ABSTRACT: This report constitutes an introductory report of interest to the standardization community on the advances made in the atomic and molecular nanotechnology regarding the ability to systematically organize and manipulate properties and behaviors of matter at the atomic and molecular levels. Basics of nanotechnology to create functional devices, materials, and systems on the 1–100 nanometer (one-billionth of a meter) length scales are presented.

The reasons why nanoscale has become important are presented. We introduce the historical aspects of nanotechnology starting with the famous 1959 lecture by R.P. Feynman. We also suggest naming the nanometer scale the 

\[ \text{Feynman (}\mu\text{m}) \text{ scale} \]

\[ \equiv 10^{-9} \text{ meter } = 10^{-3} \text{ Micron (}\mu\text{)} = 10 \text{ Angstroms (Å)} \]

We also present some recent inventions and discoveries in atomic and molecular aspects of nanotechnology, as well as ongoing related research and development activities. It is anticipated that the breakthroughs and developments in nanotechnology will be quite frequent in the coming years. A list of the activities underway to standardize the techniques, procedures, and processes being developed in this fast growing field are presented.

KEYWORDS: nanotechnology,

Introduction

Nanotechnology is the ability to build materials, devices, and systems with atomic precision [1,2]. A brief and general definition of nanotechnology is the statement by the US National Science and Technology Council [2], which states: “The essence of nanotechnology is the ability to work at the molecular level, atom by atom, to create large structures with fundamentally new molecular organization. The aim is to exploit these properties by gaining control of structures and devices at atomic, molecular, and supramolecular levels and to learn to efficiently manufacture and use these devices.” The United States National Science Foundation [2] defines nanoscience/nanotechnology as studies that deal with materials and systems having the following key properties:

1. Dimension: at least one dimension from 1–100 nanometers (nm).
2. Process: designed with methodologies that show fundamental control over the physical and chemical attributes of molecular-scale structures.
3. Building block property: they can be combined to form larger structures. Nanoscience, in a general sense, is quite natural in microbiological sciences considering that the sizes of many bioparticles dealt with (like enzymes, viruses, etc.) fall within the nanometer range.
The promise and essence of the nanoscale science and technology is based on the demonstrated fact that materials at the nanoscale have properties (i.e., chemical, electrical, magnetic, mechanical, and optical) quite different from the bulk materials. Some of these such properties are, somehow, intermediate between properties of the smallest elements (atoms and molecules) of which they can be composed and those of the macroscopic materials. Compared to bulk materials, it is demonstrated that nanoparticles possess enhanced performance properties when they are used in similar applications. There are many present and expected applications of nanotechnology including bottom-up technology (such as self-assembly) in biology, medicine, pharmaceuticals, electronics, energy, and environmental industries, which are rapidly increasing [3].

The Importance of Nanoscale

The Greek word "nano" (meaning dwarf) refers to a reduction of size, or time, $10^{-9}$ fold, which is one thousand times smaller than a micron. One nanometer (nm) is one billionth of a meter, and it is also equivalent to ten Angstroms. As such, a nanometer is $10^{-9}$ meter, and it is 10 000 times smaller than the diameter of a human hair. A human hair diameter is about 50 micron (i.e., $50 \times 10^{-6}$ meter) in size, meaning that a 50 nanometer object is about $1/1000^{th}$ of the thickness of a hair. One cubic nanometer ($\text{nm}^3$) is roughly 20 times the volume of an individual atom. A nanoelement compares to a basketball like a basketball compares to the size of the earth.

Figure 1 shows various size ranges for different nanoscale objects, starting with such small entities like atoms. Size ranges of a few nanotechnology related objects (like nanotube, single-electron transistor, and quantum dot diameters) are shown in this figure. It is obvious that nanoscience, nanoengineering, and nanotechnology all deal with very small sized objects and systems.

Nanoscale is a magical point on the dimensional scale; structures in nanoscale (called nanostructures) are considered at the borderline of the smallest of human-made devices and the largest molecules of living systems. Our ability to control and manipulate nanostructures will make it possible to exploit new physical, biological, and chemical properties of systems that are intermediate in size, between single atoms, molecules, and bulk materials.

There are many specific reasons why nanoscale has become so important, including the following [2]:

(i.) The quantum mechanical (wavelike) properties of electrons inside matter are influenced by variations on the nanoscale. By nanoscale design of materials, it is possible to vary their micro and macroscopic properties, such as charge capacity, magnetization, and melting temperature, without changing their chemical composition.

(ii.) A key feature of biological entities is the systematic organization of matter on the nanoscale. Developments in nanoscience and nanotechnology would allow us to place man-made nanoscale things inside living cells. It would also make it possible to make new materials using the self-assembly features of nature. This certainly will be a powerful combination of biology with materials science.

(iii.) Nanoscale components have very high surface to volume ratio, making them ideal for use in composite materials, reacting systems, drug delivery, and chemical energy storage (such as hydrogen and natural gas).

(iv.) Macroscopic systems made up of nanostructures can have much higher density than those made up of microstructures. They can also be better conductors of electricity.
This can result in new electronic device concepts, smaller and faster circuits, more sophisticated functions, and greatly reduced power consumption simultaneously by controlling nanostructure interactions and complexity.

**FIG. 1—**Comparison of size ranges for several entities as compared to some nanotechnology devices: SET (Single-electron transistor), GMR (Giant magneto resistive), Q-DOTS (Quantum dots); AFM = atomic force microscope, SEM = scanning electron microscope, STM = scanning tunneling microscope.

