What Are Nanoscience and Nanotechnology?
A Nano Primer

"Nano" refers to a scale of size in the metric system. ***The prefix nano*** is used in scientific units to denote ***one billionth*** of the base unit. So, **1 nanometer (nm) is 10^{-9} m,** a dimension in the world of atoms and molecules. To help put this size in perspective, one-tenth of 1 nm is approximately the size of an atom. Atoms vary in size according to the element, but their diameters range from about 0.1 to 0.5 nanometer. For example, the size of H atom is approx. 120 pm or 0.120 nm and, therefore, 10 hydrogen atoms lined up side by side measure about ~1 nm long. 1 nm is approximately 80,000 times smaller than the thickness of a human hair. A comparison of the size of nanomaterials with some natural and biological species is illustrated in Figure 1.1.

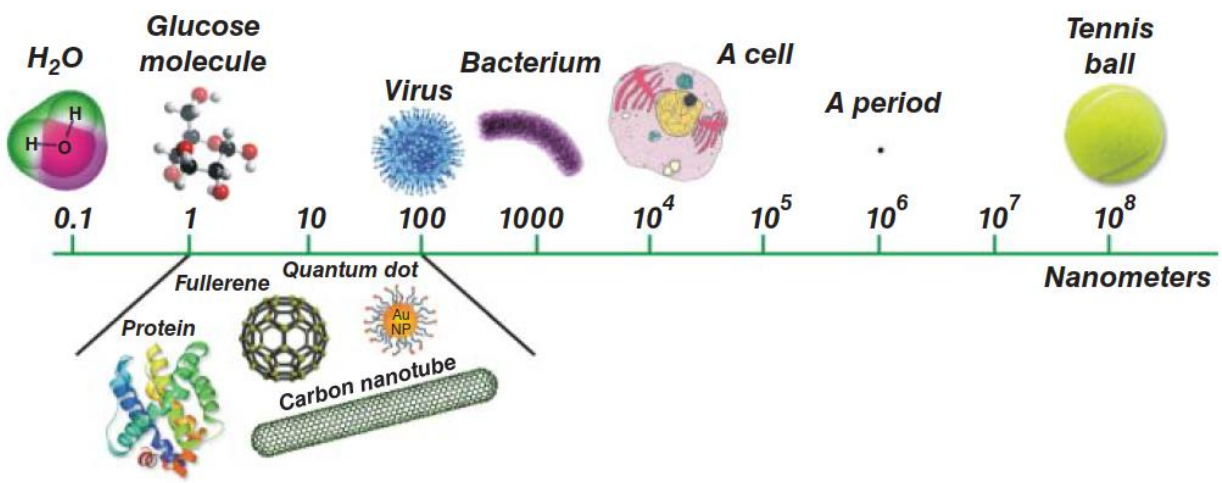
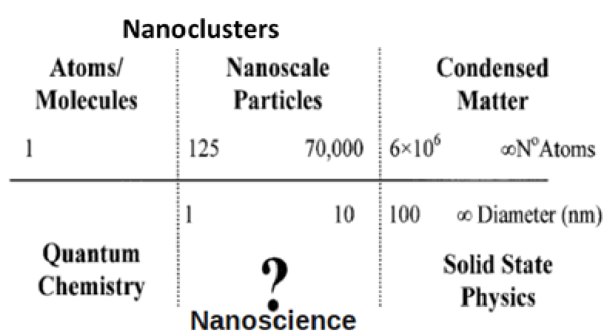


Figure 1.1 Size comparisons of objects, nanomaterials, and biomolecules.

Size relationships of chemistry, 'nanoscience', and condensed matter physics.



UNIQUENESS OF THE NANOSCALE

So why should a fundamental branch of science – one that is applicable to all sciences – be named using the *nano* prefix? ***What is so special about this length scale?*** The ***answer lies in the properties*** of any substance ***that is this small***.

Let's consider the melting point of gold. Find gold's melting point in any reference book for metals; it is listed at exactly **1,064°C** (1,947°F). This temperature can be easily verified by placing a **gold nugget** in a high-temperature furnace and increasing the temperature. When 1,064°C (1,947°F) is reached, the nugget changes its shape and forms a ball of liquid gold. Let's try the experiment again, but this time, instead of a gold nugget that we can see and easily handle, let's melt a nugget that is only ***a few nanometers in diameter*** (obviously, we'll need special equipment and methods for this, but it can be done). Surprisingly, ***gold's melting temperature in the second case is only 427°C*** (800°F). Have we made a mistake? No!

More experimentation would show that no mistakes were made, and we would actually find that ***the melting temperature of gold particles depends on the size of the particles being heated***. So why do all the reference books list 1,064°C (1,947°F) as gold's melting temperature? Because for all practical purposes, this melting temperature is accurate. If we continued our melting experiments with a range of gold particle sizes, we would find that all the gold particles **that we can see** *melt at this temperature*, from large nuggets to very small nuggets. However, ***when the nugget size is reduced to several tens of nanometers***, we would start to measure a lower melting temperature. ***In the nanosize range, the smaller the particle, the lower the melting temperature.***

This example allows us to easily and precisely *define nanoscience and nanotechnology*. **Nanoscience is the field of science that measures and explains the changes of the properties of substances as a function of size.** Like the melting of gold, the properties of any substance will remain constant as its size gets smaller and smaller—that is, until the size is reduced to the nanoscale (***depending on the substance and the property being measured, roughly 10–100 nm***). *In the dimensional nanoscale, any physical property measured will continuously change with size, and often dramatically so.* ***Nanotechnology*** **is the application of property modifications that happen at the nanoscale to some beneficial endeavor**—and what a warehouse of beneficial endeavors there are! **The promise of nanoscience is so great and the application of nanotechnology so vast that they are projected to change our world, similar to the current biological revolution occurring in genomics.**

It is important to realize from the outset that all substances, including solids, liquids, and gases, show property changes through the nanosize regime. In addition, ***not all three dimensions of a substance need be in the nanoscale*****.** For example, a *nanoparticle* (such as our small, low-melting temperature gold particles described previously) is small in all three dimensions. What if we simply confine one dimension to the nanoscale? With two dimensions unlimited, and one confined, we have created a *nanofilm*, which is a film with a thickness in the nanoscale. Will its physical properties be affected relative to the same substance with no size restrictions? Absolutely.

Consider the following example: Imagine that you have two wires made of aluminum, a metal that conducts electricity well. Imagine connecting each wire to the terminals of a battery, and then touching the surfaces of the wires together. Naturally, a circuit is formed, and an electrical current will flow from one wire to the other. However, the surface of the wires is not conductive aluminum (Al) as one might assume, but instead a thin film of aluminum oxide (Al_2O_3), which covers the aluminum metal. This is because the surface of aluminum – whether the aluminum makes up a wire, a soda can, or an airplane wing—oxidizes in air to an aluminum oxide. The apparent problem in our electrical conduction experiment is that aluminum oxide is a well-known insulator; that is, it does not conduct electricity. So how can a current flow from one wire to the other? The answer lies in the physical dimension of the thin film of aluminum oxide. The coatings on the aluminum wires are very thin, typically 1 nm thick. In this size range the electrical properties of aluminum oxide have changed. When conducting electrons perpendicular to the thin film (that is, across the film from one wire to the next), the aluminum oxide acts more like a conductor, and, therefore, the electrons are free to pass from one wire to the next. In other words, because of the dimensions and geometry of the aluminum oxide, it behaves more like a conductor than an insulator, and good electrical contact between the two wires is the result. Although this is something, we take for granted – or were never aware of in the first place – it is a dramatic result. One simply needs to imagine what electronics would be like if bulk properties also applied to thin films!

In summary, in the examples presented above, we have defined the nanoscale and nanoscience. When characteristic structural features are intermediate between isolated atoms and bulk materials in the range of approximately 1–100 nm, the objects often display attributes substantially different from those displayed by either atoms or bulk materials. We have seen surprising results for two “ordinary” phenomena that we thought we knew everything about, but which were both shown to have surprising twists. *These deceptively simple twists are what the nano revolution is all about.*

So why do nanoscale systems behave differently than bulk systems, on the one hand, and individual atoms or molecules, on the other hand? We know now that there are two fundamentally important phenomena that underlie these differences: The first is the effect of confining electrons to small dimensions, this is called **quantum confinement**. This leads to a host of changes in properties that depend on the size of the nano-object. The second is the effect of **increasing surface area** relative to the bulk meaning that the properties of atoms at the interface become more important than those in the interior of the material. In the extreme there is virtually no bulk material. Yet, for both effects, the assembly of atoms or molecules into small clusters or particles impart properties of the assembly that differ from the individual, constituent parts.

The consequence of both of these effects — quantum confinement and surface-to-volume ratio — is that **size (and morphology) matters**. And this understanding is key to the exploitation of the material properties of nanoscale objects. If we can control the size and shape of the objects, we can control the properties.

Let us clarify this little further. First, let us consider the case of surface area. For a spherical particle of radius, r, the surface area ($4\pi r^2$) to volume ($4\pi r^3/3$) ratio is given by: ($3/r$). It is evident that the smaller the particle (r), the larger is the surface area to volume ratio.

When the size of building blocks gets smaller, the surface area of the material increases by six orders of magnitude, as illustrated in Figure 1.2, while the volume remaining the same. For example, dissecting a 1 m^3 of any material into 1 nm particles increases the total combined surface area from 6 to 60,000,000 m^2, approximately 10 million times larger.

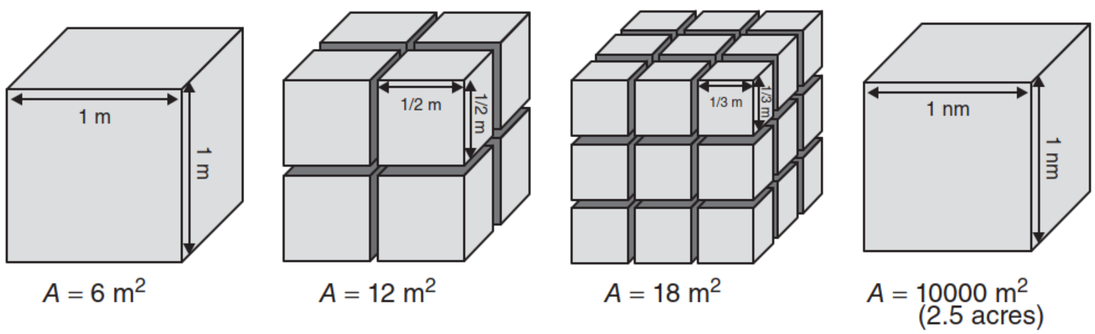


Figure 1.2 Exponential increase in the surface area on breaking cubes of a meter scale to nanometer scale.

Nanomaterials have a wider range of applications such as catalysts, cleanup, and capture of pollution and any other application where chemical reactivity is important such as medicine. This effect occurs at all length scales, but what makes it unique at the nanoscale is that ***the properties of the material become strongly dependent on the surface of the material since the amount of surface is now at the same level as the amount of bulk***. In fact, *in some cases such as fullerenes or single-walled nanotubes****, the material is entirely the surface***.

