried to stick them together so that the figure had 60 vertices. Smalley found that he create a sphere made out of 12 pentagons interlocking 20 hexagons to make a ball. The ball even bounced. To ensure that the shape fulfilled the bonding capabilities of carbon, Kroto and Curl added sticky labels to represent double bonds. The resulting shape is that of a truncated icosahedron, the same as that of a soccer ball. Smalley, Curl, and Kroto named the molecule buckminsterfullerene after the American architect and engineer Richard Buckminster Fuller who used hexagons and pentagons for the basic design of his geodesic domes.

Eleven days after they had begun, the scientist submitted their discovery to the prestigious journal Nature in a manuscript titled "C60 Buckminsterfullerene." The journal received it on the 13th of September and published it on the 14th of November 1985. The controversial discovery sparked approval and criticism for a molecule that was remarkably symmetrical and stable.

1.2.4 How Buckyballs are made?

Experimentally, Smalley, Kroto, and Curl, first created the buckyballs using Smalley's laser-supersonic cluster beam apparatus to knock carbons off of a plate and into a high pressure stream of helium atoms. They would be carried off and immediately be cooled to only a few degrees above absolute zero, where they would aggregate and form these buckyballs. This method however, resulted in low yields of buckyballs, and it took nearly five years until in 1990 newer methods developed by American and German scientists could manufacture buckyballs in large quantities.

The common method today involves transmitting a large current between two graphite electrodes in an inert atmosphere, such as Helium. This gives rise to a carbon plasma arc bridging the two electors, which cools instantaneously and leaves behind a sooty residue from which the buckyballs can be extracted.

These methods of producing buckyballs do deserve a great deal of applaud. However, humans cannot take all, or even most of, the credit for the production of fullerenes. As a matter of fact, buckyballs occur in nature, naturally, and in greater amounts than expected. Buckyballs are known to exist in interstellar dust and in geological formations on Earth. Even closer to home are the buckyballs that naturally form in the wax and soot from a burning candle, as the flame on the wick provides the sufficient conditions for such processes to occur. Buckyballs are the new sensation for us, but to Nature, they are old news.

1.2.5 Chemical and Physical Properties

Since buckyballs are still relatively new, there properties are still being heavily studied. Buckyballs' unique shape and electron bonding give them interesting properties on the physical level, and on the chemical level.

Since spheres in nature are known to be the most stable configurations, one could expect the same from fullerenes. Indeed this is one of the reasons why Smalley, Curl, and Kroto initially considered its shape. Their tests showed that it was extremely stable, and thus, they reasoned, it could be a spherical-like geodesic. Also, fullerenes are resilient to impact and deformation. This means, that squeezing a buckyball and then releasing it would result in its popping back in shape. Or perhaps, if it was thrown against an object it would bounce back; ironically just like the very soccer ball it resembles.

Buckyballs are also extremely stable in the chemical sense. Since all the carbon-carbon bonds are optimized in their configuration, they become very inert, and are not as prone to reactions as other carbon molecules. What makes these bonds special is a property called aromaticity. Normally, electrons are fixed in whatever bond they constitute. Whereas in aromatic molecules, of which hexagonal carbon rings are a prime example, electrons are free to move ("delocalize") among other bonds. Since all the fullerenes have the cyclo-hexanes in abundance, they are very aromatic, and thus have very stable, inert, carbon bonds. Buckyballs, though sparingly soluble in many solvents, are in fact the only known carbon allotropes to be soluble.

An interesting feature of Fullerenes is that their hollow structure allows them to hold other atoms inside them. The applications of this are abound, and are being studied to great extent.

Important to note about any new material is its health concerns. Although believed to be relatively inert, experiments by Eva Oberdörster at Southern Methodist University, presented some possible dangers of fullerenes. She introduced buckyballs into water at concentrations of 0.5 parts per million, and found that largemouth bass suffered a 17-fold increase in cellular damage in the brain tissue after 48 hours. The damage was of the type lipid peroxidation, which is known to impair the functioning of cell membranes. Their livers were also inflamed and genes responsible for producing repair enzymes were activated. As of 10/20/05, the SMU work had not been peer reviewed.

1.2.6 What have buckyballs contributed to science?

After the astrophysicists D.R. Huffmann and W. Kratschmer managed to produce larger quantities of fullerenes in 1990, scientists further investigated the structure and characteristics of buckyballs. Research on buckyballs has led to the synthesis of over 1000 new compounds with exciting properties, and over 100 patents related to buckyballs have been filed in the US. In addition, an important new material, nanotubes, has exploded onto the scientific scene in recent years. The discovery and manufacture of nanotubes resulted directly from research on buckyballs. Finally, although buckyballs have not yet been used in any practical applications, partly due to the high cost of material, researchers are using buckyballs to learn more about the history of our world, and companies are devising some interesting uses for buckyballs even today.