**Atomic and Molecular Basis of Nanotechnology**

The molecular theory of matter starts with quantum mechanics and statistical mechanics. According to the quantum mechanical Heisenberg Uncertainty Principle, the position and momentum of an object cannot be determined simultaneously and precisely [4,5]. Then, the first question that may come into mind is, how could one be able to brush aside the Heisenberg Uncertainty Principle to work at the atomic and molecular level, atom by atom, as is the basis of nanotechnology.

The Heisenberg Uncertainty Principle helps determine the size of electron clouds, and hence the size of atoms. According to Werner Heisenberg "The more precisely the POSITION is determined, the less precisely the MOMENTUM is known." Heisenberg's Uncertainty Principle applies only to the subatomic particles like electron, positron, photon, etc. It does not forbid the possibility of nanotechnology, which has to do with the position and momentum of such large particles like atoms and molecules. This is because the mass of the atoms and molecules is quite large, and the quantum mechanical calculation by the Heisenberg Uncertainty Principle places no limit on how well atoms and molecules can be held in place [4].
Although we have long been aware of, and many investigators have been dealing with, “nano” sized entities, the historic birth of the nanotechnology is commonly credited to Feynman. Historically, nanotechnology was for the first time formally recognized as a viable field of research with the landmark lecture delivered by Richard P. Feynman, the famous Noble Laureate physicist on December 29, 1959 at the annual meeting of the American Physical Society [6]. His lecture was entitled "There's Plenty of Room at the Bottom - An invitation to enter a new field of physics." Feynman stated in his lecture that the entire encyclopedia of Britannica could be put on the tip of a needle, and, in principle, there is no law preventing such an undertaking. Feynman then described the advances made in this field in the past, and he envisioned the future for nanotechnology. His lecture was published in the February 1960 issue of Engineering & Science quarterly magazine of the California Institute of Technology.

In his talk, Feynman also described how the laws of nature do not limit our ability to work at the molecular level, atom by atom. Instead, he said, it was our lack of the appropriate equipment and techniques for doing so. Feynman in his lecture talked about "How do we write small?", "Information on a small scale", possibility to have "Better electron microscopes" that could take the image of an atom, doing things small scale through "The marvelous biological system", "Miniaturizing the computer", "Miniaturization by evaporation", an example of which is thin film formation by chemical vapor deposition, solving the "Problems of lubrication" through miniaturization of machinery and nanorobotics, "Rearranging the atoms" to build various nanostructures and nanodevices, and behavior of "Atoms in a small world", which included atomic scale fabrication as a bottom-up approach as opposed to the top-down approach to which we are accustomed [7]. The bottom-up approach is self-assembly of machines from basic chemical building blocks, which is considered to be an ideal through which nanotechnology will ultimately be implemented. The top-down approach is assembly by manipulating components with much larger devices, which is more readily achievable using the current technology.

It is important to mention that almost all of the ideas presented in Feynman's lecture, and even more, are now under intensive research by numerous nanotechnology investigators all around the world. For example, in his lecture Feynman challenged the scientific community and set a monetary reward to demonstrate experiments in support of miniaturizations. Feynman proposed radical ideas about miniaturizing printed matter, circuits, and machines. "There's no question that there is enough room on the head of a pin to put all of the Encyclopedia Britannica," he said. He emphasized, "I'm not inventing antigravity, which is possible someday only if the laws (of nature) are not what we think," adding, "I am telling what could be done if the laws are what we think; we are not doing it simply because we haven't yet gotten around to it." Feynman’s 1959 challenge for miniaturization and his unerringly accurate forecast was met 31 years later, in 1990, by Eigler and Schweizer [8] by positioning single atoms using a nanotechnology tool called scanning tunneling microscope (STM), the result of which is shown in Fig. 2a. Note other images reported in Fig. 2 also produced by scientists at the IBM Almaden Research Center.

In 1983 Feynman talked about a scaleable manufacturing system, which could be made to manufacture a smaller scale replica of itself [9]. That, in turn would replicate itself in smaller scale, and so on down to molecular scale. Feynman was subscribing to the “Theory of Self-Reproducing Automata” proposed by von Neumann, the 1940s eminent mathematician and physicist who was interested in the question of whether a machine can self-replicate, that is, produce copies of itself (see [10] for details). The study of man-made self-replicating systems has been taking place now for more than half a century. Much of this work is motivated by the
desire to understand the fundamentals involved in self-replication and advance our knowledge of single-cell biological self-replications.

FIG. 2—Samples of nanolithography made using the scanning tunneling microscope by the scientists at IBM Almaden Research Center, San Jose, CA (www.almaden.ibm.com) as predicted by Feynman in 1959: (a) “The Beginning” - Writing one atom at a time with xenon atoms on a nickel (110) surface; (b) "atom" - This image shows iron on copper atoms forming the Kanji characters for the word “atom,” which translates as “original child.” In Japanese Kanji, writing literally with atoms —each just a few nanometers across; (c) “NANO USA” - This image is made of 112 carbon monoxide molecules on a copper surface.

Some of the other recent important achievements which Feynman mentioned in his 1959 lecture include the manipulation of single atoms on a silicon surface [11] and the trapping of single, 3-nm diameter, colloidal particles from solution using electrostatic methods [12].

In the early 1960s there was other ongoing research on small systems, but with a different emphasis. A good example is the publication of two books on "Thermodynamics of Small Systems" by T. L. Hill in the early 1960s [13]. Hill now terms thermodynamics of small systems "nanothermodynamics" [14]. Some recent developments on this subject are presented in [3,5,15].

In the 1960s when Feynman recognized and recommended the importance of nanotechnology, the devices necessary for nanotechnology were not invented yet. At that time, the world was intrigued with space exploration, discoveries, and the desire and pledges for travel to the moon, partly due to political rivalries of the time and partly due to its bigger promise of new frontiers that man had also not captured yet. Research and development in small (nano) systems did not sell very well at that time with the governmental research funding agencies, and as a result the scientific community paid little attention to it.

