Nanotechnology: Breaking Through the Next Big Frontier of Knowledge

Joseph V. Kennedy
Former Senior Economist, Joint Economic Committee for Congress

Nanotechnology is getting big. It is already a driving force in diverse fields such as physics, chemistry, biology, and information sciences. Developments coming out of research labs this year will lead to breakthrough new products in medicine, communications, computing, and material sciences sometime in the next two decades. Its impact on our lives over the next fifty years could rival the combined effects of electricity, the internal combustion engine, and the computer over the last century. As with any new technology, nanotechnology raises some safety concerns. However, its overall effects will be strongly beneficial to all sectors of society.

This article describes what nanotechnology is and how it builds on previous scientific advances. It then discusses the most likely future development of different technologies in a variety of fields and how government policy is aiding scientific advance.

What Is Nanotechnology?

A nanometer (nm) is one billionth of a meter. For comparison purposes, the width of an average hair is 100,000 nanometers. Human blood cells are 2,000 to 5,000 nm long, a strand of DNA has a diameter of 2.5 nm, and a line of ten hydrogen atoms is 1 nm. The last three statistics are especially enlightening. First, even within a blood cell there is a great deal of room at the nanoscale; therefore, nanotechnology holds out the promise of manipulating individual cell structure and function. Second, the ability to understand and manipulate matter at the level of one nanometer is closely related to the ability to understand and manipulate both matter and life at their most basic levels: the atom and the organic molecules that make up DNA.

It is difficult to overestimate nanotechnology's likely implications for society. For one thing, advances in just the last five years have proceeded much faster than even the best experts had predicted. Looking forward, science is likely to continue outrunning expectations, at least in the medium-term. Although science may advance rapidly, technology and daily life are likely to change at a much slower pace for several reasons. First, it takes time for scientific discoveries to become embedded into new products, especially when the market for those products is uncertain.

Second, both individuals and institutions can exhibit a great deal of resistance to change. Because new technology often requires significant organizational change and cost in order to have its full effect, this can delay the social impact of new discoveries. For example, computer technology did not have a noticeable effect on economic productivity until it became widely integrated into business processes. It took firms over a decade to go from replacing the typewriters in their office to rearranging their entire supply chains to take advantage of the Internet. Although some firms adopted new technologies rapidly, others lagged far behind.

Interdisciplinary

Nanotechnology is distinguished by its interdisciplinary nature. The most advanced research and product development increasingly requires knowledge of disciplines that, until now, operated largely independently. These areas include:

Physics: The construction of specific molecules is governed by the physical forces between the individual atoms composing them. Nanotechnology will involve the continued design of novel molecules for specific purposes. In addition, researchers need to understand how quantum physics affects the behavior of matter below a certain scale.

Chemistry: The interaction of different molecules is governed by chemical forces. Nanotechnology will involve the controlled interaction of different molecules. Understanding how different materials interact with each other is a crucial part of designing new nanomaterials to achieve a given purpose.

Biology: A major focus of nanotechnology is the creation of

> Nanotechnology is the current stage of a long-term trend toward understanding and manipulating matter at ever smaller scales as time goes by. Over the last century, physicists and biologists have developed a much more detailed understanding of matter at finer and finer levels. At the same time, engineers have gradually acquired the ability to reliably manipulate material to increasingly finer degrees of precision. Although we have long known much of what happens at the nanolevel, the levels of knowledge implied by 1) knowing about the existence of atoms, 2) actually seeing them, 3) manipulating them, and 4) truly understanding how they work, are dramatically different. The last two stages open up significant new technological abilities. At the nanolevel, technology has just recently reached these stages.

small devices capable of processing information and performing tasks on the nanoscale. The process by which information encoded in DNA is used to build proteins, which then go on to perform complex tasks offers one possible template. A better understanding of how biological systems work at the lowest level may allow future scientists to use similar processes to accomplish new purposes. It is also a vital part of all research into medical applications.