1.2.7 Nanotubes

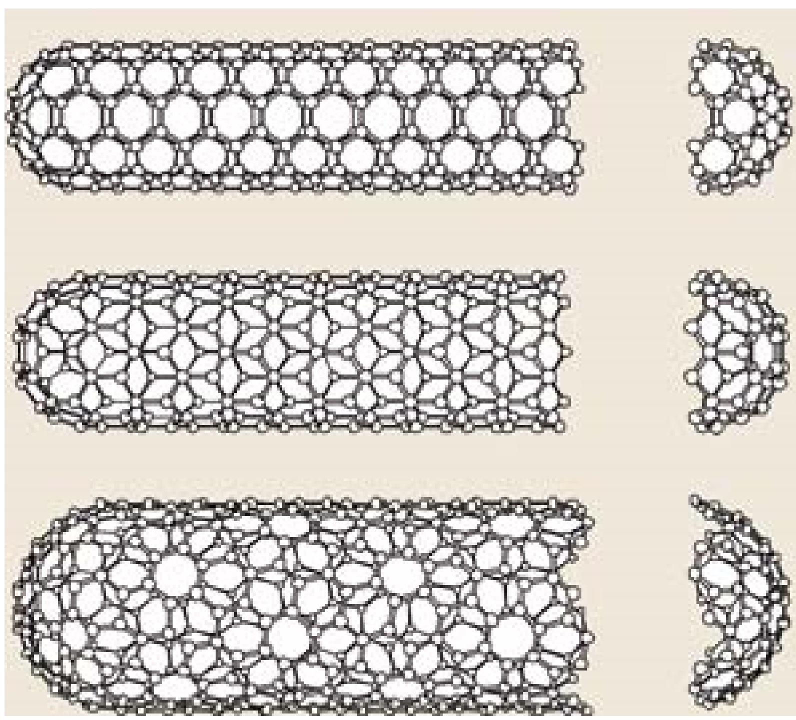

Figure 1.17

The discovery of nanotubes in 1991 by S. Iijima has been by far the buckyball's most significant contribution to current research. Nanotubes, both single- and multi-walled, can be thought of as sheets of graphite rolled into cylinders and sometimes capped with half-fullerenes. Nanotubes, like fullerenes, possess some very unique properties, such as high electrical and thermal conductivity, high mechanical strength, and high surface area. In fact, carbon nanotubes provide a clear example of the special properties inherent at the quantum level because they can act as either semi-conductors or metals, unlike macroscopic quantities of carbon molecules. These properties make nanotubes extremely interesting to researchers and companies, who are already developing many potentially revolutionary uses for them.

1.2.8 What are buckyballs teaching us about our world?

A paper published on March 28, 2000 in the Proceedings of the National Academy of Sciences (PNAS) by Becker, Poreda, and Bunch uses buckyballs to provide new evidence for early periods in earth's geological and biological history. By exploiting the unique properties of buckyballs, these three scientists were able to study geology in a new way. First of all, the unique ability to extract fullerenes (unlike graphite and diamond) from organic solvents allowed them to isolate carbon material in the meteorites, then the unique cage-like structure of fullerenes allowed them to investigate the noble gases enclosed within the ancient fullerenes. In their study, the researches found helium of extraterrestrial origin trapped inside buckyballs extracted from two meteorites and sedimentary clay layers from 2 billion and 65 million years ago respectively. The helium inside these buckyballs bears unusual ratios of 3He/4He coupled with non-atmospheric ratios of 40Ar/36Ar, which according to their research indicates extraterrestrial origin. In addition, they have shown that these fullerenes could not have been formed upon impact of the meteorite or during subsequent forest fires.iBecker, Poreda, and Bunch. 2982.

The discovery of the extraterrestrial origin of the enclosed helium has far-reaching implications for the history of the earth. For example, the existence of the carrier phase of fullerenes suggests that "fullerenes, volatiles, and perhaps other organic compounds were being exogenously delivered to the early Earth and other planets throughout time."iiBecker, Poreda, and Bunch, 2982. With more research, it might even be possible to determine whether meteorite impacts on earth could have triggered global changes or even brought carbon and gases to earth that allowed for the development of life!

1.2.9 Uses

Why does it matter? Why should anyone care? These buckyballs are giving scientists information about allotropes of carbon never before conceived. More importantly, these buckyballs might allow engineers and doctors do what was never before possible. These are some of the applications for buckyballs currently in research.