It is only appropriate to name the nanometer scale “the Feynman (φnman) scale” after Feynman’s great contribution, and we suggest the notation "φ," for it like Å as used for Angstrom scale and µ as used for micron scale.

One Feynman (φ) ≡ 1 Nanometer (nm) = 10 Angstroms (Å) = 10⁻³ Micron (µ) = 10⁻⁹ Meter (m)
Some Recent Key Inventions and Discoveries

*Scanning Tunneling Microscope*

Nanotechnology received its greatest momentum with the invention of scanning tunneling microscope (STM) in 1985 by Gerd K. Binnig and Heinrich Rohrer, staff scientists at IBM's Zürich Research Laboratory [16]. That happened 41 years after Feynman’s predictions. To make headway into a realm of molecule-sized devices, it would be necessary to survey the landscape at that tiny scale (Fig. 3). Binning and Rohrer’s scanning tunneling microscope offered a new way to do just that.

![STM and AFM](image)

**FIG. 3—Comparison of the operations of a scanning tunneling microscope (STM) and an atomic force microscope (AFM).**

STM allows imaging solid surfaces with atomic scale resolution. It operates based on tunneling current, which starts to flow when a sharp tip is mounted on a piezoelectric scanner approaches a conducting surface at a distance of about 1 nm (1 \( \phi \)). This scanning is recorded and displayed as an image of the surface topography. Actually, the individual atoms of a surface can be resolved and displayed using STM.

*Atomic Force Microscope*

The Nobel Prize award in 1986 to Binnig and Rohrer for the discovery of STM was quickly followed by the development of a family of related techniques which, together with STM, may be classified in the general category of Scanning Probe Microscopy (SPM) techniques. Of the latter technologies, the most important is undoubtedly the atomic force microscope (AFM) developed in 1986 by Binnig, Quate, and Gerber [17]. Figure 3 shows operation schematics of AFM and STM.

An AFM is a combination of the principle of STM and the stylus profilometer. It enables us to study non-conducting surfaces, because it scans van der Waals forces with its "atomic" tips. Presently several vendors are in the market with commercial AFMs. AFM and STM possess three-dimensional resolutions up to the atomic scale, which cannot be met by any other microscope. The AFMs sold by most manufacturers are generally user-friendly, and they produce detailed images. AFM has found versatile applications in nanotechnology as well as other fields of science and engineering. The main components of this tool are a thin cantilever with an extremely sharp (1–10 \( \phi \) [nm] in radius) probing tip, a 3-D piezo-electric scanner, and an optical system to measure deflection of the cantilever. When the tip is brought into contact with the surface or its proximity, or is tapping the surface, it is being affected by a combination of the...
surface forces (attractive and repulsive). Those forces cause cantilever bending and torsion, which is continuously measured via the deflection of the reflected laser beam.

The 3-D scanner moves the sample or, in alternative designs, the cantilever, in three dimensions, thus scanning a predetermined area of the surface. A vertical resolution of this tool is extremely high, reaching \(0.01 \, \phi \, [\text{nm}]\), which is on the order of atomic radius.

**Buckyballs**

By far, the most popular discovery in nanotechnology is the Buckminsterfullerene molecules. Buckminsterfullerene (or fullerene), \(C_{60}\), as shown in Fig. 4, is another allotropic of carbon (after graphite and diamond), which was discovered in 1985 by Kroto and collaborators [18]. These investigators discovered fullerene through laser evaporation of graphite. For this discovery, Curl, Kroto, and Smalley were awarded the 1996 Nobel Prize in Chemistry. Later, fullerenes with a larger number of carbon atoms (\(C_{76}, C_{80}, C_{240}\), etc.) were also discovered.

![FIG. 4—The four allotropes of carbon (Graphite, Diamond, Carbon Nanotube, Fullerene).](image)

Since the time of discovery of fullerenes over a decade and a half ago, a great deal of investigation has gone into these interesting and unique nanostructures. They have found many applications in nanotechnology. In 1990 a more efficient and less expensive method to produce fullerenes was developed by Krächmer and collaborators [19]. Further research on this subject to produce less expensive fullerene is in progress [20]. Availability of low cost fullerene will pave the way for further research into practical applications of fullerene and its role in nanotechnology as reported in Table 1.

**Carbon Nanotubes**

Carbon nanotubes were discovered by Iijima [21] in 1991 using an electron microscope while studying cathodic material deposition through vaporizing carbon graphite in an electric arc-evaporation reactor under an inert atmosphere during the synthesis of fullerenes [22]. The nanotubes produced by Iijima appeared to be made up of a perfect network of hexagonal graphite rolled up to form a hollow tube (Fig. 4).

The nanotube diameter range is from one to several nanometers, which is much smaller than its length range, which is from one to a few micrometers. A variety of manufacturing techniques has since been developed to synthesize and purify carbon nanotubes with tailored characteristics and functionalities. Controlled production of single-walled carbon nanotubes is one of the favorite forms of carbon nanotube, which has many present and future applications in nanoscience and nanotechnology. Laser ablation chemical vapor deposition joined with metal-catalyzed disproportionation of suitable carbonaceous feedstock are often used to produce carbon
nanotubes [23–25]. Figure 5 shows the scanning electron microscope (SEM) images of a cluster of nanotubes recently produced through plasma enhanced chemical vapor deposition at two different temperatures [23].