Another important attribute of nanoscale material is the fact that it is possible for the quantum mechanical properties of matter to dominate over bulk properties. One example of this is in the change in the ***optical properties***, for example, ***in the photoemission***, of many semiconductor materials as they “go nano.” Figure 1.3 illustrates how, a material whose optical properties may be considered uninteresting, simply by changing its size to the nanoscale one can control the color of the material. This effect is due to quantum confinement effect.

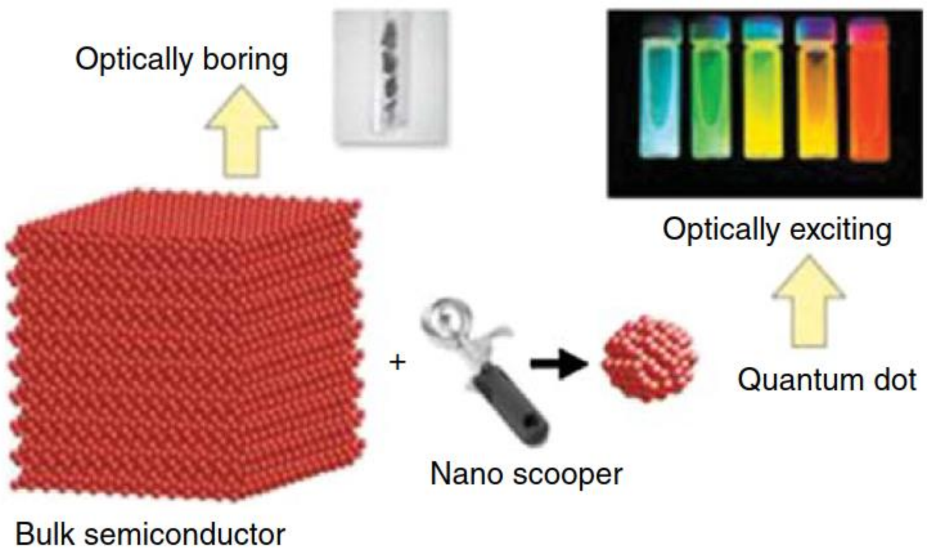


Figure 1.3 Change in optical properties of a semiconductor ranging from bulk to nanosize. Courtesy of Grossman, MIT, USA.

Important consequence of each of these properties is that they offer completely new methods of tuning the properties of materials and devices. Nanotechnology can provide unprecedented understanding about materials and devices and is likely to impact many fields. By using structure at nanoscale as a tunable physical variable, we can greatly expand the range of performance of existing chemicals and materials.

We have the basis for design of objects with predictable, known properties, so we can create new materials to fulfill particular desirable functions that solve specific problems of interest. We can create nanoparticles with desirable catalytic properties for use in catalytic converters. We can create nanoporous materials that will exclusively bind specific molecules to, for example, capture noxious gases emitted at a power plant. We can create structured assemblies that facilitate the absorption of light and capture and transfer electrons into a circuit to enhance the efficiency of solar cells. The possibilities are only limited by our imagination, and that is what makes this such an exciting field for science, engineering, and technology development. The rapidly evolving understanding of biological systems has inspired the design principles of nanotechnology researchers and the intersection of molecular biology and nanotechnology has been critical for the rapid development of the field. In addition, it turns out that the tools and techniques of nanotechnology has been instrumental in unraveling biological phenomena and the products of the nanotechnology revolution promise to have applications in the life sciences, particularly in the areas of diagnostics, therapeutics, and studies of biological structures, dynamics, and interactions.

Some specific reasons why nanoscale has become so important some of which are as the following:

(i) Nanoscale-dependent quantum mechanical (wavelike) properties of electrons inside matter and hence variation in properties, such as charge capacity, magnetization and melting temperature, etc. 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.

Nanoscience and nanotechnology are broad and interdisciplinary areas of research and development activity that have been growing explosively worldwide in the past two decades. Nanoscience has the potential for revolutionizing the methods in which materials and products are created and the range and nature of functionalities that can be accessed; nanotechnology already has a significant commercial impact that will increase exponentially in future.

DEFINITIONS AND TERMS

Nanomaterials: At first glance, it seems simple: nanomaterials are the objects or materials that are on a scale measured by the unit of a nanometer (say 1-100 nm). And this is indeed one component of almost all definitions. However, that turns out not to be sufficiently precise to communicate either scientifically or in legal terms what exactly we are working with. In fact, since the emergence of the concepts of nanoscience and nanotechnology, many definitions have been developed in different jurisdictions across the world and as of now there is no universally accepted definition.

Some definitions of nanomaterials:

• A material with any external dimension in the nanoscale (the length ranging from approximately 1 nm to 100 nm) or having internal structure or surface structure in the nanoscale — *International Organization for Standarization (ISO)*

• A chemical that is either a nano-object (*a material confined in one, two, or three dimensions at the nanoscale* (the size typically range between 1 nm and 100 nm)) or is nano-structured (*having an internal or surface structure at the nano scale*) — *OECD*

• Nanomaterials can exhibit unique optical, mechanical, magnetic, conductive, and sorptive properties different than the same chemical substances in a large size — *US Environmental Protection Agency*

• Both materials that have at least one dimension in the size range of approximately 1 nanometers (nm) to 100 nm and certain materials that otherwise exhibit related dimension-dependent properties and phenomena — *US Food and Drug Administration*

• Materials at or within the nanoscale (meaning 1 to 100 nanometers, inclusive) in at least one dimension, or has internal or surface structures at the nanoscale; or it is smaller or larger than the nanoscale in all dimensions and exhibits one or more nanoscale properties/phenomena — *Health Canada*

• A natural, incidental, or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm - 100 nm — *European Union*

Nanomaterial means a material that meets at least one of the following criteria:

• Consists of particles with one or more external dimensions in the size range of 1–100 nm for more than 1% of their number.

• Internal/surface structures in one or more dimensions in the size range of 1–100 nm.

• Specific surface-to-volume ratio >60 m^2/cm^3, excluding materials consisting of particles with a size less than 1 nm.

It may be that a unique **definition of nanomaterials** is impossible, but it seems that **a good definition needs to refer to the nanoscale (**either a **nano-object** – ***a material confined in one, two, or three dimensions at the nanoscale*** (the size typically range between 1 nm and 100 nm) or a **nano-structured** material – ***having an internal or surface structure at the nanoscale*****);** to the fact that **it has unique properties as a consequence of the scale;** and **whether it is natural or manmade.**

Though the dimension is taken as less than approximately 100 nm, some organizations in some areas such as environment, health, and consumer protection favor a larger size range from 0.3 to 300 nm to define nanomaterials. This larger size range allows more research and a better understanding of all nanomaterials and allows to know whether any particular nanomaterial shows concerns for human health or not and in what size range.

Nanomaterials can be ***nanoscale in one dimension*** (e.g., surface films) ***two dimensions*** (e.g., strands or fibers) or ***three dimensions*** (e.g., precipitates, colloids). They can exist in *single, fused, aggregated, or agglomerated forms with spherical, tubular, and irregular shapes*.

Nanocarbons such as fullerenes, carbon nanotubes, and graphene are excellent examples of nanomaterials.

Nanostructures are the ordered system of one, two, or three dimensions of nanomaterials, assembled with nanometer scale in certain pattern that includes nanosphere, nanotubes, nanorod, nanowire, and nanobelt. Nanostructured materials are classified as zero-, one-, two-, and three-dimensional nanostructures, showing typical examples with varied dimensionality in nanomaterials as in Figure 1.10 (a–i).

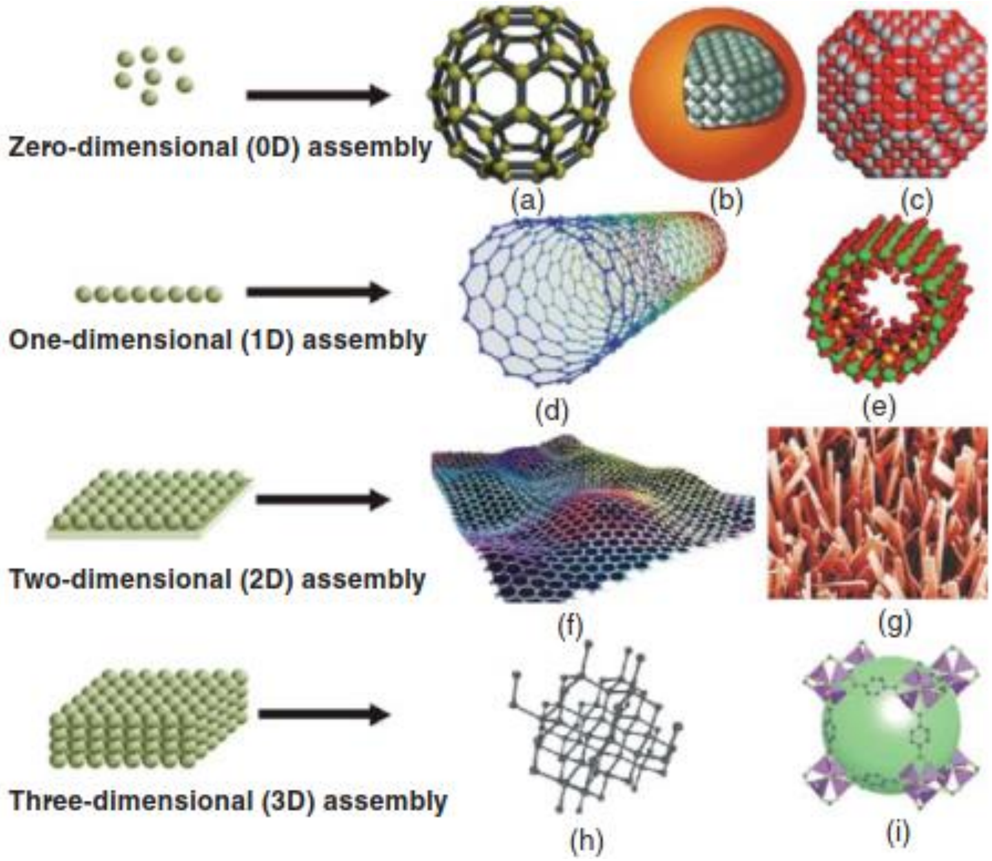


Figure 1.10 Typical examples showing varied dimensionality in nanomaterials: (a) fullerene; (b) quantum dot; (c) metal cluster; (d) carbon nanotube; (e) metal oxide nanotube; (f) graphene; (g) metal oxide nanobelts; (h) nanodiamond; (i) metal-organic frameworks (MOFs).

Nano-object: Material confine in one, two, or three dimensions at the nanoscale. This includes nanoparticles (all three dimensions in the nanoscale), nanofiber (two dimensions in the nanoscale), and nanoplates (one dimension in the nanoscale). Nanofiber are further divided into nanotubes (hollow nanofiber) nanorods (solid nanofiber) and nanowire (electrically conducting or semiconducting nanofiber) However, the term nano-object is not very popular.

Nanocluster: Larger molecular entities having tens to a few hundred atoms (viz., Au_xL_y where x number of atoms of gold make an entity binding with y number of ligand molecules).

Particle: It is a minute piece of matter with defined physical boundaries. A particle can move as a unit. This general particle definition applies to nano-objects.