Medical uses for buckyballs

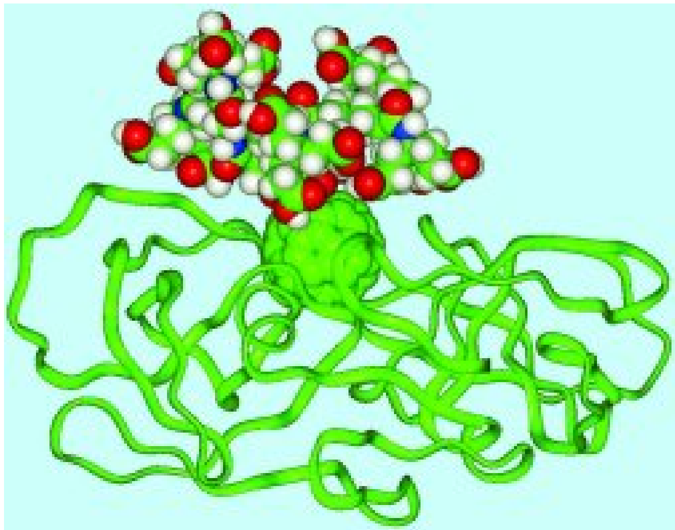

Figure 1.18

Drug Treatments
Buckyballs are now being considered for uses in the field of medicine, both as diagnostic tools and drug candidates. Simon Friedman, a researcher at the University of Kansas, began experimenting with buckyballs as possible drug treatments in 1991. Because buckyballs have a rigid structure (unlike benzene rings, often used for similar purposes), researchers are able to attach other molecules to it in specific configurations to create precise interactions with a target molecule. For example, Friedman has created a protease inhibitor that attaches to the active site of HIV 50 times better than other molecules. C Sixty, a Toronto based company that specializes in medical uses of fullerenes, plans to test on humans two new fullerene-based drugs for Lou Gehrig's disease and HIV in the near future.
Gadolinium Carriers
Another medical use for buckyballs is taking place in the field of diagnostics. Buckyballs unique cage-like structure might allow it to take the place of other molecules in shuttling toxic metal substances through the human body during MRI scans. Usually, the metal gadolinium is attached to another molecule and sent into the body to provide contrast on the MRI scans, but unfortunately these molecules are excreted from the system quickly to reduce the chance of toxic poisoning in the subject. Lon Wilson of Rice University and researchers at TDA Research have encased gadolinium inside buckyballs, where they cannot do harm to the patient, allowing them to remain inside the body longer, but still appear in MRI's. So far this application has been successfully tested in one rat. Wilson and others have begun to develop even more applications for the tiny little cages that could one day help revolutionize medicine.
Engineering Uses
Nano STM
The Scanning Tunneling Microscope (STM) is one of the foremost tools in microscopy today; boasting the ability to to map out the topology of material surfaces at atomic resolution (i.e. on the order of 0.2 nanometers). The STM achieves this feat by bringing a needle point, functioning as a probe, within just several nanometers of a sample's surface. At these minute scales, even small disturbances can cause the tip to crach into the sample and deform itself. A possible solution to this problem would be the replacement of the standard needle point with a buckyball. As discussed previously, fullerenes bear amazing resilience due to their spherical geometry, and would resist distortions from such collisions.

Buckyballs in circuits
European scientists are aiming to use buckyballs in circuit. So far, they have been able to attach a single fullerene to a copper surface, and then, through a process called shrink wrapping, fitted its center with a metal ion and made it smaller to increases electric conductivity by a hundred times.
Lubricants
Because of their shapes, they could be used equivalently to ball bearings, and thus allow surfaces to roll over each other, making the fullerenes equivalently lubricants
Superconductors
It has been shown that fitting a potassium ion in the buckyball causes it to become superconductive. Ways to exploit this are in the research stages.
Catalysts
Attaching metals onto the surface of fullerenes offers the possibility for buckyballs to become catalysts.

1.2.10 Conclusion

As we can see, we have come along way since that fateful year of 1985. Strides have been made. We have seen the rise of nanotubes and the new science of Nanotechnology. We are still studying the chemical and physical properties of buckyballs and continue to be amazed. They have already proved to us why they are important; their possible uses in medicine and in engineering are broad and profound, while the health risks they posed have yet to be fully analyzed. Only time will tell whether they will meet, or exceed our expectations as we unfold this brave new world.

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1.3 Nanotechnology: Market Growth and Regional Initiatives[8]

1.3.1 What is Nanotechnology?

There exists the popular misconception that nanotechnology is a discreet industry or sector. Rather nanotechnology is a set of tools and processes for manipulating matter that can be applied to virtually any manufactured good. Nanotechnology is an emerging and promising field of research, loosely defined as the study of functional structures with dimensions in the 1-1000 nanometer range (Figure 1.19). During the last decade, however, developments in the areas of surface microscopy, silicon fabrication, biochemistry, physical chemistry, and computational engineering have converged to provide remarkable capabilities for understanding, fabricating and manipulating structures at the atomic level (Adams, 2007).

[8]This content is available online at <http://cnx.org/content/m43446/1.1/>.

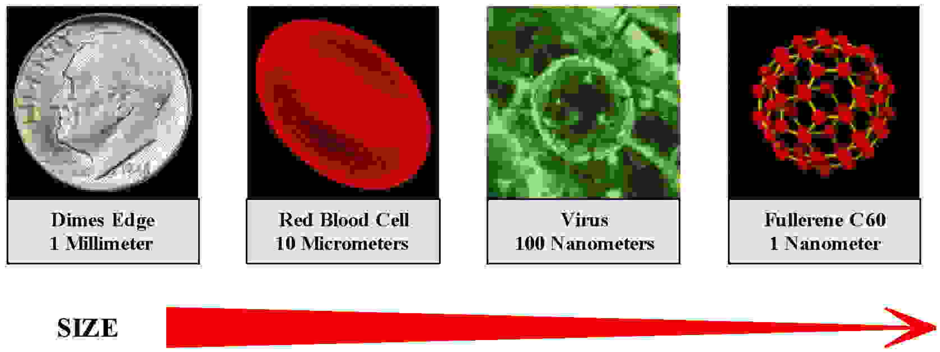

Figure 1.19: Scale of nano; Adapted from: The Scale of things (Source: Office of Basic Energy Sciences, Office of Science, U.S. Department of Energy (www.nano.gov 2009).

1.3.1.1 Sizing up Nanotechnology

Research in nanoscience has gained momentum, due to the intellectual attraction and the potential societal impact and with the forecasted global market impact across several sectors it lends nanotechnology to be a dominant and enabling technology in the 21st century. Nanotechnology is not an industry or a sector rather a set of tools and processes for manipulating matter that can be applied to virtually any manufactured good.

Nanotechnology as an emerging and disruptive force has already faced the initial challenges of public acceptance globally. Notable commentators such as HRH Prince of Wales famously commented on a potential of "Green Goo" while numerous academics examine the toxicology of the technology to guard against the next "asbestos" (Figure 1.20). Despite this often high-profile cautiousness, the technology has already found its way into the mainstream through products such as antimicrobial refrigerators.

Figure 1.20: Launch of Prince of Wales Innovation Scholars Program: HRH the Prince of Wales (right), Professor Andrew R. Barron the first Prince of Wales Visiting Innovator (center) and Professor Marc Clement Vice Chancellor of the University of Wales (far right).

