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Excerpt
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# Part I

## Introduction to Nanotechnology and Participation of Developing Countries

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CHAPTER 1

# On Nanoscience, Nanotechnology, and Nanoproducts

## Why Everyone Wants to Join this Game?

*Susan E. Reid, Roger Coronini, and Shyama V. Ramani**

## Defining what the game is all about

Do you remember the first time you encountered the idea that while the universe could be infinitely large, its basic building blocks are actually very small? These building blocks, the atoms and molecules comprising all matter, in effect make up the world of nanoscience. The basic fodder for nanotechnology, throughout our world's history, has always been at play. As described by Wilson et al. (2002), the alkali and the alkaline earth metals (Groups 1 and 2 from the Periodic Table of Elements), as well as the transition metals (Groups 3 to 12), due to their various electrical properties, make good providers of electrons, and good conductors, respectively, useful in nanotechnology. Further, carbon and silicon from Group 14 are important base materials for many nanomaterials. In other words, these atoms and various simple molecular combinations of these, not only are the building blocks of nanotechnology, but also of our world. Our understanding of this reality has developed relatively recently through the development of tools, in particular those that allow us to see (scanning probe and atomic force microscopes) and engage (lithography and masks enabling building up through deposits or chiseling away of various surfaces). Facilitated by the inert noble gases such as xenon and radon (Wilson et al., 2002), this

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has allowed humans to witness, and lately attempt to play with, the ongoing miracle of the composition and dynamics of matter operating at the nanoscale.

The nano-world has generally been defined as occurring between 0.1 and 100 nanometers and therefore covers the quantum physics and DNA spectra (CMP Cientifica, 2001). According to the Cambridge Dictionary, the definition of science is "knowledge from the systematic study of the structure and behavior of the physical world, especially by watching, measuring and doing experiments, and the development of theories to describe the results of these activities." Therefore, "nanoscience" refers to this definition as applied to the nano-world: the study of the nanostructures and nanomechanics occupying the 0.1 to 100 nanometer terrain. The many scientific disciplines comprising what is currently understood to contribute to nanoscience go beyond chemistry to encompass the sciences of molecular biology, electronics, materials science, physics (optics and quantum), and others. As such, nanoscience which is built upon many sciences, is complex, and will rely on the capabilities of researchers to integrate these sciences in meaningful ways.

What has come to be known generically as "nanotechnology" is built upon unique combinations involving many of the basic fields of science. The Cambridge Dictionary definition of technology is "the study and knowledge of the practical, especially industrial use of scientific discoveries." Industrial applications or products, such as nanotools; and nanomaterials such as nanotubes would also fall under this rubric. Consumer applications would be considered separately as consumer nanoproducts. Nanotechnology, therefore, does not refer to a single technique but to many different underlying pro-genitor technologies that enable manipulation of matter, such as measuring, designing, and mass producing at a nanoscale. Some of the most famous basic technologies to date include SEM (scanning electron microscopy)[1] and nanotubes as a basic construction material for everything from stronger and lighter tennis rackets to space elevators.

[1] SEMS allow the investigator to see an object smaller than the wavelength of light. A beam of electrons is manipulated using condenser lenses and scanning coils to create a magnetic field using fluctuating voltage. As the electron beam moves towards an object, it removes secondary electrons from its surface. A secondary electron detector registers different levels of brightness based on the number of electrons emitted and this builds an image with the aspects of the image closer to the beam appearing brighter. Primary backscattered electrons also help to determine the atomic number and topographical information. For more detailed information on SEMS, please consult Flegler et al.'s (1993) *Scanning and Transmission Electron Microscopy: An Introduction*.

Why are nanosciences and nanotechnology capturing the minds and hearts of scientists and policy makers? Consider this definition: "nanotechnology involves the intentional manufacture of large-scale objects whose discrete components are less than a few hundred nanometers wide." The vision of early proponents of nanotechnology, such as Richard P. Feynman, Ralph Merkle, and K. Eric Drexler, was to provide an inexpensive "bottom-up" manufacturing technology. According to Ralph Merkle's home page (2010), "a central concept for achieving low cost in molecular manufacturing is that of massive parallelism, either by self-replicating manufacturing systems or convergent assembly." These may be possible at the nanoscale utilizing "bottom-up" rather than "top-down" manufacturing processes and systems, potentially achievable through the use of DNA microarrays or nanobots such as flagellated bacteria. While this vision may yet be many years off, a great deal of progress has been made in developing the building blocks for such a nanotechnology future.