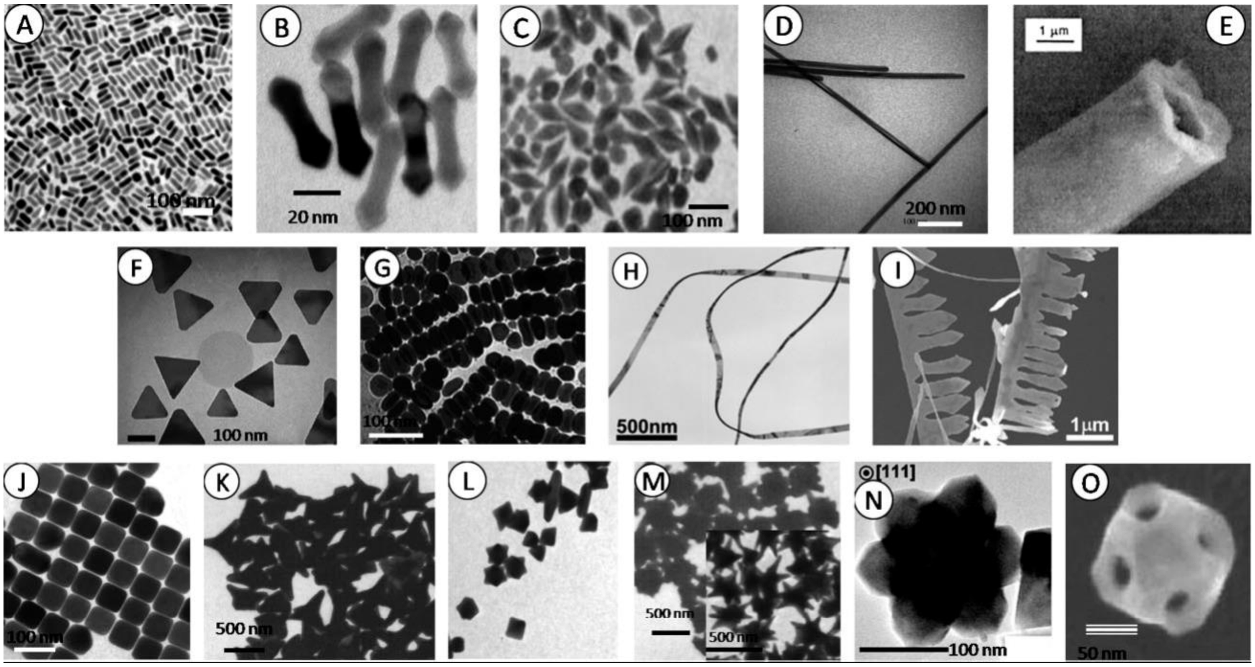
Nanoparticle: It is a nano-object with all three external dimensions in the nanoscale. Nanoparticles constitute of several tens or hundreds of atoms or molecules and can have a variety of sizes and morphologies (amorphous, crystalline, spherical, needles, etc.). Nanoparticles surfaces can act as carriers for liquid droplets or gases.

Nanoparticles of different material classes, for example, metals, semiconductors, carbon, etc. have been prepared by means of several production techniques. Industrial scale production of nanoparticulate materials such as carbon black, polymer dispersions, or micronized drugs has been established for a long time. Another important class of nanoparticulate materials is metal oxide nanopowder that includes silica (SiO_2), titania (TiO_2), alumina (Al_2O_3), or iron oxide (Fe_3O_4, Fe_2O_3); compound semiconductors (e.g., cadmium telluride, CdTe or gallium arsenide, GaAs), metals (especially precious metals such as Ag, Au), and alloys are also included in this category that are being commercialized.

Nanoparticulate matter: It refers to a collection of nanoparticles, emphasizing their collective behavior.

Nanowires and Nanotubes. Linear nanostructures such as nanowires, nanotubes, or nanorods can be generated from different material classes, for example, metals, semiconductors, or carbon, by means of several production techniques. Carbon nanotubes are one of the most promising linear nanostructures that can occur in a variety of modification (e.g., single-, or multiwalled, filled or surface modified) At present, carbon nanotubes can be produced by CVD methods on a several tons per year scale.

Nanoporous Materials. Materials with defined pore sizes in the nanometer range are of special interest for a broad range of commercial applications because of their outstanding properties with regard to thermal insulation, controllable material separation and release, and their applicability as templates or fillers for chemistry and catalysis. One example of nanoporous material is aerogel, which is produced by sol–gel chemistry. A broad range of potential applications of these materials include catalysis, thermal insulation, electrode materials, environmental filters and membranes as well as controlled release of drug carriers.



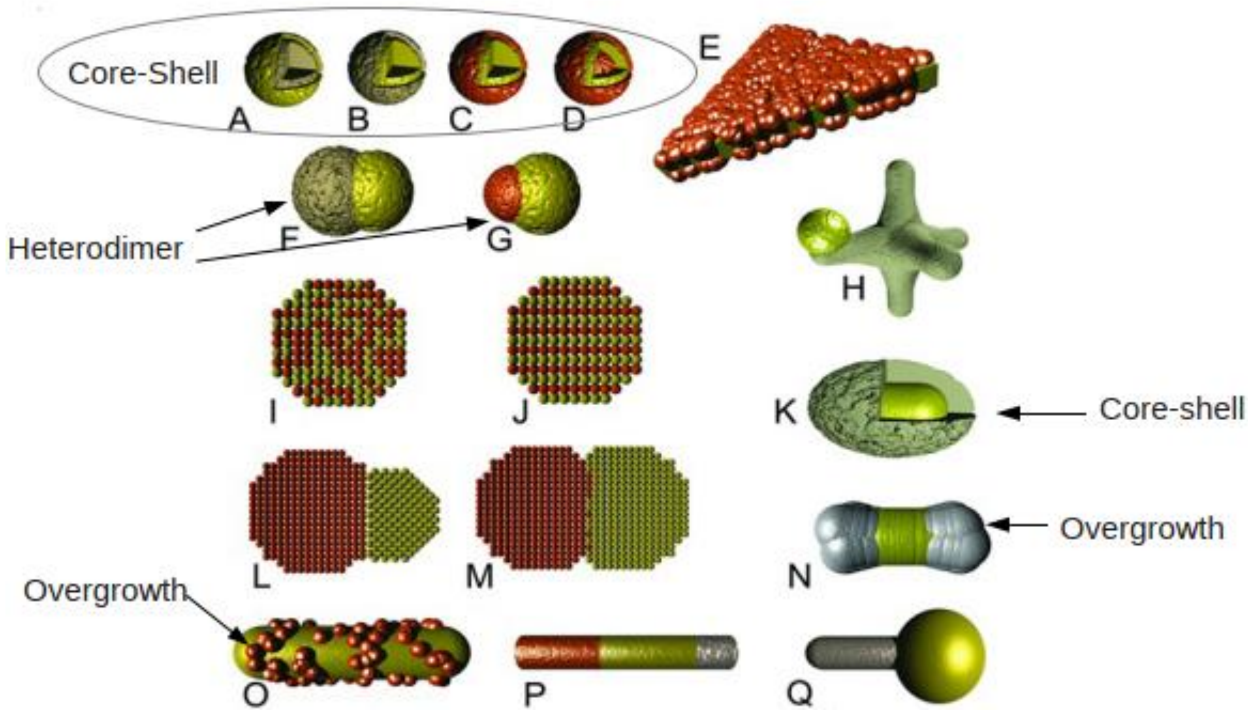
Figure…. showing examples of various shapes of nanoparticles.

Agglomerate: It is a group of particles held together by weak forces such as van der Waals forces, some electrostatic forces, and surface tension. It should be noted that agglomerate will ***usually keep*** a high surface-to-volume ratio.

Aggregate: It is a group of particles held together by strong forces such as those associated with covalent or metallic bonds. It should be noted that an aggregate ***may keep*** a high surface-to-volume ratio.

Nanolayers/Nanocoatings/Hybrid Nanomaterials

Nanolayers are one of the most important topics within the range of nanotechnology. Through nanoscale engineering of surfaces and layers, a vast range of functionalities and new physical effects (e.g., magnetoelectronic or optical) can be achieved. Furthermore, a nanoscale design of surfaces and layers is often necessary to optimize the interfaces between different material classes (e.g., semiconductor compound on silicon wafers) and to obtain the desired special properties.



Figure…. showing examples of hybrid nanoparticles (Source: Michael B. Cortie and Andrew M. McDonagh, Chem. Rev. 2011, 111, 3713–3735).

A nanocrystallite is generally understood to possess crystalline order in addition to nanoscale size. If **one dimension** of the 3D nanostructure is ***at nanoscale***, then it is called a **Quantum Well**. If **two dimensions** of the 3D nanostructure are ***at nanoscale***, then it is called a **Quantum Wire**. If all the ***three dimensions of the nanostructure are at nanoscale***, then it is called a **Quantum Dot**.

Quantum Wells, Wires, Dots:

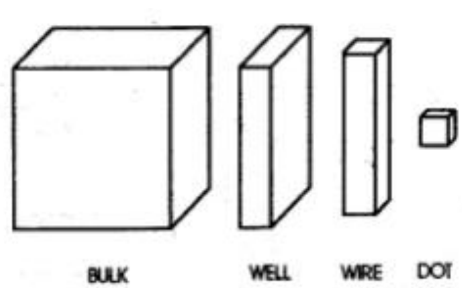


Figure 9.1. Progressive generation of rectangular nanostructures.

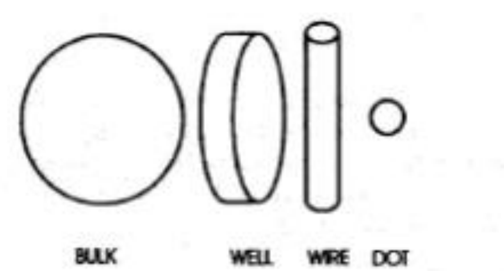


Figure 9.2. Progressive generation of curvilinear nanostructures.

TABLE 1.3 Characteristics of Nanomaterial and Their Importance

Characteristic	Importance
Size	Key defining criterion for a nanomaterial.
Shape	Carbon nanosheets with a flat geodesic (hexagonal) structure show improved performance in epoxy composites versus carbon fiber.
Surface charge	Surface charge is as important as the size or shape. It can impact adhesion to surfaces and agglomeration characteristics. Nanoparticles are often coated or "capped" with agents such as polymers (PEG) or surfactants to manage the surface charge issues.
Surface area	This is a critical parameter as the surface-to-volume (mass) ratio for nanomaterials is huge. For example, 1 g of an 8-nm-diameter nanoparticle has a surface area of 32 m^2. Nanoparticles may have occlusions and cavities on the surface.
Surface porosity	Many nanomaterials are characterized with zeolite-type porous surfaces. These engineered surfaces are designed for maximum adsorption of a specific coating or to accommodate other molecules with a specific size.
Composition	The chemical composition of nanomaterials is critical to ensure the correct stoichiometry being achieved. The purity of nanomaterials, impact of different catalysts used in the synthesis, and presence of possible contaminants need to be assessed along with possible coatings that may have been applied.
Structure	Knowledge of the structure at the nanoscale level is important. Many nanomaterials are heterogeneous, and information concerning crystal structure and grain boundaries is required.