1.3.1.2 Emergence of "nano" as a commercial opportunity

The commercial interest in nanotechnology can be tracked back over significant period. For example, the first trademarks incorporating "nano" was registered in 1965 though this has grown rapidly over recent years. (Lux Research, 2006) Nanotechnology is a disruptive technology crossing many industrial sectors and at the middle of the last decade had already become incorporated in over $50 billion worth of products sold worldwide. The growth of scale has been matched by the growth of scope, with products ranging from nano-formulated drugs through to high performance nanophosphate batteries. A key breakthrough was the discovery of fullerene by Harry Kroto (University of Sussex, United Kingdom), Bob Curl and Richard Smalley (Rice University, Texas), which has become a major enabler in numerous technologies for sectors across the board. The discovery of fullerene helped put the then-emerging field of nanotechnology, which involves making products from designer molecules, into the limelight. Besides the 1996 Nobel Prize in Chemistry, Smalley was awarded the Irving Langmuir Prize, the Franklin Medal, and the Ernest O. Lawrence Memorial Award (Kanellos 2005).

1.3.2 Nano Applications and Technology

Growth and development of nanotechnology has exploded over recent years, though as shown in Figure 1.21, below this trend was lead by the United States with a massive increase in patenting activity starting in the mid 1990s (Huang et al. 2004).

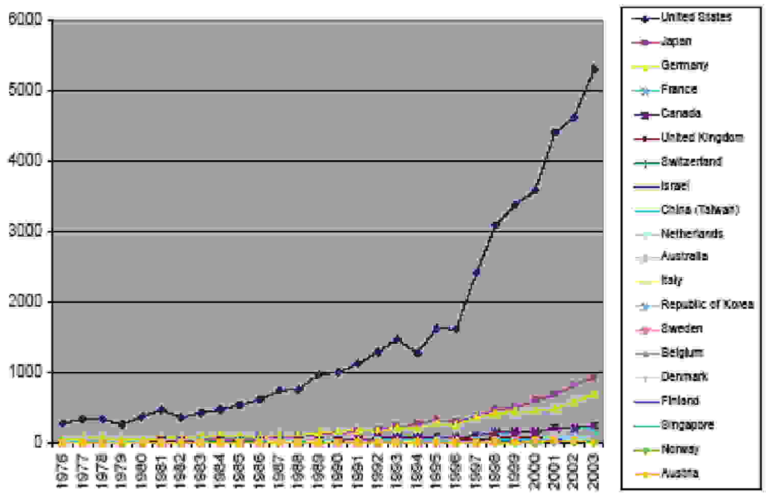

Figure 1.21: A plot of the publications from the top nanotechnology countries by year (Huang et al. 2004).

To date, nanotechnology has seen selective application in high-end products, most of which is within high-performance applications for the automotive and aerospace sectors.

Having established this presence in performance engineering applications, nanotechnology is now becoming embedded within IT applications such as microprocessors and memory chips built using new nanoscale processes (Lux Research, 2004). By 2014 it is projected that 50% of electronics and IT will incorporate nanotechnology (Lux Research 2004).

Although Bio-Life Science is currently the leading sector in nanotechnology development, the rate of innovation across all sectors is significant. Other technological fields that experienced rapid growth in patenting activity in 2003 were those relating to transistors and other solid-state devices, semiconductor device manufacturing, optical waveguides, and electric lamp and discharge (Huang et al. 2004). Figure 1.22 shows an overview of sectoral breakdown of nanotechnology. It is worth noting that sectors such as Materials and Chemicals are in effect enablers for broader sectors, and integrate into the supply and value chains of other sectors. (OSTP 2005). Examples of such materials are carbon nanotubes and quantum dots, which have applications in all sectors.

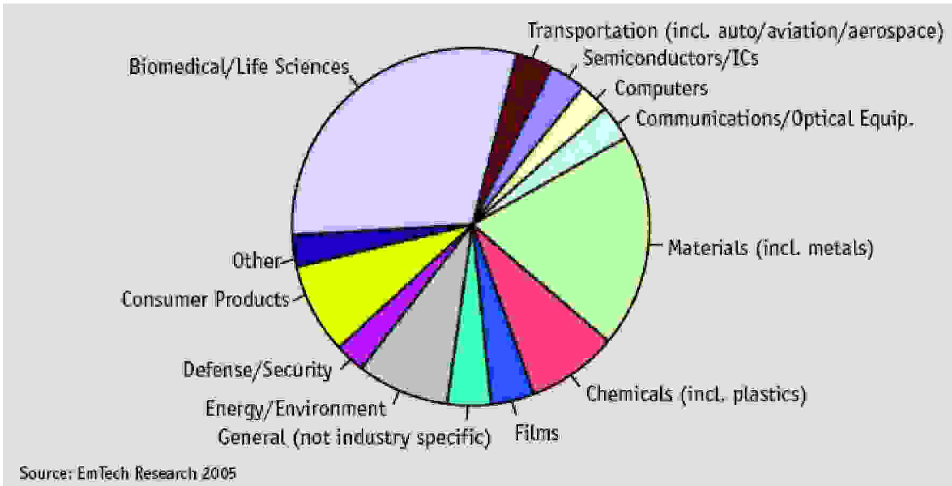

Figure 1.22: Target industries for companies involved in R&D, manufacture, sale, and use of nanotechnology in 2004 (total number of companies = 599). Source (EmTech 2005).

Industrially it has been shown that the leading participants in nanotechnology development are the large-scale industrial actors such as IBM, Intel, and L'Oreal, reflecting the complex and expensive nature of development (EmTech 2005).

In terms of economic impact it is projected that 11% of total manufacturing jobs worldwide will involve manufacture of products incorporating nanotechnology. This will have a result in a paradigm shift in requirements upon supply chains and shift the nature of competition by introducing radical new entrants. This shift is set to accelerate as mass production processes are developed and the cost of materials is driven down, making product opportunities more viable.