## *The new beginnings*

A first conquest is happening in the creation of the "nanomaterials" space. Carbon atoms and xenon atoms, typically 1/10$^{th}$ of a nanometer, in special molecular arrangements, such as "nanotubes" (Harris, 1999), are the basis for this whole new class of nanomaterials. These star products, "nanotubes," are carbon-based graphite cylinders with unusual electrical properties and represent one of the earliest developments in the nanomaterials space. Based on their importance, an increasing number of applications, and potential applications, the USPTO (United States Patent Technology Office), IPC (International Patent Classification) on WIPO (World Intellectual Property Organization), and the EPO (European Patent Office) each now recognize "nanotechnology" as a separate class of inventions (class 977, class Y01N, and class Y01N, respectively). In addition, the IPC has added another separate class just for "nanostructures" called Class B82B. Some linkages between the combination of sciences involved with nanoscience and related nanotechnologies, and products are illustrated in the case of nanomaterials in Table 1.1.

**Table 1.1:** Nanomaterials: From science to technology to product innovation

| *Sciences* | *Nanotechnologies* | *Product example* |
|---|---|---|
| Electronics, Mechanics, Physics, Chemistry | Nanobelts, Nanomotors, Nanosprings, Nanowires | The "Nanomotor" from Klocke Nanotechnik for military ultra-vacuum and underwater applications |

*Contd.*

*Contd.*

| *Sciences* | *Nanotechnologies* | *Product example* |
|---|---|---|
| Physics, Chemistry | Nanoparticles, Nanotubes, Nanofibres, Nanocrystals, Fullerenes, Quantum Dots, Nanoporous Materials | Ecosynthetix's starch adhesives for McDonald's hamburger containers which take less time and energy to dry because of the small size of the molecules |
| Chemistry, Biology, Physics | Organic and Inorganic hybrid nanostructures | Silver nanowires for highly efficient solar PV cells (not yet commercialized) |
| Biology, Electonics, Physics | Molecular Electronics and Photonics | California Molecular Electronics Chiropticene® switching technology aimed at providing 16 terabits of data storage in a device. The size of a cubic inch providing capacity 34 times more than one of the today's 60 GB hard drives |

*Source*: Extracted from author's databases collected from 2000–12.

Based largely on the unique properties of nanomaterials which are claimed to be endowed with characteristics such as being stronger, lighter, faster, more self-correcting, less expensive, etc., nanotechnology is being touted as the "next big thing" which will have a revolutionary impact on most of our lives and in the most important consumer and business sectors of the economy worldwide. Since nanotechnology is an "enabling technology," just like the internet or electricity; it will provide the tools, materials, and devices for a new generation of technological development. Some of the current and short-term-to-fruition product and process applications in the areas of the life sciences, medicine, electronics, optics, information technology, telecommunications, aerospace, and energy are listed in Table 1.2.

**Table 1.2:** Current short-term areas of application of nanotechnologies (0–5 years) potential low hanging fruit

| *Area* | *Description/Examples* |
|---|---|
| High-speed Computing | Development of new electronic devices (IBM's "Millipede", Intel, Compaq, Motorola, Nanosys) |
| Computer Memory | NRAM chips and Memory processes using various organic nano semi-conductors (Nantero), porphyrins (ZettaCore), chyropticenes (California Molecular Electronics) |