<table>
<thead>
<tr>
<th>TABLE 1—Some present and envisioned future applications of fullerene.</th>
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<tbody>
<tr>
<td>Astrochemistry</td>
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<tr>
<td>Batteries</td>
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<td>Drug delivery</td>
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<tr>
<td>Geochemistry</td>
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<tr>
<td>Hydrogen storage</td>
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<tr>
<td>Lubricant</td>
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<tr>
<td>Magnetic resonance imaging contrast agents</td>
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<tr>
<td>Medicine</td>
</tr>
<tr>
<td>Nano ball bearings</td>
</tr>
<tr>
<td>Solar cells</td>
</tr>
<tr>
<td>Superconductors</td>
</tr>
<tr>
<td>Tough protective coatings</td>
</tr>
<tr>
<td>Trapping reactive species</td>
</tr>
<tr>
<td>Variety of biological applications</td>
</tr>
<tr>
<td>DNA photocleavage</td>
</tr>
<tr>
<td>Neuroprotection</td>
</tr>
<tr>
<td>Anti-bacterial and anti-virus activity</td>
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</tbody>
</table>

FIG. 5—Carbon nanotubes produced using plasma-enhanced chemical vapor deposition at various temperatures [23]. SEM images of deposited carbon nanotubes at (a) 650°C, (b) 700°C.

Carbon nanotubes and fullerenes are shown to exhibit unusual photochemical, electronic, thermal, and mechanical properties [26–29]. It is also shown that single-walled carbon nanotubes (SWCNTs) could behave like metallic, semi-metallic, or semi-conductive one-dimensional objects [26], and their longitudinal thermal conductivity could exceed the in-plane thermal conductivity of graphite [27]. Very high tensile strength (~100 times that of steel) of ropes made of SWCNTs has recently been determined experimentally [28]. When dispersed in another medium, it is demonstrated that SWCNTs could retain their intrinsic mechanical attributes or even augment the structural properties of their medium host [29]. SWCNTs have similar electrical conductivity as copper and similar thermal conductivity as diamond.

There is a great deal of interest and activity today to find applications for fullerene and carbon nanotube, some of which are reported in Table 2. There are many ongoing research
activities to understand the characteristics of carbon nanotubes, including their physicochemical properties, their stability and behavior under stress and strain, their interactions with other molecules and nanostructures, and their utility for novel applications [3,30,31].

### TABLE 2—Some present and envisioned future applications of carbon nanotube.

<table>
<thead>
<tr>
<th>Composite</th>
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<tbody>
<tr>
<td>CRT emitter</td>
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<tr>
<td>Field emission display (FED)</td>
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<tr>
<td>Fuel cell electrode</td>
</tr>
<tr>
<td>Gas sensors</td>
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<tr>
<td>High density device</td>
</tr>
<tr>
<td>Hydogen storage</td>
</tr>
<tr>
<td>LCD backlight</td>
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<tr>
<td>Microwave device</td>
</tr>
<tr>
<td>Nanocapsule</td>
</tr>
<tr>
<td>Nanopipet</td>
</tr>
<tr>
<td>Nanoscale wire</td>
</tr>
<tr>
<td>Nanotweezer</td>
</tr>
<tr>
<td>Oil absorbent</td>
</tr>
<tr>
<td>Secondary battery</td>
</tr>
<tr>
<td>Single electron transistor (SET)</td>
</tr>
<tr>
<td>STM/AFM tip</td>
</tr>
<tr>
<td>Ultra small diods</td>
</tr>
<tr>
<td>Vacuum fluorescent display (VFD)</td>
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<tr>
<td>White light source</td>
</tr>
</tbody>
</table>

### Diamondoids

The smallest diamondoid molecule was first discovered and isolated from Czechoslovakian petroleum in 1933. The isolated substance was named adamantane, from the Greek for diamond. This name was chosen because it has the same structure as the diamond lattice, highly symmetrical and strain free as shown in Fig. 6. It is generally accompanied by small amounts of alkylated adamantanes: 2-methyl-; 1-ethyl-; and probably 1-methyl-; 1,3-dimethyl; and others. From the bionanotechnology point of view, diamondoids are in the category of organic nanostructures [32].

![FIG. 6—Molecular structures of diamondoid molecules. These compounds have diamond-like fused ring structures, which can have many applications in nanotechnology. They have the same structure as the diamond lattice, i.e., highly symmetrical and strain free. The rigidity, strength, and assortment of their 3-D shapes make them valuable molecular building blocks.](image)
The unique structure of adamantane is reflected in its highly unusual physical and chemical properties. The carbon skeleton of adamantane comprises a small cage structure. Because of this, adamantane and diamondoids in general are commonly known as cage hydrocarbons. In a broader sense they may be described as saturated, polycyclic, cage-like hydrocarbons. The diamond-like term arises from the fact that their carbon atom structure can be superimposed upon a diamond lattice. The simplest of these polycyclic diamondoids is adamantane, followed by its homologous diamantine and tria-, tetra-, penta-, and hexamantane.

Diamondoids have diamond-like fused ring structures, which can have applications in nanotechnology [7,33,34]. They have the same structure as the diamond lattice, i.e., highly symmetrical and strain free. Diamondoids offer the possibility of producing a variety of nanostructural shapes. We expect them to have the potential to produce possibilities for application as molding and cavity formation characteristics due to their organic nature and their sublimation potential. They have quite high strength, toughness, and stiffness compared to other known molecules.

Diamondoids are named as the building blocks for nanotechnology [7,33–35]. Table 3 constitutes a partial list of applications of diamondoids in nanotechnology and other fields [3,36].

