



Nanotechnology's Future

Over the next two decades, this new field for controlling the properties of matter will rise to prominence through four evolutionary stages By MIHAIL C. ROCO

Today nanotechnology is still in a formative phase—not unlike the condition of computer science in the 1960s or biotechnology in the 1980s. Yet it is maturing rapidly. Between 1997 and 2005, investment in nanotech research and development by governments around the world soared from \$432 million to about \$4.1 billion, and corresponding industry investment exceeded that of governments by 2005. By 2015, products incorporating nanotech will contribute approximately \$1 trillion to the global economy. About two million workers will be employed in nanotech industries, and three times that many will have supporting jobs.

Descriptions of nanotech typically characterize it purely in terms of the minute size of the physical features with which it is concerned—assemblies between the size of an atom and about 100 molecular diameters. That depiction makes it sound as though nanotech is merely looking to use infinitely smaller parts than conventional engineering. But at this scale, rearranging the atoms and molecules leads to new properties. One sees a transition between the fixed behavior of individual atoms and molecules and the adjustable behavior of collectives. Thus, nanotechnology might better be viewed as the application of quantum theory and other nano-specific phenomena to fundamentally control the properties and behavior of matter.


Over the next couple of decades, nanotech will evolve through four overlapping stages of industrial prototyping and early commercialization. The first one, which began after 2000, involves the development of passive nanostructures: materials with steady structures and functions, often used as parts of a product. These can be as modest as the particles of zinc oxide in sunscreens, but they can also be reinforcing fibers in new composites or carbon nanotube wires in ultra-miniaturized electronics.

The second stage, which began in 2005, focuses on active nanostructures that change their size, shape, conductivity or other properties during use. New drug-delivery particles could release therapeutic molecules in the body only after they reached their targeted diseased tissues. Electronic compo-

nents such as transistors and amplifiers with adaptive functions could be reduced to single, complex molecules.

Starting around 2010, workers will cultivate expertise with systems of nanostructures, directing large numbers of intricate components to specified ends. One application could involve the guided self-assembly of nanoelectronic components into three-dimensional circuits and whole devices. Medicine could employ such systems to improve the tissue compatibility of implants, or to create scaffolds for tissue regeneration, or perhaps even to build artificial organs.

After 2015–2020, the field will expand to include molecular nanosystems—heterogeneous networks in which molecules and supramolecular structures serve as distinct devices. The proteins inside cells work together this way, but whereas biological systems are water-based and markedly temperature-sensitive, these molecular nanosystems will be able to operate in a far wider range of environments and should be much faster. Computers and robots could be reduced to extraordinarily small sizes. Medical applications might be as ambitious as new types of genetic therapies and antiaging treatments. New interfaces linking people directly to electronics could change telecommunications.

Over time, therefore, nanotechnology should benefit every industrial sector and health care field. It should also help the environment through more efficient use of resources and better methods of pollution control. Nanotech does, however, pose new challenges to risk governance as well. Internationally, more needs to be done to collect the scientific information needed to resolve the ambiguities and to install the proper regulatory oversight. Helping the public to perceive nanotech soberly in a big picture that retains human values and quality of life will also be essential for this powerful new discipline to live up to its astonishing potential. 

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Rearranging atoms leads to new properties.