Nanomaterials are of interest because at this scale unique optical, magnetic, electrical, and other properties emerge. Their size allows them to exhibit novel and significantly improved physical, chemical, and biological properties, and phenomena. These emergent properties have the potential for great impacts in electronics, medicine, and other fields. Nanomaterials are cornerstones of nanoscience and nanotechnology. The creation of functional materials, devices, and systems through control of matter on the nanometer length scale (1–100 nm) and the exploitation of their novel phenomena and properties (physical, chemical, biological) at that length scale are the subject matters of the nanoscience and nanotechnology.

Nanoscience is a new discipline associated with the study of nanomaterials, which are assemblies of atoms or molecules on a nanoscale ranging roughly from 1 to 100 nm, and their phenomena.

Nanotechnology is the construction and use of functional structures designed from atomic or molecular scale with at least one characteristic dimension measured in nanometers. Nanotechnology can be defined as research and development that involves measuring and manipulating matter at the atomic, molecular, and supramolecular levels at scales measured in approximately 1–100 nm in at least one dimension.

In summary, nanoscience refers to **exploring** the preparation and properties of materials at small scales while nanotechnology refers to **exploiting** our understanding of the properties of materials at the small scale.

The United States National Nanotechnology Initiative argues that the concept of nanotechnology encompasses nanoscale science, engineering, and technology where nanoscience is seeking to understand the fundamental properties and nanoengineering is seeking to effectively use these properties. In this context, they state that "*nanotechnology is the understanding and control of matter at dimensions between approximately 1 and 100 nanometers where unique properties enable novel applications not feasible when working with bulk materials or even single atoms or molecules*." Nanotechnology therefore includes visualizing, measuring, modeling, designing, and manipulating chemical matter at this small scale. Whatever the exact use of the terminology, it is evident that for us to exploit nanoscale phenomena, we need to understand what is so different about matter at this scale.

One **foundation** for understanding the nanoscale work was created more than a century ago with the development of **quantum mechanics**. This is the theoretical framework that replaces classical Newtonian mechanics when the scale is small. Thus, we have had a theoretical machinery to describe behaviors of atoms and electrons in molecules to explain concepts such as bonds to form molecules. This machinery is now able to explain many of the ***key properties of nanomaterials that arise from confining electrons and molecules to small spaces***.

A second **foundation** for understanding the properties of nanomaterials was established a few centuries ago when the field of **thermodynamics** emerged. While thermodynamics primarily provides the means of understanding the flow of energy through systems, it also ***provides insight into the energetics of surfaces***, which become very important as the surface to volume ratio increases for small particles. The energetics of interactions between surfaces has also been explored for a long time in the field known as colloid science and this can be extended to the nanoscale as well.

A third **foundation** for understanding some peculiarities of small systems was also developed more than a century ago as **Statistical Mechanics** created a ***bridge between quantum mechanics and thermodynamics***.

While not a foundation, in the same sense as those listed above, **electromagnetic radiation (light) and its interaction with matter** has proven a critical tool for studying nanoscale systems. Therefore, we need to explore various aspects of interaction of light with matter with ***particular emphasis on absorption and emission processes***, which are easily observed even for very small systems or systems with only a few nanoscale materials.

So, what is new about nanotechnology? It appears that we have known a lot about small systems for a long time and indeed we have. However, there are new developments that have emerged in two areas: visualizing and manipulating at a small scale. The ability to visualize matter at a small scale has steadily improved as tools such as x-ray diffraction and electron microscopy has developed to the point where we can determine structural properties of pieces of material as small as a few nanometers across. In some cases, it is now even possible to study the structure and behavior of individual molecules. Most importantly, however, the last several decades have seen invention of new tools that in addition to visualizing individual atoms and molecules, have allowed us to manipulate these almost at will. This new element of control has fed the excitement around nanoscience and nanotechnology and laid the foundation for new design principles.

Furthermore, our understanding of biological processes has developed rapidly in this century and has revealed that much of life is based on systems that operate at the nanoscale, such as membranes, catalytic protein complexes, and synthetic and repair mechanisms. This new insight has provided inspiration for development of nanotechnologies that mimic biological processes in a number of ways. Thus, the emergence of nanotechnology as a topic of great interest arises from the convergence of long-standing understanding of material properties, of new tools to visualize and manipulate individual atoms or molecules, and of new ways to design new structures or materials based on understanding of molecular biological systems. In addition, growth of the power to compute has enabled modeling and calculations of systems on larger and larger scales from atoms up to assemblies of molecules in nanoscale structures.

STRATEGIES FOR SYNTHESIS OF NANOMATERIALS

Preparation of nanoparticles is an important branch of the materials science and engineering. Nanoparticles can be produced by a whole series of chemical, physical, or biological processes, some of which are totally new and innovative, while others have existed for a very long time. Four major processes are employed in synthesizing the new nanoparticles: gaseous phase, vapor deposition, wet chemistry, and grinding.

Several of the processes for producing nanoparticles are similar to the existing chemical production processes.

(i) The gas phase method includes gas-phase evaporation method (resistance heating, high-frequency induction heating, plasma heating, electron beam heating, laser heating, electric heating evaporation method, vacuum deposition on the surface of flowing oil, and exploding wire method), chemical vapor reaction (heating heat pipe gas reaction, laser-induced chemical vapor reaction, plasma-enhanced chemical vapor reaction), chemical vapor condensation, and sputtering method.

(ii) Liquid phase method for synthesizing nanoparticles mainly includes precipitation, hydrolysis, spray, solvent thermal method (high temperature and high pressure), solvent evaporation pyrolysis, oxidation–reduction (room temperature and atmospheric pressure), emulsion, radiation-assisted chemical synthesis, and sol–gel processes.

(iii) Solid phase method includes thermal decomposition, solid-state reaction, spark discharge, stripping, and milling method. Most of these methods result in very fine particles that are more or less agglomerated. The powders are amorphous or crystalline and show a metastable or an unexpected phase, the reasons for which are far from being clear.

All these syntheses of nanoparticles carried out in the solid, liquid, or gaseous state are classified into two basic approaches in the literature: ‘‘**top-down**’’ and ‘‘**bottom-up**’’ approaches. **Top-down** approach uses the physical and lithographic principles of micro- and nanotechnology and achieves structure sizes in the medium to lower nanometer range, starting from a large materials entity. On the other hand, in the **bottom-up** approach, ionic, atomic, or molecular units are assembled through various processes to form structures in the nanometer range. The bottom-up approach is governed primarily by the chemical synthesis principles. If the process of assembling of the starting elements into a nanoentity is understood, the bottom-up approach allows, in principle, the design and formation of nanoparticles of any size and morphology.

It may be necessary to use chemical additives (surfactants, dispersants, etc.) to obtain a uniform and stable dispersion of particles. Owing to the small sizes, any surface coating of the nanoparticles strongly influences the properties of the particles as a whole. Studies have shown that the crystallization behavior of nanoscale silicon particles is quite different from micron-sized powders or thin films. It was observed that tiny polycrystallites are formed in every nanoparticle, even at moderately high temperatures.

Historical and Societal Aspects of Nanoscale Science and Technology

The origins of Nanoscience

Nanoscale science is typically defined to be relevant between 1 nm and perhaps 100 nm. With the advent of X-rays in the late 1800s, crystallographers were working at the nanometer scale or smaller as atomic arrangements in crystals were first determined in 1912. However, scientific historians say the earliest beginnings of nanoscale science and technology began in 1959, the year that Richard Feynman, a quantum physicist and one of the 20th-century's greatest scientists, gave a speech to the American Physical Society entitled "There's Plenty of Room at the Bottom." Feynman was fascinated by the notion of scaling, and in this speech, he imagined that a single bit of information could be stored in a nanospace (specifically a 125-atom cluster), an exceptionally bold prediction at that time. At that scale of miniaturization, he estimated that all the text ever written in books in the history of the world could be stored within a cube 0.2 mm on a side (thus his lecture title).

Feynman's genius was his realization that *all things do not simply scale down in proportion*, which is now considered the *cornerstone of nanoscience*. He was predicting that when **materials were scaled down to the nanometer size range, they would behave differently**, which could be turned into an advantage. Near the end of his talk, he posed the ultimate challenge when he said: "I am not afraid to consider the final question. Can [we] arrange atoms the way we want, all the way down?" The general reaction to his comments was amusement, as statements like these were considered scientifically radical, not necessarily visionary, at the time. For example, in the 1950s one of the great theoretical physicists of the last century, Erwin Schrödinger, predicted that we would never experiment with just one atom or molecule. However, in the late 1980s the direct manipulation of individual atoms by humans became a reality. Unfortunately, Feynman did not live long enough to witness this monumental achievement.

HISTORICAL PERSPECTIVE

Thousands of years BC, people used natural fabrics such as cotton, wool, and silk and processed them into products. What makes these **fabrics** so special that they developed a network of pores of size 1–20 nm for typical **nanoporous materials**? *Owing to their nanoporous structure, natural fabric possesses high utilitarian properties of absorbing sweat, quickly swelling, and getting dried soon*. Since ancient times, people mastered the art of making bread, wine, beer, cheese, and other foodstuffs where fermentation processes at the nanolevel are critical. Romans in the pre-Christian era introduced metals with nanometric dimensions in glass-making: a cup describing the death of King Lycurgus (4th century, Roman) contains nanoparticles of silver and gold (Figure 1.8a). It was found that the nano-sized particles were of silver (66.2%), gold (31.2%), and copper (2.6%) embedded in the silica glass. The nanocrystals cause the glass to appear ruby-red when the light source is inside the cup (transmitted light; as shown) and entirely yellowish-green when the light source is outside the cup (reflected light). Light absorption and scattering by these nanoparticles determine the different colors. The stained-glass windows of the great medieval cathedrals also contain metallic nanoparticles.

Figure 1.8 (a) Lycurgus cups. Courtesy of Trustees of the British Museum. © The Trustees of the British Museum; (b) ancient Maya fresco painting. © 2005. With permission of The Royal Society of Chemistry.

The colors of certain Mayan paintings (Figure 1.8b) also stem from the presence of metallic nanoparticles. Mayan artisans concocting in the eighth century the unique pigment we now know as Maya Blue have endured their lively blue tones for more than 12 centuries of harsh jungle environment. Maya Blue is not an ordinary organic dye nor is it any simple mineral; it is a hybrid organic–inorganic nanocomposite in which the organic dye molecules are protected within palygorskite, a complex natural clay. Art history of India and China is also filled with examples of nanotechnology. Photography, which was developed in the 18th and 19th centuries, provides a more recent example of the use of silver nanoparticles. Nanostructured catalysts have also been investigated for over 70 years. In the early 1940s, precipitated and fumed silica nanoparticles were being manufactured and sold in the United States and Germany as substitutes for ultrafine carbon black for rubber reinforcements. Nano-sized amorphous silica particles have found large-scale applications in many everyday consumer products, ranging from nondiary coffee creamer to automobile tires, optical fibers and catalyst supports. In addition, the definition of nanoparticles based on size allows us to include colloids and soils that have been used for over a hundred years.