Computer Science: Moore's Law and its corollaries, the phenomena whereby the price performance, speed, and capacity of almost every component of the computer and communications industry has improved exponentially over the last several decades, has been accompanied by steady miniaturization. Continued decreases in transistor size face physical barriers including heat dissipation and electron tunneling that require new technologies to get around. In addition, a major issue for the use of any nanodevices will be the need to exchange information with them.

Electrical Engineering: To operate independently, nanodevices will need a steady supply of power. Moving power into and out of devices at that scale represents a unique challenge. Within the field of information technology, control of electric signals is also vital to transistor switches and memory storage. A great deal of research is also going into developing nanotechnologies that can generate and manage power more efficiently.

Mechanical Engineering: Even at the nanolevel, issues such as load bearing, wear, material fatigue, and lubrication still apply. Detailed knowledge of how to actually build devices that do what we want them to do with an acceptable level of confidence will be a critical component of future research.

"Detailed knowledge of how to actually build devices that do what we want them to do with an acceptable level of confidence will be a critical component of future research."

Impacts

With so many sciences having input into nanotechnology research, it is only natural that the results of this research are expected to have a significant impact on four broad applications (nanotechnology, genetics, information technology, and robotics) that interrelate in a number of ways:

Nanotechnology: Nanotechnology often refers to research in a wide number of fields including the three listed below. But in its limited sense, it refers to the ability to observe and manipulate matter at the level of the basic molecules that govern genetics, cell biology, chemical composition, and electronics. Researchers can then apply this ability to advance science in other fields. The broader definition of nanotechnology applies throughout most of this paper, but it is worth remembering that advances in other sciences depend on continued improvements in the ability to observe, understand, and control matter at the nanolevel. This in turn will require more accurate and less expensive instrumentation and better techniques for producing large numbers of nanodevices.

Biotechnology (Genetics): Nanotechnology promises an increased understanding and manipulation of the basic building blocks underlying all living matter. Though the basic theory of genetic inheritance has been known for some time, biologists do not fully understand how life goes from a single fertilized egg to a living animal. Questions exist on exactly how the information encoded in DNA is transcribed, the role of proteins, the internal workings of the cell and many other areas. On a basic level, research is allowing us to tease out the genetic basis for specific diseases and in the future may reliably allow us to correct harmful mutations. But what would a full understanding of the genetic process give us? Could we develop DNA that uses a fifth and sixth molecule? Could the existing process be reprogrammed to code for more than 20 amino acids? To what extent is it possible to create brand new proteins that perform unique functions?

A better understanding of biological processes is obviously needed in order to deliver the health benefits that nanotechnology promises. But it is also important for many reasons outside of biology. Those comfortable with traditional manufacturing techniques may at first have difficulty with the concept of building a product up from the molecular level. Biology offers a template for doing so. A single fertilized egg in the womb eventually becomes a human being: a system of incredible complexity from a simple set of instructions 2.5 nm in diameter. Scientists are hopeful that similar processes can be used to produce a range of other structures.

Information Technology: Progress in information processing has depended on the continued application of Moore's law, which predicts a regular doubling of the number of transistors that can be placed on a computer chip. This has produced exponential improvements in computing speed and price performance. Current computer technology is based on the Complementary Metal Oxide Semiconductor (CMOS). The present generation of computer chips already depends on features as small as 70 nanometers. Foreseeable advances in nanotechnology are likely to extend CMOS technology out to the year 2015. However, at transistor densities beyond that, several problems start to arise. One is the dramatic escalation in the cost of a new fabrication plant to manufacture the chips. These costs must be amortized in the cost of the transistors, keeping them expensive. Second, it becomes increasingly difficult to dissipate the heat caused by the logic devices. Lastly, at such small distances, electrons increasingly tunnel between materials rather than going through the paths programmed for them. As a result of these constraints, any continuation of Moore's Law much beyond 2015 is likely to require the development of one or more new technologies.