1.3.3 Nano Market Growth

Although the most ambitious, potentially world-changing nanotechnology applications are still in development, marketplaces associated with nanotechnologies are already forecasted to be worth billions and are projected to exceed $2.6 trillion within 15 years (Texas Nanotechnology Report, 2008).

1.3.3.1 Global

Due to the potential impacts of nanotechnology, there has been, and is, a strong global interest across governments, business, venture capitalists, and academic researchers. From the period of 1997 to 2005, approximately $18 billion were invested globally in nanotechnology by national and local governments (Cientifica 2006). Governments in the United State, Japan, and Western Europe are among top global nano technology spenders, with global collective governmental spending annually some ~$4.6 billion. This represents just under 50% of total expenditure with the remainder coming from major corporations including a minor proportion from venture capitalists (Lux Research, 2008). However, despite the initial lead of the United States in nanotechnology investment it is now been overtaken by Europe for government expenditure and by Asia for corporate investment (Nano Report, 2006).

The global nanotechnology market has been examined in great detail by a range of academic and commercial organisations. A particularly detailed and comprehensive ongoing study by Lux Research Corporation

(2004, 2006, and 2008) provides a useful breakdown of existing activity together with projections of future trends. This work presents growth in nanotechnology manufacturing as a sector towards a global value of some $2.6 trillion dollars by 2014. This is broadly equivalent to the current size of the ICT sector and ten times larger than Biotechnology.

1.3.3.2 Regional

Countries across the world, including China, Japan, and several European countries, have made nanotechnology leadership and a national priority, working to catch up with the lead established by the United Sates in the field. Even developing countries in areas like Africa, South America, and Malaysia have established government-funded nanotechnology programs and research centres (Cientifica 2006).

Regionally, the U.S. is forecast to remain the largest nanomaterials market due to its large, technologically advanced economy and is top 4 in ranked positions in most major nanomaterials areas, including electronics, consumer goods, pharmaceuticals, and construction materials. (Europe is currently competitive with 31% on the materials market, however there is a clear gap in government spending). The report indicates that Japan is the leading nanomaterials investor in R&D on a per capita basis (Freedonia Group, 2003).

Previous sections have outlined the breadth and growth potential of market sectors in nanotechnology. The transformational nature of endeavour in the field can support establishment of clusters spanning numerous sectors. An example of this is the development of a nanotechnology cluster in the State of Texas. Table 1.1 highlights leading firms within the cluster from a range of sectors.

Company	**City**	**Sales**	**Industries**
LynnTech Inc	College Station	$14.3	Healthcare, Semiconductors, Energy, etc.
Southern Clay Products	Gonzales	$12.2	Construction
Applied Optoelectronics Inc.	Sugarland	$10.0	Telecom, Cable TV, Semiconductors, etc.
Zyvex Corporation	Richardson	$10.0	Aerospace, Defense, Healthcare, Semiconductors, Telecom, etc.
Molecular Imprints	Austin	$8.0	Healthcare, Semiconductors, etc.
Introgen Therapeutics Inc.	Austin	$1.9	Biopharmaceuticals
Applied Nanotech Inc.	Austin	$1.4	Communications, Semiconductors, etc.
Advanced Bio Prosthetic Surfaces	San Antonio	$1.3	Medical Devices

continued on next page

Nanospectra Bio-sciences	Houston	$1.0	Medical Devices

Table 1.1: Revenues (in millions) for selected Texas early stage nanotechnology companies (Source: Nanotechnology Foundation of Texas, 2008).

1.3.3.3 Bio-Nano Life Science

It is projected that by 2014 Healthcare and life sciences applications will finally become established as nano-enabled pharmaceuticals and medical devices emerge from lengthy human trials (Lux Research 2004). Within the sector pharmaceuticals alone will represent an annual global market worth ~ $180 billion (Hobson 2009).

Available research shows that using 2003 figures the biomedical / life science industry was the largest sector involved in the R&D, manufacture, sale and use of nanotechnology. In 2003, four of the five top assignees for nanotechnology patents in 2003 were electronics companies, although the field of chemistry (molecular biology and microbiology) had the greatest number of nanotechnology patents both in 2003 and in previous years (Freedonia Group, 2003).

Considering Life Science as the "Leading" sector for nanotechnology applications, it could be asked why the apparent throughput of products remains low. It is worth stressing that due to the extensive development and rigorous regulatory pathways involved, this creates a particularly long time to market for innovations in the sector. In addition this is compounded by the need for framework to catch up with and effectively accommodate nanotechnology advances. It was highlighted by the US FDA in 2008 and again in 2009 that there was a lack of qualified people within the agency to be able to properly facilitate nano through approvals (ANH 2008, 2009)

Within the combined sectors of Bio and Life Science exist numerous segments and markets which represent significant opportunities themselves. For example, the Medical Devices market is growing at ~9% each year presenting opportunities for nanotechnology applications. Meanwhile, other segments such as in-vitro diagnostics and medical imaging represent markets of ~$18 billion and ~$14 billion respectively (EPT 2005). It was highlighted by the Chairman of the Wellcome Trust, Sir William ('Bill') Castell in 2010 that "it is the low hanging fruit of diagnostics and imaging that will bring nano into forefront of healthcare" (Castell 2010). Within each of these sectors nanotechnology has the potential to be immensely disruptive. For example, within the field of drug delivery systems, a market worth ~$43 billion, there is significant potential for technologies such as Au (gold) particles (Cientifica 2008) and micro-needles (www.belasnet.be 2008), Figure 1.23 and Figure 1.24, respectively.