**TABLE 3—Some present and envisioned future applications of diamondoids.**

| Antiviral drug | Cages for drug delivery | Combinatorial chemistry |
| Design of molecular capsules | Design of multifunctional drug systems and drug carriers |
| Drug Targeting | Fluorescent molecular probes | Gene Delivery |
| Design of artificial red blood cell | Host-guest chemistry | Nanorobots |
| Molecular machines | Molecular Probe | Nanodevices |
| Nanofabrication | Nanomodule | Organic molecular building blocks in formation of nanostructures |
| Pharmacophore-based drug design | Positional assembly | Self-assembly |
| Shape-targeted nanostructures | Synthesis of supramolecules | Semiconductors |

**Cyclodextrins, Liposome, and Monoclonal Antibody**

At the same time that chemists, materials scientists, and physicists have been experimenting with structures like buckyballs, carbon nanotubes, and diamondoids, biologists have been making advances with other nanoscale structures like cyclodextrins [37], liposomes [38], and monoclonal antibodies [39]. These biological nanostructures have many applications, including drug delivery and drug targeting.
Cyclodextrins, as shown in Fig. 7, are cyclic oligosaccharides. Their shape is like a truncated cone, and they have a relatively hydrophobic interior. They have the ability to form inclusion complexes with a wide range of substrates in aqueous solutions. This property has led to their application for encapsulation of drugs in drug delivery.

![Chemical formula and structure of Cyclodextrins](image)

**Fig. 7**—Chemical formula and structure of Cyclodextrins – For \( n = 6 \) it is called \( \alpha\)-CD\( \times \); \( n = 7 \) it is called \( \beta\)-CD\( \times \); \( n = 8 \) it is called \( \gamma\)-CD\( \times \). Cyclodextrins are cyclic oligosaccharides. Their shape is like a truncated cone, and they have a relatively hydrophobic interiors. They have the ability to form inclusion complexes with a wide range of substrates in aqueous solution. This property has led to their application for encapsulation of drugs in drug delivery.

Liposome is a spherical synthetic lipid bilayer vesicle, created in the laboratory by dispersion of a phospholipid in aqueous salt solutions. Liposome is quite similar to a micelle with an internal aqueous compartment. Liposomes, which are in nanoscale size range, as shown in Fig. 8, self-assemble based on hydrophilic and hydrophobic properties, and they encapsulate materials inside. Liposome vesicles can be used as carriers for a great variety of particles, such as small drug molecules, proteins, nucleotides, and even plasmids to tissues and into cells. For example, a recent commercially available anticancer drug is a liposome, loaded with doxorubicin, and it is approximately 100-nm in diameter.

![Cross-section of a liposome](image)

**Fig. 8**—Cross-section of a liposome, a synthetic lipid bilayer vesicle that fuses with the outer cell membrane and is used to transport small molecules to tissues and into cells.
A monoclonal antibody protein molecule consists of four protein chains, two heavys, and two lights, which are folded to form a Y-shaped structure (see Fig. 9). It is about 10 nm in diameter. This small size is important, for example, to ensure that, intravenously administered, these particles can penetrate small capillaries and reach cells in tissues where they are needed for treatment. Nanostructures smaller than 20 $\phi$ [nm] can transit out of blood vessels.

![Antibody & its Structure](image)

**FIG. 9—**An antibody is a protein (also called an immunoglobulin) that is manufactured by lymphocytes (a type of white blood cell) to neutralize an antigen or foreign protein.

### Research and Development Activities

The atomic-scale and cutting-edge field of nanotechnology is likely to have a revolutionary impact on the way things will be done, designed, and manufactured in the future. Nanotechnology is entering into all aspects of science and technology, including, but not limited to, aerospace, agriculture, bioengineering, biology, energy, the environment, materials, manufacturing, medicine, military science, and technology. It is an atomic and molecular manufacturing approach for building chemically and physically stable structures one atom or one molecule at a time. Presently, some of the active nanotechnology research areas include nanolithography, nanodevices, nanorobotics, nanocomputers, nanopowders, nanostructured catalysts and nanoporous materials, molecular manufacturing, diamondoids, carbon nanotube, and fullerene products, nanolayers, molecular nanotechnology, nanomedicine, and nanobiology.

We have known for many years that several existing technologies depend crucially on processes that take place on the nanoscale. Adsorption, lithography, ion-exchange, catalysis, drug design, plastics, and composites are some examples of such technologies. The "nano" aspect of these technologies was not known, and, for the most part, they were initiated accidentally by mere luck. They were further developed using tedious trial-and-error laboratory techniques due to the limited ability of the time to probe and control matter on nanoscale. Investigations at nanoscale were left behind as compared to macro scale because significant developments of the nanoscale investigative tools have been made only recently.

The above mentioned technologies, and more, stand to be improved vastly as the methods of nanotechnology develop. Such methods include the possibility to control the arrangement of atoms inside a particular molecule and, as a result, the ability to organize and control matter simultaneously on several length scales. The developing concepts of nanotechnology seem pervasive and broad. It is expected to influence every area of science and technology, in ways that are clearly unpredictable.