*Contd.*

*Contd.*

| *Area* | *Description/Examples* |
|---|---|
| Photolithography | Nano-dip pens to build or repair photolithographic masks (Northwestern University/Nanosphere/NanInk) |
| Materials/ Coatings Manufacturing | Materials such as nanotubes and their large-scale manufacture (CNI/C Sixty, Mitsui), new stain-free and light-weight fabrics (Nano-tex), new materials (tennis rackets and other exercise equipment), paints and coatings, sunscreens and cosmetics (Nanophase Technologies, L'Oreal), dental bond agents (NanoSilver), high-performance tires and car parts like superstrong running boards (GM), new flat screen monitors (Samsung), thin films (Ntera), electronic paper (Bell Labs, E Ink), hard plastics for bottles that are better in sealing $CO_2$ to keep drinks fresh (Miller Brewing Co. purchased from Voridian Co.) |
| Micro and Nanofluidics | MEMS, NEMS, labs-on-a-chip, biosensors (Sandia's microfluidics project, Nanogen's automotive sensors, Cyrano Sciences electronic nose) |
| Environment and Energy | Buckytubes which can store hydrogen for batteries, electric motors, nanomotors, and encapsulation systems for bioremediation (US Navy) |
| Agriculture | Biodegradable chemicals using bioengineering for plant growth/insect protection (Monsanto) |
| Defense | Landmine detectors (University of Connecticut) |
| Healthcare/Bio-pharmaceuticals | Biosensors and fluidics as mentioned above enables better medical diagnostics (MicroCHIPS Inc, Agilent), drug delivery systems (iMEDD, Target Therapeutics for cancer, Smith & Nephew's silver nanocrystal lined bandages for killing bacteria), implants, super-strong artificial muscles (University of Texas Dallas, University of British Columbia) |

*Source*: Extracted from author's databases collected from 2000–12.

One of the most interesting thing that has happened at the advent of modern nano in the form of new products is that the first products in the market place were not industrial, as is often the case with new generic technologies, but rather, consumer focused. For instance, with respect to the computer, which is a good example of a typical technology development – first the applications started in the industrial sector (mainframes for the military, and so on) and then moved out to the consumer sector. Whereas, in the world of nanotechnology, we would argue that biotechnology is an important part of this nanoworld, the consumer sector has been the first one to reap its major benefits. Early developments that have been made in the consumer goods sector include new nanotech-based products in automotives, paints, clothings, and cosmetics (much based on nano-encapsulation technology). For example, the largest corporate holder of EPO patents in nanotechnologies, for the period 1978–2006, is a cosmetics manufacturer L'Oreal (Chen et al., 2008).

## *How does science marry technology?*

While nanotechnology is coming to capture the public imagination, important strides are being made in the nanosciences, as evidenced by over a dozen of Nobel Prizes having been awarded in the area thus far. Further, the impact on various disciplines has been broad; including for example, life sciences, electronics, information technology, medicine, aerospace, energy, and environment. These are being so rapidly capitalized in the form of technologies and patented that we are likely to see new applications emerging as illustrated in Table 1.3.

**Table 1.3:** Projected long-term areas of application of nanotechnologies (+5 years)

| *Area* | *Description/Companies where extant or universities* |
|---|---|
| High-speed Computing | DNA as programming language and structural materials: Post-silicon molecular electronics and quantum computing (Molecular Electronics Corp/Rice University, Penn State, NYU, UCLA/HP, QSR/HP/MIT, IBM, AT&T) |
| Manufacturing | Bottom-up manufacturing of large-scale structures at no cost (a la Drexlerian vision) (Rice University's "nanocar") |
| Communications | Full-time interconnectivity through retina, clothing, embedded electronics |
| Robotics | Nanobots to cure diseases, administer drugs (Quantum International, iRobot, Intuitive Surgical) |
| Healthcare/Bio-pharmaceuticals | Prosthetics (DARPA), Cosmetic Medicine (skin and hair color changes, wrinkle treatments, fat levels maintenance) (L'Oreal), preventative medicine |
| Environment and Energy | Smart Dust (University of California, Berkeley, University of Alberta, Dartmouth) for energy storage and harvesting, as well as environmental monitoring, solar cells in roofing tiles (Solar3D, Dow, SunPower), siding that provides electricity using solar paint (University of Notre Dame) |

*Source*: Extracted from author's databases collected from 2000–12.