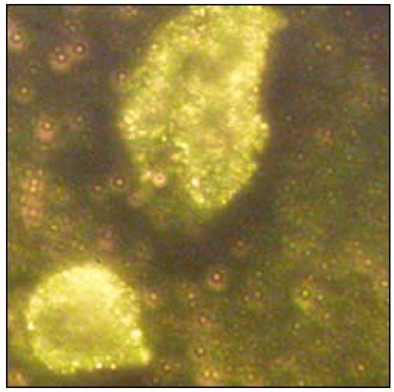

Figure 1.23: Image of gold nanoparticles (Source: Cientifica 2008).

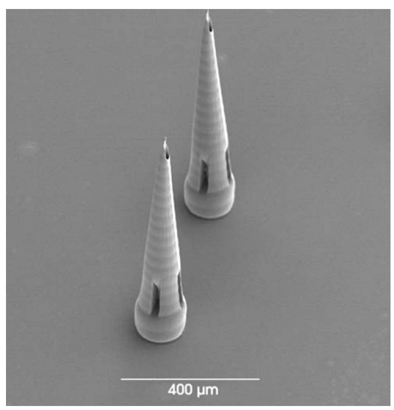

Figure 1.24: SEM image of micro-needles (Source: www.belasnet.be[9]).

1.3.4 Regional Nanotechnology Initiatives

The Southwest Wales Region has seen significant investment over recent years into its Knowledge Economy infrastructure. These investments have come from European Structural Funds, Welsh Assembly Government, academia, and the private sector. These initiatives include specific actions to support key growth sectors such as Life Science, Performance Engineering and ICT. Examples include:

- **Technium**: A network of incubation/innovation centres across Wales to support new enterprise and inward investment. The initiative has been considered as a component within a sub-regional innovation system (Abbey et al., 2008) and its economic impact appraised by external commentators.

[9]http://www.belasnet.be/

- **Institute of Life Science (ILS)**: The ILS represents collaboration between the University of Wales Swansea, the NHS and IBM to support the emerging regional Life Science Cluster. Combined with the parallel initiatives of the "Blue-C" Supercomputing facility and activities in Health Informatics, ILS has now entered a second phase to expand its interactions with the NHS and crate new facilities for business incubation, clinical trials and imaging.
- **Other academic-industrial Research Centres**: A number of specialist research centres have been established over recent years with a focus on industrial engagement. For example, the National Centres for Mass Spectrometry, and Printing and Coating have effectively combined leading research groups with an agenda of collaborating between academic research areas and industry. A further and directly relevant major example of such an initiative is the Multidisciplinary Nanotechnology Centre, this discussed in more detail in the following section.

1.3.4.1 Multidisciplinary Nanotechnology Centre

In 2002 University of Wales, Swansea led a partnership involving UW Aberystwyth, UW College of Medicine and Cardiff University to create an infrastructure for development of cutting edge nanotechnology research. The Centre, which remains in operation, is multi-faceted, focusing on "boundary projects" operating in multidisciplinary fields. Core components of the initiative include:

- Specialist laboratories focused around a central hub at UW Swansea.
- State of the art research equipment with particular focus on imaging and fabrication.
- A team of over 50 researchers leading in their respective fields.
- A portfolio of "boundary projects" drawing in further support from Research Councils and industry.

The initiative has established itself as a leading research centre the success of which was recently reflected in the excellent outcome of the School of Engineering in the 2008 Research Assessment Exercise (RAE).

1.3.4.2 Centre for NanoHealth "Son of MNC"

One of the prime foci of the Centre for NanoHealth (CNH) is the field of "Nanomedicine". The reasons for specific interest in the field include the facts that:

- It is an extremely large field ranging from in vivo and in vitro diagnostics to therapy including targeted delivery and regenerative medicine.
- It has to interface nanomaterials (surfaces, particles, etc.) or analytical instruments with "living" human material (cells, tissue, body fluids).
- It creates new tools and methods that impact significantly existing conservative practices
- It builds upon established and emerging academic and commercial strengths within the cluster such as the MNC and Schools of Medicine and Engineering.

In the near future, the second and the third points represent the biggest challenge for developing nano-medical tools and devices, because due to the novelty of the field no infrastructures of European scale have evolved yet, which create the necessary close proximity between experts and facilities of different areas. This is essential for innovations in this field, and to create the condition of the fast translation of research results to the clinic for patients.

To overcome this problem a distributed infrastructure of specialised European poles of excellence of complementary expertise is a necessary first step. Each centre or node should already have: excellence in one area of nano-technology (surfaces, particles, analytics, integrated systems, etc.), a biological and/or medical research centre and hospital, and (most importantly) companies, which have access to and knowledge of the relevant markets. The missing expertise should be quickly and very easily accessible within this network of distributed infrastructures and expert pools:

- 'Dedicated clinics or hospital units developing and testing nanotechnology based tools, devices and protocols should be supported in the key places across Europe.'
- 'In fact, a few technological/ clinical centres will have to specialise on the transfer of nanomedical systems from the bench to the patient's bed – the "clinicalisation" of the nanomedical devices – to take into account its specificities.'
- 'Testing patient's bio-samples on nanobio-analytical systems, implanting an in vivo nanobio device or injecting a nanotech based drug carrier require a specific environment in dedicated clinics as close as possible to nanotechnology centres, which is not currently found in the usual university hospitals.'
- 'These places will also be key support facilities for joint training of medical doctors and technology developers.'
- 'A European infrastructure based on such places with complementary nanotechnological and biomedical excellences will have the capacity to build up scientific and technical expertise at the interface between "nano" and "bio" to speed up the development of tools and devices for the market.'
- 'Upgrading and combining these places therefore is crucial for effective market oriented developments in nanobiotechnology, because speed is the most critical key factor of success for bringing nanomedical devices or methods to the market in a competitive situation.'