Nanotechnology will also help solve other technology and science problems. For example, we are just now starting to realize the benefits that nanostructuring can bring to the following:
(a) wear-resistant tires made by combining nanoscale particles of inorganic clays with polymers, as well as other nanoparticle reinforced materials
(b) greatly improved printing brought about by nanoscale particles that have the best properties of both dyes and pigments as well as advanced ink jet systems
(c) vastly improved new generation of lasers, magnetic disk heads, nanolayers with selective optical barriers, and systems on a chip made by controlling layer thickness to better than a nanometer
(d) design of advanced chemical and bio-detectors
(e) nanoparticles to be used in medicine with vastly advanced drug delivery and drug targeting capabilities
(f) chemical-mechanical polishing with nanoparticle slurries, hard coatings, and high hardness cutting tools

The following selected observations regarding the expected future advances are also worth mentioning at this juncture [2]:

(A) The most complex arrangements of matter known to us are those of living entities and organs. Functions of living organisms depend on specific patterns of matter on all various length scales. Methods of nanotechnology could provide a new dimension to the control and improvement of living organisms.
(B) Photolithographic patterning of matter on the micro scale has led to the revolution in microelectronics over the past few decades. With nanotechnology, it will become possible to control matter on every important length scale, enabling tremendous new power in materials design.
(C) Biotechnology is expected to be greatly influenced by nanotechnology in a couple of decades. It is anticipated that, for example, this will revolutionize healthcare to produce ingestible systems that will be harmlessly flushed from the body if the patient is healthy but will notify a physician of the type and location of diseased cells and organs if there are problems.
(D) Micro and macro systems constructed of nanoscale components are expected to have entirely new properties that have never before been identified in nature. As a result, by altering and design of the structure of materials in the nanoscale range, we would be able to systematically and appreciably modify or change selected properties of matter at macro and micro scales. This would include, for example, production of polymers or composites with most desirable properties which nature and existing technologies are incapable of producing.
(E) Robotic spacecrafts that weigh only a few pounds will be sent out to explore the solar system, and perhaps even the nearest stars. Nanoscale traps will be constructed that will be able to remove pollutants from the environment and deactivate chemical warfare agents. Computers with the capabilities of current workstations will be the size of a grain of sand and will be able to operate for decades with the equivalent of a single wristwatch battery.
(F) There are many more observations in the areas of inks and dyes, protective coatings, dispersions with optoelectronic properties, nanostructured catalysts, high reactivity reagents, medicine, electronics, structural materials, diamondoids, carbon nanotube and
 fullerene products and energy conversion, conservation, storage, and usage which are also worth mentioning.

(G) Many large organic molecules are known to form organic nanostructures of various shapes as shown in Figs. 6 and 10, the deriving force of which is the intermolecular interaction energies between such macromolecules [40–42].

![Organic nanostructure self-assemblies of various shapes](image)

FIG. 10—Organic nanostructure self-assemblies of various shapes [40,41].

There has been an appreciable progress in research during the past few years on organic nanostructures, such as thin film nanostructures, which have excellent potential for use in areas that are not accessible to more conventional, inorganic nanostructures. The primary attraction of organic nanostructures is their potential for molding, coating, and the extreme flexibility that they have in being tailored to meet the needs of a particular application. The organic nanostructure materials are easily integrated with conventional inorganic nanostructures (like semiconductor devices), thereby providing additional functionality to existing photonic circuits and components. Some progress has been made in understanding the formation and behavior of organic nanostructures that might be formed to serve as elements of nanomaterials and also on synthetic strategies for creating such structures [40–42]. The ultimate goal is to achieve a better understanding of the fundamental molecular processes and properties of these nanostructures, which are dominated by grain boundaries and interfaces. In understanding the behavior and the properties of these nanostructures, the potential for technological applications will be considered.

Table 4 demonstrates a number of the major expected future and few present activities and possibilities resulting from advances in nanotechnology. According to this table, the impact of implementation of nanotechnology is quite broad. The list of possibilities is expanding quite rapidly.

The impacts of nanotechnology advances are being felt in broad areas of science and technology. It should be pointed out that nanoelectronic, nanolithography, nanosensors, and drug delivery industries have a much clearer and more distinguished future.

Table 5 demonstrates the expected trend in nanolithography advances indicating various technologies under investigation for development of pilot and production lines of ICs (integrated circuits). As an example, the half pitch of the dynamic random access memory (DRAM), a type of memory used in most personal computers, (i.e., smallest feature size) is expected to go below the 100 φ [nm] mark by about 2005. Unpredictable adverse economical factors could probably delay the pace of such developments and hence affect the projected milestone dates shown in Table 5.

As of the year 2000, the mass-produced and inexpensive miniaturization process by the semiconductor industry reduced the line widths on IC chips down to about 100 φ [nm] via extension of the standard photolithography [43]. It is argued that since the wavelength of laser
light source determines the width of the smallest line that could be formed on a wafer, to pattern ever-finer lines by the use of photolithography, the industry is now making the transition from a krypton-fluoride excimer laser light source, with wavelength of 248 $\phi [nm]$, to argon-fluoride lasers emitting at 193 $\phi [nm]$ wavelength. Within a few years, even argon-fluoride wavelength will be too long, and the Fluoride lasers at 157 $\phi [nm]$ wavelength would be needed. This should bring about serious optical-property-of-materials challenges, as most common optical materials do not transmit at this low wavelength. Below the fluoride laser wavelength lies the transition to extreme ultraviolet range, known as “soft” X-rays, with a wavelength of about 13 $\phi [nm]$.

**TABLE 4—Some of the expected future products and possibilities resulting from advances in nanotechnology.**

<table>
<thead>
<tr>
<th>Biological</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drug delivery</td>
</tr>
<tr>
<td>Antimicrobial (Drug-resistant bacteria)</td>
</tr>
<tr>
<td>Biochip (lab-on-chip)</td>
</tr>
<tr>
<td>Targeted therapeutics</td>
</tr>
</tbody>
</table>

**Tools**

Software: (Modeling & simulation of nanomaterials, Virtual reality)

- Nanocompositioning
- Nanomanipulators
- Nanoimaging techniques (STM, AFM, ...)

**Nanodevices**

Nanoelectronics (Logic devices, Memory, Display, Field-Emission devices)

- Nano/Bio chemical/biological sensors
- Optical Components

**Interface Phenomena**

High surface area (Catalysts, Coating, etc.)