In 1857, Faraday had described the use of colloidal gold in his experiments. In his lecture at Royal Society, Faraday presented a purple color slide, stating that it contained "gold reduced in exceedingly fine particles, which becoming diffused, produced a ruby red fluid The various preparations of gold, whether ruby, green, violet or blue etc. consist of that substance in a metallic divided state." Faraday postulated correctly about the physical state of colloids; he also described how a gold colloid would change color (turning blue) on adding salt. Since then, colloidal science has evolved a lot. In the early twentieth century Gustav Mie presented the Mie theory, which is a mathematical treatment of light scattering that describes the relationship between metal colloid size and optical properties of solutions containing them. The Nobel Prize winner for Quantum Electrodynamics, Richard Feynman, said, "Nature has been working at the level of atoms and molecules for millions of years, so why do we not?" Since his call in a lecture in 1959, nanotechnology has made tremendous progress not only in technical disciplines but also in medicine and pharmaceutics. World began speculating on the possibilities and potential of nanometric materials and on the fact that the manipulation of individual atoms could allow us to create very small structures whose properties would be very different from larger structures with the same composition. Moreover, in an even more radical proposition, he thought that, in principle, it was possible to create "nanoscale" machines through a cascade of billions of factories. According to him, these factories would be progressively smaller scaled versions of machine, hands, and tools. In these speculations, he also suggested that there are various factors that uniquely affect the nanoscale level. Specifically, he suggested that as the scale got smaller and smaller, gravity would become more negligible, while van der Waals attraction and surface tension would become very important. 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). Richard Feynman is considered as the "Father of Nanotechnology," although he never explicitly mentioned the term "Nanotechnology."

The evolution of integrated chips may also be considered as the part of history of nanotechnology. The first transistor invented in 1947 was a bulk macro-object. To keep with the demand for miniaturization, the dimensions of the transistor have been reduced considerably in the last 30 years. In the year 2002, the nanosize was reached with the achieved size of a single transistor as 90 nm. As on today, a single transistor in an Intel Core 2 Quad Processor is 45 nm. In order to keep pace with Moore's law, transistor would be as small as 9 nm by 2016. However, this dimension is below the fabrication capabilities of last-generation tools used in the microelectronic industry. Numerous novel approaches such as quantum computing and molecular engineering are under investigation to achieve the workable transistor of this size. Material science/engineering is also full of examples of nanomaterials! Often these were produced inadvertently and were not characterized at the nanoscale since the analytic tools were not available. For instance, the process of anodizing was first patented in early 1930s. This represents one of the most important processes used in industry to protect aluminum from corrosion. It consists of depositing a thin protective oxide layer on the aluminum surface. The inventors were not, however, aware that the protective layer is actually a nanomaterial; the anodic layer is composed of hexagonally close-packed channels with diameter ranging from 10 to 250 nm or greater. The first use of the term “nanotechnology” was by Norio Taniguchi in 1974 at the International Conference on Precision Engineering (ICPE). His definition referred to “production technology to get extra high accuracy and ultra-fine dimensions, that is, the preciseness and fineness on the order of 1 nm (nanometer), 10^{-9} m, in length.” The development of nanotechnology has been enabled by the invention of two analytical tools that have revolutionized the imaging (and manipulation) of surfaces at the nanoscale. These are the scanning tunneling microscope (STM) and the atomic force microscope (AFM). The AFM and STM are capable of imaging surfaces at an atomic resolution. Both the instruments were invented by Binning and his coworkers at IBM Zurich. Invention of these versatile tools practically opened the doors of nanoworld to the scientists. With the advent of the STM, scientists were given the tool not only to image surfaces with atomic resolution but also to move individual atoms. The STM is the first step in realizing Feynman’s vision of atom-by-atom fabrication. In the 1980s, the basic idea of this definition was explored in much more depth by Eric Drexler, who promoted the technological significance of nanoscale phenomena and devices through speeches and the books, Engines of Creation: The Coming Era of Nanotechnology and Nanosystem: Molecular Machinery, Manufacturing, and Computation and so the term acquired its current sense. Birth of “Cluster Science” in the late 1980s gave further momentum to the development of nanoscience and nanotechnology. In another development, the studies on the synthesis and properties of metallic and semiconductor nanocrystals led to a fast-increasing number of metal and metal oxide nanoparticles and quantum dots.

NANOSCIENCE IN NATURE

Nanostructures are plentiful in nature. In the universe, nanoparticles are distributed widely and are considered to be the building blocks in planet formation processes. Indeed, several natural structures including proteins and the DNA diameter of around 2.5 nm, viruses (10–60 nm), and bacteria (30 nm to 10 μm) find the above definition of nanomaterial, while others are of mineral or environmental origin. For example, these include the fine fraction of desert sand, oil fumes, smog, fumes originating from volcanic activity or from forest fires and certain atmospheric dusts. Biological systems have built up inorganic–organic nanocomposite structures to improve the mechanical properties or to improve the optical, magnetic, and chemical sensing in living species. As an example, nacre (mother-of-pearl) from the mollusk shell is a biologically formed lamellar ceramic, which exhibits structural robustness despite the brittle nature of its constituents. These systems have evolved and been optimized by evolution over millions of years into sophisticated and complex structures. In natural systems, the bottom-up approach starting from molecules and involving self-organization concepts has been highly successful in building larger structural and functional components. Functional systems are characterized by complex sensing, self-repair, information transmission and storage, and other functions all based on molecular building blocks. Examples of these complex structures for structural purposes are teeth, such as shark teeth, which consist of a composite of biomineralized fluorapatite and organic compounds. These structures result in the unique combination of hardness, fracture toughness, and sharpness. The evolution has worked on much smaller scales too, producing finely honed nanostructures, parts less than a millionth of a meter across, help animals climb, slither, camouflage, flirt, and thrive.

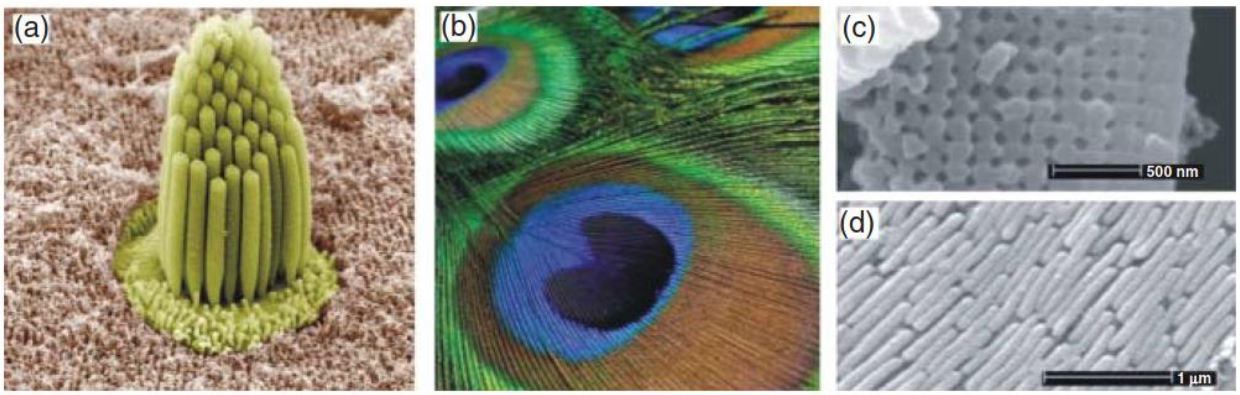


Figure 1.4 Nanotechnology in nature: (a) electron microscopic image of a sensory patch in amphibian ears. http://scinerds.tumblr.com/post/35542105310/stereocilia-stairsteps; (b) peacock feather showing barbules, representing a photonic lattice; (c and d) electron microscopy image of transverse and longitudinal sections of barbules. © 2003. With permission of National Academy of Sciences, USA.

Figure 1.4a shows an electron microscopic image of *a sensory patch in amphibian ears,* which consists of a single bundle of *stereo cilia projecting from the epithelium of the papilla*, and acts **as a nanomechanical cantilevers that measure deflection as small as 3 nm because of sound waves**. Many of the shimmering colors in butterfly's wings are produced not with pigments but with nanostructures. The *scales on their wings are patterned with nanoscale channels, ridges, and cavities made of chitin, a protein*. Unlike pigments, which create color by absorbing some wavelengths of light and reflecting the rest, ***the nanostructures are shaped so that they physically bend and scatter light in different directions, sending particular colors back to our eyes***. This scattering can also make them iridescent (i.e., the color changes with the angle one sees it from. When infrared radiation hits the chitin nanostructures, their shape changes because of expansion, thus changing the colors they display. Figure 1.4b shows glittering colors of peacock feather where ***barbs project directly from the main feather stem, and barbules (~0.5 mm long) attached to each side of the barb generate the typical "shimmer" of iridescence.***

Electron microscopy (Figure 1.4c and d) of barbules reveals a highly ordered structure of melanin rods of high refractive index embedded in keratin of lower refractive index with air tube between each square of melanin rods. **The whole array of melanin rods, keratin matrix, and air holes comprises a 2D photonic crystal.** There is much interest on mimicking these natural wonders with potential applications in optical engineering and communications. ***Less seriously, photonic crystal pigment-free paints would not fade, fabrics might be more vibrant.***

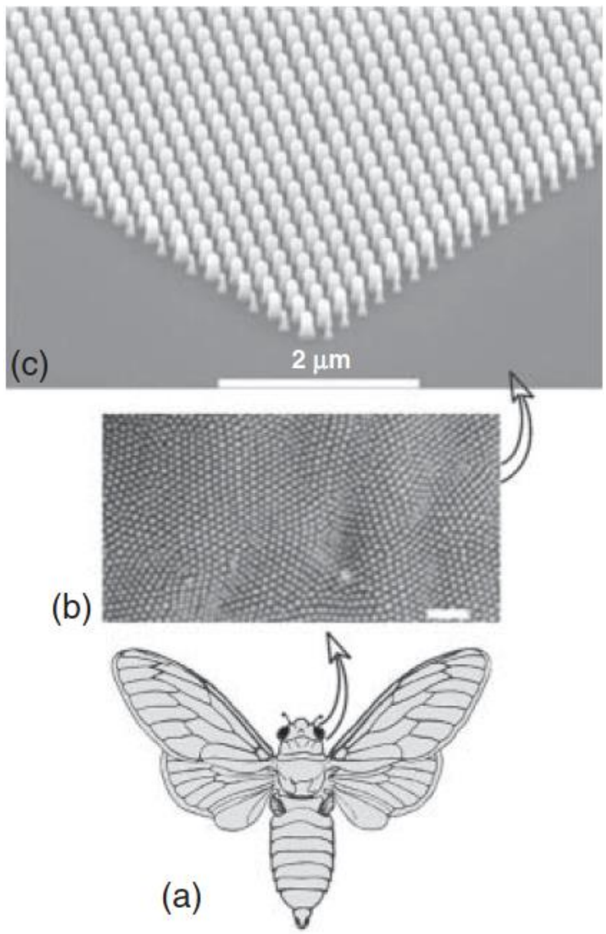


Figure 1.5 Natural and fabricated antireflective surfaces: (a) schematic of a moth; (b) scanning electron micrograph of ***antireflective surface of a moth's eye*** (scale bar = 1 µm); (c) ***biomimetic replica of a moth eye fabricated with ion- beam etching***. © 2007 Nature Publishing Group.