In August of 2002 the University of Wales Swansea (Swansea University) made a bold step in development of collaboration within Wales for Nanotechnology. Combining University of Wales Swansea (UWS), University of Wales Aberystwyth (UWA), University of Wales College of Medicine (UWCM) and Cardiff University (CU) with the objective to create the infrastructure for the development of a cutting-edge nanotechnology research centre at UWS. The centre brought together internationally-leading scientists, and achieved added value by creating new opportunities for research in emerging area of acknowledged importance. By definition, the centre is multi-faceted, focussing effort into new 'boundary' projects where the synergy of three key groups of staff from the School of Engineering (Chemical and Biological Process Engineering, and Electronic Engineering) and the Department of Physics, form the broad knowledge base; these groups, totalling over 50 researchers. Furthermore, inclusion of complementary research groups that were established in the newly created Clinical School, Biological Sciences, and the EPSRC Mass Spectrometry Unit based in the then Chemistry Department and the Welsh Centre for Printing and Coating have also be prioritised. The realisation of this centre was achieved through:

- The creation of a coherent physical space, housing specialist laboratories and research personnel acted as a 'central hub' to foster research interaction in a multidisciplinary environment where cross fertilisation of ideas, techniques and technologies flourish.
- The purchase of state of the art equipment to support nanotechnology research in several 'boundary areas'. The new equipment, which had capabilities not presently available in Wales, or indeed internationally, brought together microscopy and spectroscopy and had applications in nano-fabrication. Scanning probe microscopes that allow structural, mechanical, electronic, optical and chemical properties of surfaces and interfaces to be probed on the nano-length scale under a variety of environments formed a powerful platform. High-speed cameras that permit the observation of processes on the nano-time scale in conjunction with scanning probe microscopes were required. The equipment complemented the existing instruments at Swansea.
- The appointment of talented research staff and research students working within the new, shared laboratories created the multidisciplinary environment and helped facilitate skill and knowledge transfer.
- Initiation of 'boundary projects' in the fabrication of nano-functional materials and devices, for example, bio-electronic systems, biological units, membranes, sensors, tissue engineering and biomedical materials. Manipulation of chemical, structural, electronic and optical properties of such systems on the nanoscale formed a central theme.
- Securing a long-term growth strategy for the Multidisciplinary Centre of Nanotechnology by continuous innovation leading to enhanced support from Funding Councils and Industry.
- Bringing international experts in nanotechnology to Wales to visit the new Centre and to work there for extended periods. Reciprocal visits of Centre staff and students to internationally leading nanotechnology laboratories.

- Creating a pan-Wales Centre for Nanotechnology where the instrumentation and facilities are open to researchers from all institutions of Higher and Further Education.

Collaboration, including joint project work, was undertaken with research teams from the UWCM, CU and the Physics Department at UWA built on successful collaborations that were already underway. They anticipated that the Centre's scanning microscopy-and-spectroscopy and nano-fabrication laboratories would be of particular interest to groups working in the fields of dermal wound healing and biomaterials (UWCM), organic thin films (UWA), nano-modelling and semiconductor and bio-chip technologies (UC). Furthermore, smaller groups who do not have critical mass or developing groups with potential in the field of nanotechnology were encouraged to participate.

The lead organization was the University of Wales Swansea a research-led institution. Of particular relevance to the proposal were its areas of strength and international recognition in Engineering and the Physical Sciences, which housed the nanotechnology expertise. The University recognised the need to support research selectively through the promotion and development of Centres with a critical mass of personnel and resources and an international profile. The University physically reorganized its Departments on campus to promote this strategy. The proposal was well-suited to take advantage of these developments. The proposed Centre for Nanotechnology resonated with the establishment of the Swansea Clinical School, in which there were recent staff appointments at senior levels in cognate biomedical areas. The University participated in forming all-Wales Networks of Excellence and the Centre for Nanotechnology forming a pivotal role acting as one of those networks. The development of a Multidisciplinary Centre of Nanotechnology on the UWS campus feeds into this strand of activities. Along with opportunities for interactions with local industry, through the established Technium project for knowledge exploitation, consistent with UWS' stated goals.

Links of the proposed programme with external schemes and initiatives are exemplified by the work of the two key strands, the Centre for Complex Fluids Processing (Chemical and Biological Process Engineering) and the Semiconductor Interface Group (Electronic Engineering). The former has been endorsed and funded by an EPSRC Platform Grant; an award given only to world leading groups to provide continuity for longer term research and international networking. The latter has been successful in attracting EPSRC and industrial funds to support nanotechnology projects within the electronics and sensing sector; research carried out by this group and the Power Electronics Centre (Electronic Engineering) was seen to be instrumental in attracting International Rectifiers and PureWafer, SMEs to set-up in Swansea. Both strands of research are also in receipt of a Higher Education Funding Council of Wales (HEFCW) funding, which has been awarded on the basis of technical excellence and a proven track record of successful collaboration with industry.

The rapidly developing area of nano-technology research area at the time was certain to be a growth area within Wales. At the time Cardiff University planned to create a multidisciplinary Research Institute for Micro and Nano-science (IMNOS) and it was seen that it would be vital for Swansea and the Cardiff centres to work closely together and co-ordinate their activities, based on their previous solid record of collaboration.

The MNC set up four key panels to govern over specific areas for the Centre:

- A core management panel that comprises of three senior academics with international research reputations at the highest level and extensive experience of programme that is responsible for programme management, finance and staffing.
- Multidisciplinary Research Panel responsible for shaping research strategy across the breadth of activities.
- Research Forum to allow creative input to the research direction and projects from all Centre participants including the Panel members, research staff and research students.
- International Expert Panel appointed to advise on scientific direction. Advice from interested industrial parties will be continuously sought at an early stage using existing mechanisms. Research Officers employed on the programme will be required to formally report their work bi-monthly and the UWS Graduate School Postgraduate Student Monitoring Scheme will be adopted for PhD students. These formal measures will be accompanied by Centre Seminar Days, where progress on all fronts can be monitored and discussed by all members of the Centre.