**Synthesis & Assembly**

- Self-assembly
- Chemical precipitation
- Physical/Chemical aerosol techniques (Clusters, Nanoparticles)

**Materials**

Use of molecular-building-blocks in composite/coating

- Single-molecule coating
- Lab-on-chip
- Antitumor agents
- Fabrics
- Metal powders
- Ceramic fibers
- Clays
- Crystals
- Rocket fuel
- Thin films
- Coatings
- Skin care

**Molecular Machines**
TABLE 5—The International Technology Roadmap for Semiconductors 2004 Update Overall Roadmap Technology Characteristics’ goals, or "nodes," for rapid decreases in chip size and increases in computer-processor speed (from http://public.itrs.net/).

<table>
<thead>
<tr>
<th>Year of Production</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology Node</td>
<td>hp90</td>
<td>hp90</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DRAM ½ Pitch (nm)</td>
<td>100</td>
<td>90</td>
<td>80</td>
<td>70</td>
<td>65</td>
<td>57</td>
<td>50</td>
</tr>
<tr>
<td>MPU/ASIC Metal I (MH) ½ Pitch (nm)</td>
<td>120</td>
<td>107</td>
<td>95</td>
<td>85</td>
<td>76</td>
<td>67</td>
<td>60</td>
</tr>
<tr>
<td>MPU/ASIC ½ Pitch (nm) (Un-contacted Poly)</td>
<td>107</td>
<td>90</td>
<td>80</td>
<td>70</td>
<td>65</td>
<td>57</td>
<td>50</td>
</tr>
<tr>
<td>MPU Printed Gate Length (nm)</td>
<td>65</td>
<td>53</td>
<td>45</td>
<td>40</td>
<td>35</td>
<td>32</td>
<td>28</td>
</tr>
<tr>
<td>MPU Physical Gate Length (nm)</td>
<td>45</td>
<td>37</td>
<td>32</td>
<td>28</td>
<td>25</td>
<td>22</td>
<td>20</td>
</tr>
<tr>
<td>Cell area factor [a]</td>
<td>8</td>
<td>8</td>
<td>7.5</td>
<td>7</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Cell area [Ca = a²] (nm²)</td>
<td>0.082</td>
<td>0.065</td>
<td>0.048</td>
<td>0.036</td>
<td>0.028</td>
<td>0.019</td>
<td>0.015</td>
</tr>
<tr>
<td>Cell array area at production (% of chip size) §</td>
<td>63.00%</td>
<td>63.00%</td>
<td>63.00%</td>
<td>63.00%</td>
<td>63.00%</td>
<td>63.00%</td>
<td>63.00%</td>
</tr>
<tr>
<td>Generation at production §</td>
<td>1G</td>
<td>1G</td>
<td>1G</td>
<td>2G</td>
<td>2G</td>
<td>4G</td>
<td>4G</td>
</tr>
<tr>
<td>Functions per chip (Gbits)</td>
<td>1.07</td>
<td>1.07</td>
<td>1.07</td>
<td>2.15</td>
<td>2.15</td>
<td>4.29</td>
<td>4.29</td>
</tr>
<tr>
<td>Chip size at production (mm²) §</td>
<td>139</td>
<td>110</td>
<td>82</td>
<td>122</td>
<td>97</td>
<td>131</td>
<td>104</td>
</tr>
<tr>
<td>Gbits/cm² at production §</td>
<td>0.77</td>
<td>0.97</td>
<td>1.31</td>
<td>1.76</td>
<td>2.22</td>
<td>3.27</td>
<td>4.12</td>
</tr>
</tbody>
</table>

DRAM = dynamic random access memory; MPU = Microprocessor Unit; ASIC = Application-Specific Integrated Circuit. For DRAM, key drivers of chip size are cell-area-factor (cell area in units of minimum feature size squared), cell-array-area percentage, and the number of functions per chip.

The Semiconductor Industry Association periodically outlines future prospects and challenges in a technology "roadmap." Anticipated milestones are called "nodes," defined as a bi-yearly reduction in the size of commercially manufactured chips, leading to an increase in chip density by a factor of two. Nodes are expressed as distances in nanometers, half the distance, or pitch, between lines in a set of equally wide, equally spaced lines etched into a chip like a DRAM or MPU (microprocessor unit). Nodes at 90, 65, 45, and 32 φ [nm] are expected to be reached within the decade. In nanotechnology, this method of fabrication (i.e., photolithography) is referred to as “top-down” approach. The standard microelectronic fabrication for inexpensive and mass-produced integrated circuit chips could reach its limit, and then we will speak of nanofabrication, something not yet converged, and a subject of intense research.

Many other unpredictable advances resulting from nanotechnology are inevitable. Thus, the future prospects for nanotechnology actually represent a revolutionary super-cutting-edge field that is expected to eventually become the foundation for many disparate areas that we cannot even foresee at this time. It is then no wonder that it is considered to lead the humanity to the next industrial revolution.

Future Prospects in Nanotechnology

Presently, nanotechnology, together with its associated research discipline of nanoscience, constitute the complete spectrum of activities spanning the whole spectrum of physical,
chemical, biological, and mathematical sciences. The emerging fields of nanoscience and nanotechnology are also creating the necessary experimental and computational tools for the design and fabrication of nano-dimensional electronic, photonic, biological, and energy transfer components, such as quantum dots, atomic wires, operating on nanoscopic length scales, etc.

Nanoscience and nanotechnology should have major impacts on several key scientific and technological activities in a not too distant future. Expansions on these subjects will have much to do on the technological advances in instruments and tools of fabrication and manipulation in nano scale. Such instruments and tools are the means for live visualization and manipulation in a nano world. They are presently expensive, and as a result, not available to many investigators. Technological advances are always followed with reduction of prices, as has been the case with the electronic and communication industry products in recent decades.