The compound eye of arthropods uses nanoscale features to enhance their visual sensitivity. An insect's compound eye has about 50–10,000 individual facets, ***which are studded with an*** array of nanoscale protuberances called "***corneal nipples***" (Figure 1.5a and b), ***each with its own***

set of optical machinery*.** **These tiny structures of size ranging from 50 to 300 nm cut down the glare that reflect off the insect eye.** The nanoscale nipple pattern on moth eyes ***has inspired new antireflective coatings (Figure 1.5c) for solar cells. Spider silks are some of the toughest materials known to man, stronger than steel, and their webs can withstand gusts of wind. The spider's silks get their strength from just nanometers of thin crystal proteins, which are stacked with hydrogen bonds, allowing the silk to stretch and flex under pressure.

These are only a few of the countless examples of how nature employs nanotechnology in different methods, of course, with the most important technology to us being the human body itself, which contains billions of nanoscale machines! It is both fascinating and humbling to observe that despite all of the phenomenal technological advances in nanoscale synthesis and characterization, in most cases we are still unable to build nanotechnology-based devices that even come close to nature.

Naturally Occurring Nanomaterials

Naturally occurring nanomaterials may originate from one of the following sources:

(i) Natural erosion and volcanic activity

Nanoparticles are part of mineral world since they are naturally produced from erosion and volcanic explosions.

(ii) Clays

Minerals such as clays are a type of layered nanostructured silicate materials that are characterized by a fin 2D crystal structure. Mica, one among them, is the most studied. In mica, a large number of silicate sheets are held together by relatively strong bonds. On the other hand, montmorillonite, a smectic type of clay, has relatively weak bonds between layers. Each layer consists of two sheets of silica held together by cations such as Li^+, Na^+, K^+, and Ca^{2+}. The presence of the cations is necessary for compensating the overall negative charge of the single layers. The layers are 20–200 nm in diameter laterally and come into aggregates called tactoids, which can be about 1 nm or more thick. The fin nanostructure of clays determines their properties. As an example, the nanostructured clay swells to several times of the original volume, when water is added to it, due the opening of the layered structure by the water molecules that replaces the cations. Clay swelling is a significant factor in soil stability and is taken into account in constructing roads.

(iii) Natural colloids

Naturally occurring liquid colloids, such as milk, blood, aerosols (e.g., fog), are some of the examples of natural colloids. In these materials, nanoparticles are dispersed in the medium (liquid or gas) but do not form a solution, rather they form a colloid. All these materials have the characteristic of scattering light and often their color (such as in the case of milk and blood) are due to the scattering of light by the nanoparticles that makes them up.

(iv) Mineralized natural materials

Many of the natural materials such as shells, corals, and bones are formed by the self-assembly of calcium carbonate crystals with other natural materials, such as polymers, to form fascinating three-dimensional (3D) architectures. For instance, a shell is grown layer-by-layer coating of protein supported by chitin, a polysaccharide polymer. The proteins act as a nanoassembly mechanism to control the growth of calcium carbonate crystals. Around each crystal remains a honeycomb-like matrix of protein and chitin. This relatively “flexible envelop” is fundamental for the mechanical properties of the shell and mitigate cracking. The size of each crystal is around 100 nm. As a result, the mollusk shell has extraordinary physical properties, namely, strength and resistance to compression.

Nanoscience in Action in Biological World

Two most significant examples of active nanoscience in biological world include the following:

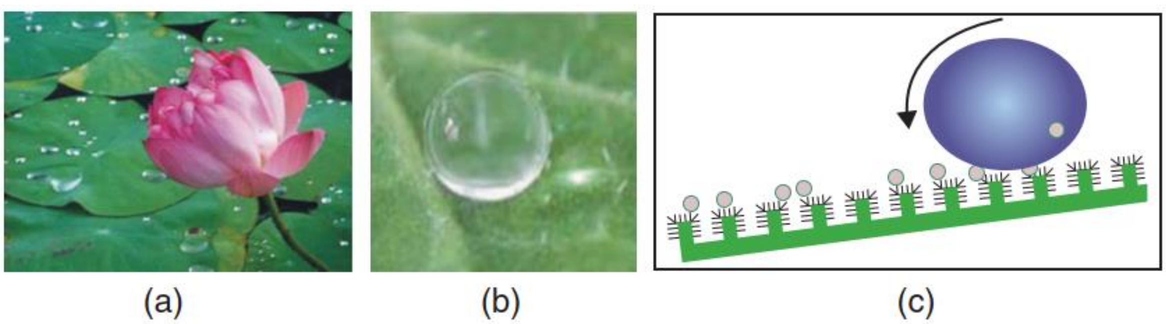


Figure 1.6 (a) Lotus (Nelumbo nucifera) plant; (b) spherical water droplet on a nonwettable lotus plant leaf. © 2003 Nature Publishing Group; (c) self-cleaning: a drop picks up the dirt particles as it rolls off the leaf’s surface.

(i) Lotus effect

Although the water repellency of lotus had long been recognized, its scientific basis was understood only in 1997 when two botanists Wilhelm Berthelot and Christophe Neinhuis, at the University of Bonn in Germany, examined leaf surfaces of lotus using a scanning electron microscope that resolves structures as small as 1–20 nm. Figure 1.6a shows a nonwettable lotus plant leaf. The self-cleaning property is due to the “**Super hydrophobicity**” of the convex papillae on the surface of leaves, which is coated with wax crystals of nanoscopic dimension of approximately 10–100 nm (Figure 1.6b). Water drop picks up the dirt particles as it rolls off the leaf's surface, showing self-cleaning process (Figure 1.6c). Several other plants such as Nasturtium and cabbages also show lotus effect.

The papilla greatly reduces the contact area of water droplets with it. Every epidermal cell forms a micrometer-scale papilla and has a dense layer of epicuticular waxes superimposed on it. Each of the papillae consists of branch-like nanostructures on the surface, for example, of the lotus leaves, the almost spherical water droplets will not come to rest and simply roll off if the surface is tilted even slightly, which is now usually referred to as the "**Lotus effect**." The self-cleaning effects of the surfaces of the lotus flower have been attributed to the combined micro- and nanostructure, which in combination with hydrophobic groups give the surface a water and dirt-repellent behavior. In the past few years, numerous companies have realized products resembling the surface morphology and chemistry of the lotus flower such as paint, glass surface, and ceramic tiles with dirt-repellent properties.

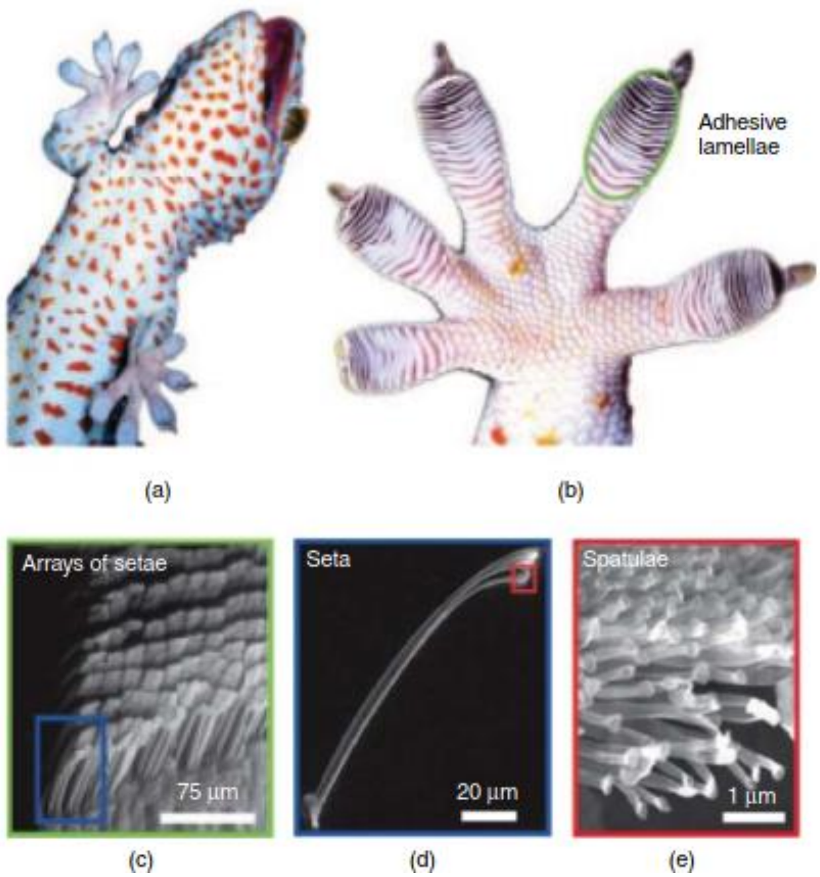


Figure 1.7 Gecko's adhesive system structure: (a) ventral view of a tokay gecko (Gekko gecko); (b) sole of the foot showing adhesive lamellae; (c) microstructure: part of a single lamella showing arrays of setae; (d and e) nanostructure: single seta with branched structure at the upper right area, terminating in hundreds of spatular tips. © 2005 National Academy of Sciences, USA.

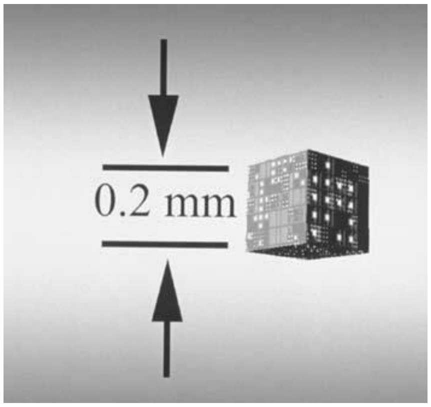
(ii) **Geckos Technology**

Geckos are one of the few species in the animal kingdom that are known for sticky toes that allow them to climb up walls, even hang upside down on ceiling and at the same time can walk on a leaf; they owe this ability to nanoscale attachment elements. As illustrated in Figure 1.7a–e, on the sole of a gecko's toes there are about a billion tiny adhesive hairs, ~200 nm in both width and length. These hairs put the gecko in direct physical contact with the surface. Spatula-shaped ends on the hairs provide strong adhesion. Industry is researching the evolution of these properties in order to develop artificial dry adhesive systems. Potential applications include reusable adhesive fixture with the strength of duct tape, which can be removed as easily as a sticky note.

Some more examples of naturally occurring materials such as cotton, spider's silk, and opals are also worth mentioning for their nano features and unique properties. Cotton has nanoscale arrangement of cellulose fiber showing high strength, durability, and absorbance. Spider silk showing five-time higher strength than that of steel has natural supramolecular organization of fibroid at nanoscale. Precious stone opal consists of spheres of silicon dioxide (150–300 nm diameter) in a hexagonal or cubic close-packed lattice. These ordered silica spheres produce the internal colors by causing the interference and diffraction of light passing through the microstructure of the opal. The realization that nature can provide the model for improved engineering has created a research field called "biomimicking" or bio-inspired material science. It has been possible to process several types of nanostructures inspired from biological nanomaterials, which provide new technological opportunities and potential for applications.

How Has Nanotechnology Already Affected our everyday lives?