The aim of the recently funded (2009) Centre for NanoHealth (CNH) aim is to deliver the next generation of Healthcare via the application of Nanotechnology as described above. CNH will achieve this through research & development, demonstration and deployment, and Skills innovation system. In doing so, the goal of CNH is to underpin the development of skills and enterprise people required for Wales to realise its potential in an emerging nanotechnology sector.

CNH has identified that future healthcare lies in new novel technologies that permit early disease intervention, supported by new diagnostics and treatments in non-hospital environments e.g., the home, community clinic or local General Practitioners (GP) surgery. With the key being rapid intervention at the earliest possible instance for disease detection and treatment through the use of therapeutic devices, sensors, diagnostics and other applications.

The £20 million CNH project will firmly establish the region as a world leading interdisciplinary centre offering a Research and Development, Demonstration and Deployment, and Skills innovation system for NanoHealth, where basic research is fed into the Centre from the MNC and ILS in Swansea (see Figure 1.25).

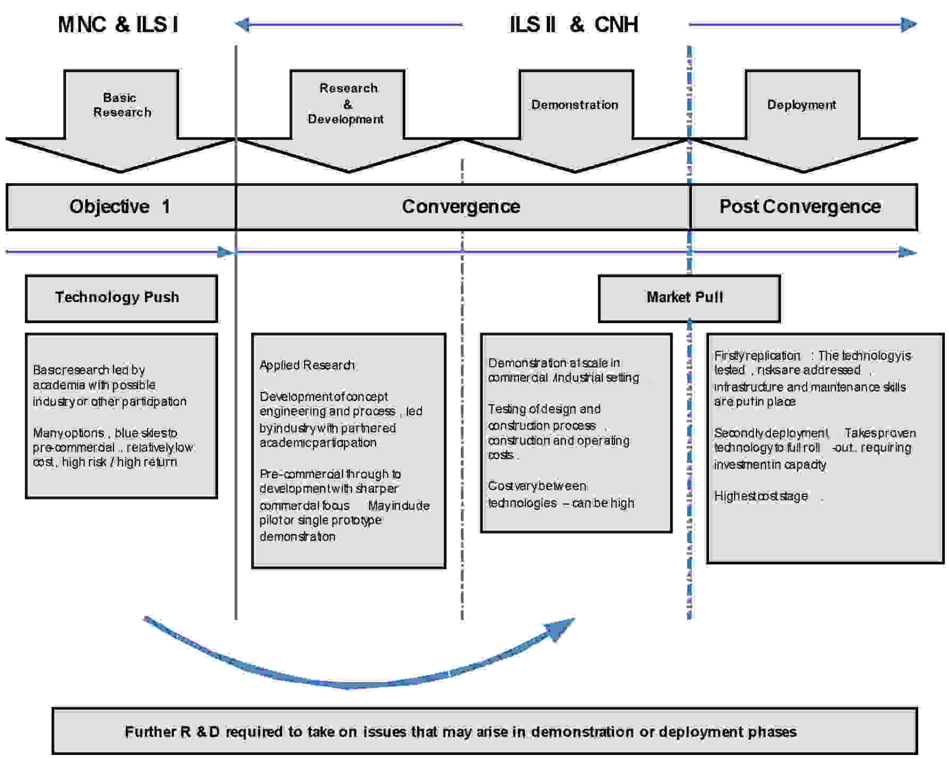

Figure 1.25: Innovation system adapted from: The Research and Development, Demonstration and Deployment and Skills Innovation System (DTI 2007).

CNH brings together, within a single physical and state of the art facility, Clinicians from the local Trust Hospital, Life Scientist Researchers from Swansea University's School of Medicine and Engineers/Physical Researchers from Swansea's School of Engineering to work closely with business to deliver innovations in healthcare. The CNH goal is to be a multidisciplinary environment integrating specialist facilities for nanofabrication, nano-characterisation, and biomedical development, coupled with the added benefit of business incubation space, which is adjacent to a clinical research unit and hospital. The Centre aspires to support the ambitions of the Science Policy by delivering personalised medicine solutions and enhanced diagnostics capabilities, for treatment in the home and community outlets, not only support the economic development agenda but also transform the way in which healthcare is delivered.

The Centre for NanoHealth (Figure 1.26) is funded through Convergence funding and is tasked with not only research but also to assist Welsh SMEs to work on the development of new healthcare technologies from initial concept to the point where they can be deployed commercially. Within Wales the private sector, and in particular Welsh SMEs, are not likely to be able to invest adequately in the initial R&D area due to the lack of funds, preventing them from capitalising on any returns relative to the costs and risks involved. The role of the CNH is to address this failure by providing the region with the required infrastructure to facilitate a level of investment from the private sector to develop new technologies in the area of NanoHealth; ultimately returning wider economic, health and environmental benefits to the Southwest Wales region.

Figure 1.26: Institute of Life Science II and Centre for NanoHealth, Swansea University.

CNH will provide a world-class infrastructure for the commercialisation of science based around one of the three key themes targeted by the Science Policy: Health. It will actively attract inward-investing R&D activity and create a pipeline of opportunities, which it can incubate and develop. Adding to developing a regional 'critical mass' of activity, supporting an emerging life science cluster and linking directly to healthcare provision in Wales.

1.3.5 Bibliography

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