The decisive and important leading role of molecular-based techniques for the study of matter in the fields of nanoscience and nanotechnology is well understood. Any development in this field will have a great deal to do with advances in these techniques. Advances in the molecular based study of matter in nanoscale will help to understand, simulate, predict, and formulate new materials utilizing the fields of quantum and statistical mechanics, intermolecular interaction, molecular simulation, and molecular modeling [5,42]. We may then be able to understand how to design new molecular building blocks, which could allow self-assembly or self-replication to advance the bottom-up approach of producing the necessary materials for the advancement of nanotechnology. The past trend of the contributions of molecular based study of matter in macroscopic technologies is indicative of the fact that its future influence into nanoscience and nanotechnology is quite promising [3].

**Standardization in Nanotechnology**

As progress is made in nanotechnology toward our ability to manipulate matter on an atomic and molecular scale, it will become necessary to develop national and international standards in material properties, measurements, nomenclature, and terminology. In general, standards are needed (i) for consistent characterization and measurement of all nanomaterials, (ii) to facilitate the inter-operability of nanoscale devices and system architectures, and (iii) to enable all parties involved to communicate in common terms [44]. It is estimated that about 2000 companies in 35 countries are committed to nanotechnology already. Standardization will help to bring about faster commercialization of nanotechnology. There is a variety of standardization activities initiated or underway by different organizations, some of which are presented below.

**ANSI**

In August 2004 the American National Standards Institute (ANSI) created the Nanotechnology Standards Panel (http://www.ansi.org/nsp/), a new coordinating body for the development of standards in the area of nanotechnology. The Office of Science and Technology Policy in the Executive Office of the President asked ANSI to address this area of standardization in support of academics, various industries, the investment community, and government agencies that utilize nanotechnology. ANSI-NSP serves as the cross-sector coordinating body for the purpose of developing standards in the area of nanotechnology, including, but not limited to, nomenclature/terminology, materials properties, and testing, measurement and characterization procedures.

Objectives of the ANSI-NSP are defined below:
• Coordinate and provide a forum for academia, individual industries, standards developing organizations, and governmental entities to define needs, determine work plans, and establish priorities for updating standards or creating new standards.
• Solicit participation from nanotechnology-related sectors and academia that have not traditionally participated in the voluntary standards system, and work cooperatively to achieve the mission of the ANSI-NSP.
• Facilitate the timely development and adoption of standards responsive to identified needs in the area of nanotechnology in general and nomenclature/terminology specifically.
• Facilitate and promote cross-sector collaborative efforts between standards developing organizations to establish work plans and develop joint and/or complementary standards.
• Where standards do not exist, obtain agreement from a standard developer to initiate development of the standard in a timely manner.
• Establish and maintain liaison with other national, regional, and international standards efforts addressing nanotechnology issues so as to create identical or to harmonize existing standards.
• Establish and maintain a database of nanotechnology standards, accessible from the Internet, and capable of generating updates, notices, and reports.
• Identify any impediments preventing the timely adoption of needed American National Standards.
• Make widely available the results of the ANSI-NSP’s work.

ASTM International

ASTM International (http://www.astm.org/) has initiated activities (ASTM Committee E56 on Nanotechnology) to address issues related to standards and guidance materials for nanotechnology and nanomaterials, as well as the to coordinate existing ASTM standardization related to nanotechnology needs. ASTM Committee E56 is pending final approval at the April 2005 meeting of the ASTM International Board of Directors. The scope of ASTM Committee E56 will be two-fold: 1) The development of standards and guidance for nanotechnology and nanomaterials, and 2) The coordination of existing ASTM standardization related to nanotechnology needs. ASTM Committee E56 is composed of subcommittees that address the following specific segments within the general subject area covered by the technical committee:

• E56.01 Terminology & Nomenclature
• E56.02 Characterization
• E56.03 Environmental & Occupational Health & Safety
• E56.04 International Law & Intellectual Property
• E56.05 Liaison & International Cooperation
• E56.06 Standards of Care/Product Stewardship
• E56.90 Executive
The International Association of Nanotechnology (http://www.ianano.org/) is a non-profit organization with the goal to foster scientific research and business development in nanotechnology for the benefits of society. IANT forms consortia with affiliated organizations and stakeholders to establish an international standard in toxicology testing procedures and safety guidelines for nanoparticles, while evaluating potential regulations and public policy concerning nanotechnology.

NIST

NIST’s mission regarding nanotechnology is: “Researchers in the seven major laboratories of the National Institute of Standards and Technology (http://www.nist.gov/) are developing measurements, standards, and data crucial to private industry’s development of nanotechnology products for a diverse global market. NIST is working to meet needs shared by the many industries that will require higher-resolution measurements of length, time, force, mass, chemical composition, mechanical properties, and other variables that correspond to the scales of nanotechnology. Complementary efforts aim to develop and “harden” capabilities for manufacturing nanotechnology products.”

Conclusions

A momentous scientific and technological activity has begun, which is our ability to systematically organize and manipulate matter on an atomic and molecular level. Significant accomplishments in performance and changes of manufacturing paradigms are predicted to lead to several breakthroughs in 21st century.

The answer to the question of how soon will nanotechnology mature depends a great deal on the intensity of activities of the scientific and standardization communities or even entire industries. That certainly depends on the efforts by the research and development funding agencies, which are mostly powered by government funds.

Future developments and implementation of nanotechnology could certainly change the nature of almost every human-made object and activity. Its ultimate societal impact is expected to be as dramatic as the first industrial revolution and greater than the combined influences that aerospace, nuclear energy, transistors, computers, and polymers have had in this century.

References