Before the "nano" label became so popular over the last decade, scientists and engineers were hard at work developing useful products that use nanoscale particles and thin layers with properties specifically targeted for various purposes. Nanosize particles of zinc, cerium, and indium oxides are already used in electronics, fuel additives, optics, and personal care products such as sunblock and cosmetics. Stain- and wrinkle-resistant pants sold by Eddie Bauer, Lee Jeans, Gap, and other retailers use nanotech fiber and coating technologies. In the computing world, nanotechnology has already had a great impact on data storage. Several years ago, computer disk drives were quickly approaching the theoretical limit in data density for the existing technology of magnetic storage – 20 to 40 gigabytes (GB) per square inch – but nanotechnology provided a major change in hard disk design. On the surface of a disk, a layer of the metal ruthenium three atoms thick (which is much less than 1 nm) is sandwiched between two much thicker magnetic layers. This allows for smaller than previously obtainable magnetic domains in the layers above and below the ruthenium, while remaining stable over time. As a result, data could be stored at much higher densities, which allowed for the creation of 400 GB desktop drives (equivalent to the data on 80 DVDs or 600 CDs), 200 GB drives in notebook computers, and 6 GB drives in small handheld devices. Today, small handheld devices can hold hundreds of GBs, enough for tens of thousands of songs and hundreds of hours of video. Even these numbers will seem small in a few years; however, the point is that nanotechnology provided the quantum leap in disk design needed to continue to propel industry forward. The most sweeping nanotechnology application occurred in the heterogeneous catalysis industry. Heterogeneous catalysts promote chemical reactions on surfaces and nanosize particles. This technology has played a key role in leading a multitrillion dollar chemical industry worldwide, and the technology is used in hundreds of applications, from refining oil to breaking down toxic car emissions through catalytic converters.



Richard Feynman estimated that all the text ever written in books in the history of the world could be stored within a cube 0.2 mm tall.

COMMERCIAL APPLICATIONS

Many nanotech-based products have already been developed and are commercially available. The nanotech industry is poised for rapid growth with many additional nanotech-based products presently in their developmental stage and expected to be commercialized in the near future. The most common commercially exploited nanoparticles in various areas are those of silver, gold, iron metals, oxides of silicon, aluminum, titanium, iron, zinc, and carbon nanomaterials such as carbon nanotubes (CNT) and graphene. These materials are used for their specific and unique chemical, physical, and biological properties together with established technology for their scaled production now. It is also important to note that products are rarely 100% nanotechnology based; nanotechnology will be added to a product and form a part of it. Some of important sectors where nanotechnology-based products are available commercially are given in following sections.

Food Industry

Silver is currently the most common nanoparticle that is used in the food industry. Silver has long been known as an effective antimicrobial agent and in its nanoform can now be easily impregnated invisibly into almost any product to aid in the destruction of bacteria and viruses. This has important applications in the food industry in terms of manufacturing, preserving, and storage. Although the use of nanotechnology directly in food products is limited, however, several food supplements are available that contain nanoparticles as the main active ingredient.

The most common nanoparticles used in these supplements comprise silver, gold, copper, or calcium. It is unknown what effect these metals may have on cells and the body as a whole. Refrigerators and food containers are also now available with a silver nanoparticle lining to deter the growth of bacteria and mold. It is not known whether silver nanoparticles can be absorbed by the food while it is being stored and later ingested.

Cosmetics

The fascinating group of nanoparticles known as fullerenes, the C_{60} form, which resemble small “Footballs” of carbon atoms, are being used in cosmetics in the form of face creams to remove other unwanted particles, such as free radicals, which are believed to cause damage to the body and skin. Sun creams are now available with titanium dioxide nanoparticles. The micron-sized particles are used as sunblock but are white in color and are not used in sun creams that need to be invisible when applied. The nanoparticle form is colorless as the particles are too small to reflect visible light, but still retain their ultraviolet sun-blocking properties that are highly desirable for a sun cream.

Textile

Textile industry is making increasing use of nanomaterials to make them more functional and smarter. For example, nanosilver is playing a lead role because of its antimicrobial properties. Clothes can also be treated with nanofilm to make them stain, water and static resistant. These films, which are only a few atoms thick, could be in contact with skin over prolonged periods. Very little information is available what the long-term effect could be, although in the short term most products appear safe as nanotechnology has been used in clothes for several years now.

Medicine

The use of silver nanoparticles for use in medical devices is a hot topic. Nanosilver kills a broad range of harmful microbes and has been shown to be effective against the Methicillin-resistant Staphylococcus aureus (MRSA) superbug and the HIV virus. This could prove beneficia in terms of providing sterile equipment, beds, and wound dressings that limit the spread of harmful bacteria. Nanomedicine is not limited to simple single-element nanoparticles such as silver. More complicated nanoparticles can perform certain tasks such as homing in on cancer cells to destroy them or drug delivery that can send drugs directly into cells. Nanotechnology could also be used to produce new sensors that can detect whether a person has certain types of cancer using only a few drops of blood.

Electrical and Electronic Goods

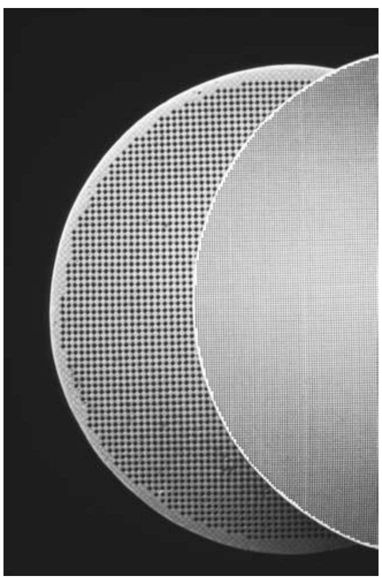
For the majority of electrical goods, nanotechnology has come from a natural evolution of microtechnology. In order to fi more components into an electronic chip to make it more powerful, the components are made to be smaller. Over the period of time, components that used to be several hundred micrometers are now several hundred nanometers. In this aspect, nanotechnology only represents an arbitrary milestone, as a micron-sized transistor works in the same manner as a nano-sized transistor. Virtually all forms of nanotechnology used in electronics are embedded and are believed to pose a low human health risk and no additional risk to the environment over microtechnology. However, there are many areas that are having a greater impact including quantum computing, nanoelectrical mechanical systems (NEMS), and new display technologies.

Quantum computing uses the quantum mechanical effects available at the nanoscale that gives new methods of performing computational operations. Essentially, some computing tasks that have to be performed sequentially with a standard computer can be performed all at once using a quantum computer. This could dramatically increase the speed of databases, which underpin businesses, and, increasingly, the Internet. NEMS are effectively nano-sized machines that currently perform simple tasks. This type of nanotechnology is currently one of the closest analogies to nano-sized robots, the other type being biological nanomachines that are made from biological molecules. These can produce nano-sized motors and sensors. Applications for NEMS could be very broad, for example, monitoring the environment or even medical nanorobots for targeting cancers or repairing tissues. These examples are still very much in the preliminary or theoretical stage, but once developed could have a huge impact.

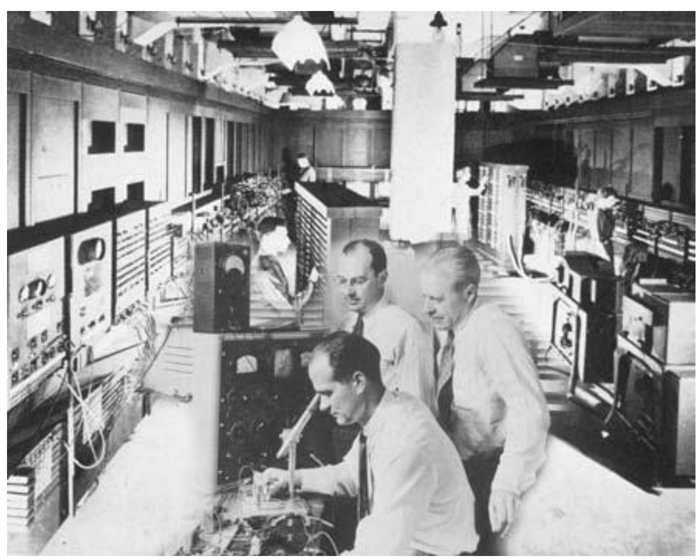
Recent display technologies use carbon nanotubes or nano-sized structures to efficiently emit electrons to be used to excite a phosphor display. This type of technology should have the advantage of being lightweight and efficient Another new display technology is the organic semiconductor film The term organic is used because the semiconductor material is made of organic or carbon-based polymers. These films may one day be printed off as plastic to provide cheap flexible displays. The nanotechnology element, which lies in the structure of the semiconductor, is not thought to pose any particular new risk over conventional plastics.

What could Nanotechnology mean to society in the long Run?

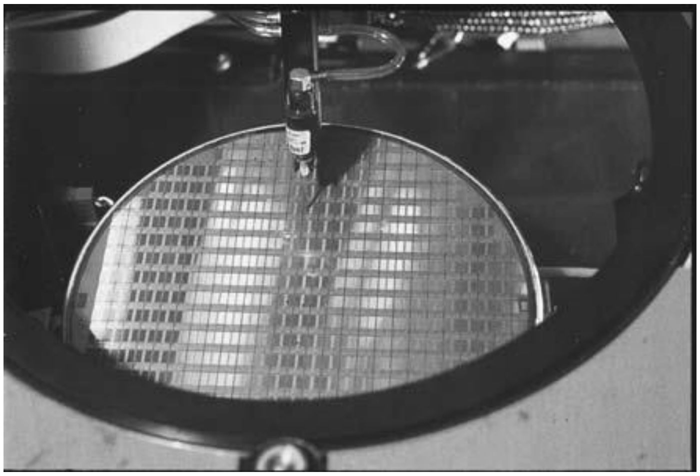
In its report *Nanotechnology: Shaping the World Atom by Atom*, the National Science and Technology Council stated that nanotechnology “stands out as a likely launch pad to a new technological era because it focuses on perhaps the final engineering scales people have yet to master” (NSTC 1999). Nanoscience has applications in all areas of science, and nanotechnology has applications for most fields of technology, including robotics, chemical and mechanical engineering, medicine, computing, and so on. Because of these widespread applications, it is widely anticipated that the future impact of nanotechnology will eventually far exceed the impact of the silicon-based integrated circuit (computer technology as we know it today). Like the present molecular biology revolution (e.g., genomics, proteomics) and other health-related sciences, the importance of nanoscale science and technology is so sweeping and so vast that boundaries cannot be reliably defined, and limits cannot be clearly foreseen. Scientific historians know all too well that technology predictions are notoriously inaccurate. Shortly after the invention of the solid state transistor at Bell Labs (the invention that made modern computers possible), experts published predictions in the March 1949 issue of *Popular Mechanics*: Futuristic calculators (computers) would add 5,000 numbers per second and weigh only 1,400 kg, while consuming 10 W of power. Today, a laptop computer weighing just 1 kg can add millions of numbers per second using about 1 W of power. So who can reliably say today what a quantum computer—built from the bottom up using nanotechnology—will be able to do in the future, or which fields will be most dramatically affected by nanoscience? Besides unimaginably powerful computing devices, one can easily anticipate great advances in medical diagnostic tools, chemical sensors, communication devices, environmental restoration methods, construction materials, and cancer treatments, just to name a few. It is this small scale—where we have the ability to put molecules and atoms to new uses—that fuels the hope and hype surrounding nanotechnology. What seems certain is that nanotechnology will make a dramatic and lasting impact on every scientific feld and also in every major area of modern technology. The nanorevolution is here to stay.