How exactly does science marry technology to produce a blockbuster product? If we look at the developed countries that have already invested in these areas, we can identify many clear examples of success from the synergistic effects of scientific and technological integration. For instance, consider the following example coming from the new field of molecular computing. GenoRX, a US-based company, combines CMOS (Complementary metal-oxide-semiconductor) technology, used for constructing circuits, with gene chip technology (cDNA microarrays from a large number of genes) to perform sequencing (massively parallel) on a chip without PCR (Polymerase chain reaction), DNA[2] amplification, or fluorescent tagging, which are

[2] Deoxyribonucleic acid or DNA is a nucleic acid which carries genetic instructions for biological development in all cellular forms of life and many viruses.

time consuming processes. According to p.1 of Pisharody et al. (2006), the invention

> provides biosensors for the detection of nucleic acids, such as double stranded DNA. The biosensors are electrodes on a solid support that have means for binding nucleic acids near the electrodes. The nucleic acids are captured such that they span the electrode pair, and the capture can be detected by electrical means.

In other words, these biosensors use voltage current characteristics between electrodes to determine the readout at the DNA end. Such devices can be seen to have useful applications as diagnostic tools in medicine (i.e., genetic screening), agriculture (i.e., pesticide measurement), and environmental applications (i.e., core samples).

Will Ryu (2000) points out – the data density of DNA is impressive. He explains as follows:

> Just like a string of binary data is encoded with ones and zeros, a strand of DNA is encoded with four bases, represented by the letters A, T, C, and G.[3] The bases are spaced every 0.35 nanometers along the DNA molecule, giving DNA a remarkable data density of nearly 18 Mbits per inch. In two dimensions, if you assume one base per square nanometer, the data density is over one million Gbits per square inch. Compare this to the data density of a typical high performance hard drive, which is about 7 Gbits per square inch – a factor of over 100,000 smaller.

The other strength of DNA beyond its memory capacity is that it works in a massively parallel fashion. According to Ryu (2000):

> Just like a CP[4] has a basic suite of operations like addition, bit-shifting, logical operators (AND, OR, NOT NOR) etc. That allow it to perform even the most complex calculations, DNA has cutting, copying, pasting, repairing and many others. And note that, in the test tube, enzymes do not function sequentially, working on one DNA at a time. Rather, many copies of the enzyme can work on many DNA molecules simultaneously. This is the power of DNA computing.

Nanotechnology has also started transforming industrial organization in some markets. Firms experimenting with nanotechnology include established

[3] adenine (A), thymine (T), cytosine (C), and guanine (G).

[4] CP refers to the central processing unit of a computer, which is the primary element carrying out its functions.

firms as well as new ones. In terms of new firms active in NST, near the advent of 2010,[5] a global estimate of the number of companies involved in the nanotechnology space is that there now exist at a minimum, from the G12 countries, in excess of 500 materials companies, approximately 200 tools companies and at least 100 systems and devices companies on a global level.

There are also those companies that have evolved to provide the services and information needs for the newly emerging area. For the device and systems companies (i.e., those working on Nano-electomechanical (NEMS) systems in accelerometers, actuators, control systems, nano-fluidics (lab-on-a-chip), and other areas such as intelligent materials like "Smart Dust"), the challenge is that while technically possible in many cases, quantity production based on sound economics is still not readily feasible, and the world still awaits many of the promised next-generation products.

## *What of the future? Rising to the challenges*

From a practical standpoint, a key issue for scientists and practitioners in all countries is the physical property challenges related to working with these technologies. The physics governing the behavior of molecules changes when moving from the nanoscopic scale to the mesoscopic scale to the macroscopic scale (Roukes, 2002). At each level of complexity, new properties appear and the challenges of quantum mechanics become multiplied when dealing in this space.

> What often emerge at the mesoscale are phenomena that involve the coherent or collective interactions amongst the fundamental constituents-be they electrons, atoms, or molecules. Despite being 'nanoscopic' (that is of nanometer dimensions), mesoscopic structures comprise fundamental building blocks in numbers that are too large, in general, to allow easy theoretical modeling using conventional approaches of quantum physics or chemistry. (Roukes, 2002, viii–ix)

Herein lays one of the major problems currently encountered with scale-up by many researchers and companies.

A second key challenge that exists related to bringing the promise of nanotechnology to fruition is the problem of scaling up of production processes and scaling up from a simple process/product into a product capable of delivering desired benefits to consumers. On the production process scale-up issue, no company has yet figured out how to build mass quantities of high-quality

[5] Based on a database that the authors have been working with for over 10 years.