Future advances will likely bring us closer to a world of free memory, ubiquitous data collection, massive serial processing of data using sophisticated software, and lightening-fast, always-on transmission. What happens when almost all information is theoretically available to everyone all the time?

Cognitive Sciences (Robotics): Continued advances in computer science combined with a much better understanding of how the human brain works should allow researchers to develop software capable of duplicating and even improving on many aspects of human intelligence. Although progress in artificial intelligence has lagged the expectations of many of its strongest proponents, specialized software continues to advance at a steady rate. Expert software now outperforms the best humans in a variety of tasks simply because it has instantaneous access to a vast store of information that it can quickly process. In addition, researchers continue to develop a much better understanding of how individual sections of the brain work to perform specific tasks. As processing power continues to get cheaper, more and more of it will be applied to individual problems.

Government Policy Toward Nanotechnology

Nanotechnology is still in its early stages. Many of the most valuable commercial applications are decades away and require continued advances in basic and applied science. As a result, government funding still constitutes a large proportion of total spending on research and development. Within the United States, this spending is guided by the National Nanotechnology Initiative (NNI). The NNI coordinates the policy of twenty-five government agencies, including thirteen that have budgets for nanotechnology research and development. It has set up an infrastructure of over thirty-five institutions across the country to conduct basic research and facilitate the transfer of technology to the private sector. For fiscal year 2008, President Bush has requested $1.45 billion for research directly related to nanotechnology (see **Figure 1**).

The NNI's strategic plan sets out four main goals:

- Maintain a world-class research and development program to exploit the full potential of nanotechnology.
- Facilitate the transfer of nanotechnology into products for economic growth, jobs, and other public benefits.
- Develop educational resources, a skilled workforce, and the supporting infrastructure to advance nanotechnology.
- Support responsible development of nanotechnology.

The NNI is clearly geared toward developing the technology on a broad front, correctly seeing it as the source of tremendous benefits to society. Its mission is not to see whether we should go forward with research and development. It is to go forth boldly, while trying to discover and deal with possible risks.

Presently, the United States leads the world in most areas of research. However, other countries, including China, also see research in nanotechnology as being vital to their ability to create value in tomorrow's economy. It is not necessary, nor would it even be desirable, for the United States to lead in every aspect of this broad field. However, continued leadership on a broad range of applications is critical to our nation's continued ability to compete in world markets. In addition, in a few areas, such as defense applications, international leadership has important strategic implications.

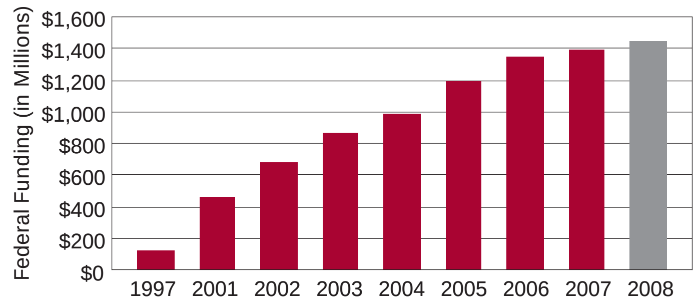
What Does Nanotechnology Mean for Us?

The simple answer is that, over the next fifty years, consumers will see a growing range of new products that dramatically transform their lives. If properly managed, these products will dramatically improve human health, change the structure of society, and open up new possibilities for human potential.

On a more basic level, managers must begin to study how today's discoveries could transform their business in the next five to ten years. By now every business, even those far removed from the computer industry, has been significantly affected by the revolution in communications and computing. Nanotechnology's influence will be equally broad. First, it will create the capacity for new products with much better performance characteristics and less waste. Second, by continuing the communications revolution, it will give companies new ways to organize work and distribution lines. Third, it will transform the environment within which the business competes.

The world we live in will continue to get faster, more complex, and smaller.

Figure 1
U.S. Federal Funding for Nanotechnology Research



Source: U.S. National Nanotechnology Initiative