Automotive catalytic converters produced by Corning, Inc. Nanoparticles of platinum or rhodium reside on the surface of the honeycomb ceramic structure. As hot exhaust gases pass through the channels, toxic nitrous oxides and carbon monoxides are converted to nitrogen and carbon dioxide gases.



In the background is ENIAC, the first fully operational large-scale electronic digital computer with its 18,000 vacuum tubes, 70,000 resistors, and 10,000 capacitors (Philadelphia, 1948). The inset in the foreground shows William Shockley (sitting) and John Bardeen and Walter Brattain (standing behind) in the same year, shortly after their invention of the solid state transistors that would lead to modern computers.



An eight-inch diameter “wafer” of modern computer chips, before they are separated to go into individual machines or computers. Each silicon chip may contain more than one billion solid state transistors.

Metal Transport Nanoscience

Toxic metals and metalloids, such as lead, cadmium, chromium, and arsenic, are naturally present in the environment but can also be artificially introduced into the environment via inadvertent release from industrial processes such as mining or manufacturing. The movement of these toxic substances in the environment is of great concern. Metal mobility ultimately depends on (1) the chemical reactivity of any particular metal, and (2) the part of the environment through which that metal is moving (e.g., soil, groundwater, rivers or lakes, the atmosphere). A fundamental question that can be easily overlooked is whether the metal in question is moving in the environment as an aqueous (water-based) species (as a single metal atom surrounded by water molecules and, therefore, “dissolved”), within or on a metal oxide nanoscale particle called a nanoparticle), or perhaps attached to an organic molecule. If the metal in question passes through a submicron filter (e.g., a filter that traps particles larger than 0.2 microns, which is 200 nm), then it is often assumed to be dissolved. However, if in reality the metal is attached to the surface of a particle 10 nm in size, it will pass through the filter, but it is not dissolved. That is, metals can be and presumably often are transported within or on nanoparticles, not as aqueous species. These metals interact with the environment very differently depending on how they are transported. Another layer of complexity can occur if a toxic metal is attached to a nanoparticle surface, but then interactions with bacteria release the metal from the surface.

NANOSCIENCE AND NANOTECHNOLOGY FUTURE

In the initial phases of the discovery of the nanotechnology world, the excitement created great expectations that nanotechnology was the next phase of economic development, following the path of information technology and biotechnology. These expectations are slowly being met, but perhaps not at the rate hoped for in the early days. Still, there is strong evidence that the impact and applications of nanotechnology will be **pervasive**, **persistent**, and **powerful**. Starting in 2005, the Woodrow Wilson International Center for Scholars and the Pew Charitable Trust started a project on Emerging Nanotechnologies to keep track of the development of nanotechnologies and to help ensure that the potential benefits of these technologies can be developed with an eye to continual public engagement to minimize potential risks of their introduction. Their website (http://www.nanotechproject.org/) has been and will remain a valuable resource for both the public and specialists. One component of the project is the creation of an ongoing inventory of consumer goods and other applications that use nanotechnology as a key component. During the first decade or so, this inventory has grown to nearly two thousand products across a large number of domains, supporting the notion of nanotechnology applications being pervasive, persistent, and powerful.

Pervasiveness

Because nanotechnology is first and foremost about creating and applying new materials with new properties from, for the most part, known chemical matter, it may be viewed as a special branch of material science. This means that we expect nanomaterials to become integral parts of products in just about every discipline or area that affects consumers and society, ranging from energy, transportation, manufacturing, and climate change to agriculture, health, communications, and food. The Project of Emerging Nanotechnologies consumer products inventory lists the nanotechnology-enabled products in a number of broad categories such as appliances, including those for kitchens and laundry; automotive; electronics and computers; food and beverage; health and fitness; and home and garden. In addition, they feature applications in agriculture, environmental remediation, and medicine. There are very few domains in which nanotechnology will not be or become an important component. As an example, the areas of agriculture and food currently support research and development projects in areas as diverse as veterinary medicine, sustainable agriculture, biosensors, bio-processing for foods, pathogen detection, and environmental processing.

Persistence

The success of nanotechnology to date is based on the convergence of disciplines ranging from chemistry, biology, and physics to various branches of engineering, mathematics, computational sciences and business. As a consequence of the meeting of different minds, the approach to nanosciences more often than not involves multidisciplinary teams that have changed how we think about conducting research in this domain. We now exploit our ability to **visualize** structure, function, and dynamics at the nanoscale with ever-increasing precision; to integrate this information to **design** structures and materials with predictable and desirable properties; and to **control** the assembly of the parts or the machining of components at the molecular level. This holistic approach is broadening the scope of possible areas of application of nanoscience and means that the applications of nanotechnology will persist and evolve just as applications of electronics and computational paradigms persist and evolve. Once unearthed, nanoscience and nanotechnology will be with us forever as platforms for research and technology development. That said, it is important to recognize that nanoscience and nanotechnology provide us with enabling technologies that will most likely be critical or integral components of other technologies, that are improved or are made to exist as a result of their presence. In some cases, the nanotechnologies will make products that are smaller or faster, in other cases that are easier to produce or cheaper, and in yet other cases that break new ground.

Power

The National Nanotechnology Initiative reported in 2010 on the first decade of evolution of nanotechnology with focus on the United States, but with global information included. This report, titled *Nanotechnology Research Directions for Societal Needs in 2020. Retrospective and Outlook* provided a thorough review of the progress in research as well as on the economic impact and provided projections and predictions about how the next decade would unfold. There were a number of exciting findings which demonstrated how nanotechnology had the potential to become a powerful economic driver for the future. During nearly a decade, research investments, publications, patent applications, products market, and the workforce associated with nanotechnology grew by an astounding rate of about 25% per year and by 2009, the global value of nanotechnology enabled products had reached about *US*$250*B*. The report predicted that during the next decade, this growth would continue and reach a total value of *US*$3*T*. Equally interesting was the analysis of how the nanotechnology products and processes were anticipated to evolve. Starting with applications of passive nanostructures, moving through active nanostructures to nanosystems to converging technologies, the field was projected to become more and more sophisticated in its application of the unique properties of materials and systems that operate at the nanoscale and taking advantage of our abilities to visualize, design, and control.

To date, many of the commercial products are based on passive nanostructures incorporated into coatings, polymers, or ceramics where they provide desirable properties to the product. For example, the presence of nanoparticles in a thin film can improve on the permeability properties of the film by simply creating barriers to simple diffusion across the film. A number of other products take advantage of the unique properties to create active nanomaterials. For example, one of the most commonly used nanomaterials is silver nanoparticles which have been shown to have great anti-bacterial properties, most arising from the enhanced surface reactivity of the small silver nanoparticles. As a result, silver nanoparticles now appear in products as diverse as socks, cutting boards, refrigerators, and washing machines. The following generation of products will depend on nanosystems that are responsive to their environment to achieve desirable objectives. For example, nanoparticles may be assembled to contain drugs in structures from which they cannot escape unless the particles are subjected to a specific environment which causes a structural change that releases the drug. Such nanosystems are yet to be commercially developed to a great extent, but the research is rapidly moving forward. Ultimately, the report predicts, nanotechnologies will merge with biotechnologies, information technologies, and cognitive sciences to create large complex, multifunctional technologies that have the power to transform our societies and existence in profound ways — perhaps for the better and perhaps for the worse. It is important to recognize that in many cases the economic impact may not arise from the nanomaterials themselves, but rather from the products they enable. The value chain will start with the nanomaterials and end with the nano-enabled products as illustrated in Figure 1.1

Figure 1.1: Illustration of the value chain of nanotechnology based products.

The nanomaterials will be nanoparticles, nanofibers, nanowires, dendrimers or other similar nano-objects. They may have to be produced in large quantities and therefore will become commodity products where the lowest price is most important. Examples include the use of nanoparticles such as nanoscale zerovalent iron (nZVI) for environmental remediation. Alternatively, they may be produced in small quantities for highly specialized purposes, such as quantum dots that are used in medical diagnostic applications. The nanointermediates are components that contain nano-objects integrated into a functional unit, such as coatings and printer toners, that can be used as final products, or optical components, memory chips, and sensors that generally are incorporated into the final products. In these intermediates, the nanomaterial may constitute only a very small part, but they are critical for imparting new or better properties. For example, nanoparticles constitute only a few percent by mass in plastic films that are used as permeability barriers, but they improve the permeability properties of the film significantly. The nano-enabled products are the final products that consumers will purchase and use and include anything from beer bottles to automobiles, from sunscreens to clothing, and from cell phones to robots. The cost of the nanomaterials or nanostructures may only be a small fraction of the total, but the value of the final product depends critically on the performance of the nanomaterials. For example, there are devices that can test for the presence of specific proteins, such as the human chorionic gonadotrophin protein, which is a marker for pregnancy in the early stages. When the protein is present it causes aggregation of nanoparticles coated with antibodies to the protein, which in turn causes a change in color. In the pregnancy tests, the gold nanoparticles act as a specific biosensor, even though they constitute only a fraction of the material or the cost of the test device.

MOVING FORWARD

The promises of nanoscience and nanotechnology are vast and appear almost unlimited. Just as communications and information technology applications have changed and will continue to change the way we operate as a society in most profound ways — think the Internet of things — we may expect nanotechnologies not only to support that ongoing change but to introduce new paradigms that will have an equally surprising and unpredictable impact. To be part of this change in the future, we need to be educated and understand better how the nanoscale world works so that we may understand both the positive impact and the potential for negative impact, for there is seldom progress in technology without new ancillary challenges. There are cautionary tales to learn from the way other technologies emerged in the recent past. For example, biotechnology applications were hampered significantly by public reluctance to accept genetically modified agricultural products. This was in part because some companies were seen to exploit the technology in such a way as to cause exclusive uses and effectively preventing normal agricultural practices. There were therefore significant ethical issues raised in the commercialization processes. Moreover, the ability to sequence entire genomes has created interesting privacy issues — who has the right to know? Likewise, the ability to modify the genome of individuals raises significant questions about whether such technologies should be applied at all. Correspondingly, in the domain of information technology, applications have become so pervasive that it is difficult to see how we can live without them. However, the emergence of the cloud and the presence of the internet have exposed weaknesses in terms of security and privacy of information. It is inevitable that the development of new nanotechnology-based applications will raise similar questions of the possible health, environmental, ethical, and legal impact of these applications. For example, one of the keys to the use of nanomaterials is that we can impart new properties to these materials, but that begs the question of whether we understand all of the effects of these new properties. Will these materials create unintended consequences for health or the environment? These are issues that need to be addressed as the field of nanotechnology matures. Meanwhile, the excitement is there, and we believe that the information will allow the reader to prepare for participating in the nanotechnology revolution either as an active creator of new science or new nanotechnologies or as a participant in the incorporation of these into new products.