Chapter 1

Convergence at the Nanoscale

Nanoscience and nanotechnology are not merely "the next big things," offering investors the chance to get in on the ground floor of new industries. More importantly, they promote the unification of most branches of science and technology, based on the unity of nature at the nanoscale. Already, information technology incorporates hardware with nanoscale components, and biotechnology is merging with nanotechnology in many areas. Indeed, unless these technologies converge, further progress in most fields will be impossible. More controversially—but also more significantly—the convergence is prepared to encompass cognitive science. This vast unification is often called NBIC, from the initials of its four main components: Nanotechnology, Biotechnology, Information technology, and Cognitive science. The result will be new cognitive technologies that promise to put the behavioral and social sciences for the first time on a rigorous foundation.

This book reports the latest developments in, and tantalizing possibilities related to, convergence at the nanoscale. The perspective taken here is that of a social and information scientist who has been centrally involved in major collaborative projects to assess the implications of nanoscience and nanotechnology.

THE MEANING OF "NANO"

Convergence of NBIC technologies will be based on *material unity at the nanoscale* and on *technology integration from that scale*. The building blocks of matter that are fundamental to all sciences originate at the nanoscale—that is, the scale at which complex inorganic materials take on the characteristic mechanical, electrical, and chemical properties they exhibit at larger scales. The nanoscale is where the fundamental structures of life arise inside biological cells, including the DNA molecule itself. Soon, the elementary electronic components that are the basis of information technology will be constructed at the nanoscale. Understanding the function of the human brain requires research on nanoscale phenomena at receptor sites on neurons, and much brain research will be facilitated by nanoscale components in microsensor arrays and comparable scientific tools. Thus nanotechnology will play an essential role both in achieving progress in each of the four fields and in unifying them all.

Although perhaps everyone understands that "nano" concerns the very small, it is nevertheless difficult to get a picture of how small a nanometer really is: one billionth (thousand-millionth) of a meter. A billionth of a meter is the same as a millionth of a millimeter, and the smallest U.S. coin, the "thin" dime, is about a millimeter in thickness. If you were somehow able to shrink yourself down until you were only a nanometer tall, then in comparison a dime would seem to be 175 kilometers (about 100 miles) thick. The DNA in the cells of our bodies is between 2 and 3 nanometers thick, though as much as several millimeters long, so it has the proportions of a long piece of fine thread, curled up inside the chromosomes. Atoms and water molecules are smaller than a nanometer, whereas the wavelength of visible light ranges from approximately 400 nanometers at the violet end of the spectrum to approximately 700 nanometers at the red.

In 1960, the General Conference on Weights and Measures refined the metric system of measurement, among other things defining the nanometer as one billionth of a meter. Another unit for measuring tiny distances was already widely used in spectroscopy and nuclear physics, the ångström, which is 0.1 nanometer. In principle, the ångström became obsolete in 1960, but, in fact, it is still used today.

During the next few years, "nano" concepts became widely disseminated throughout the cultures of civilized nations. For example, the 1966–1967 sci-fi television series *Time Tunnel* used the word "nanosecond" as part of the countdown to operate its time machine: "One second, millisecond, microsecond, nanosecond!" The term "nanotechnology" was apparently first used by Professor Norio Taniguchi of Tokyo Science University in a 1974 paper, in which it described the ultimate standard for precision engineering."[1]

Recently, people have been coining "nanowords" at a furious pace. For an article I published in *The Journal of Nanoparticle Research* in 2004, I counted titles containing "nano" on the Amazon.com website, finding 180 books that fit the bill.[2] Some contain two "nano" words, such as *Societal Implications of Nanoscience and Nanotechnology*, edited by Mihail ("Mike") C. Roco and myself in 2000. Altogether, there were 221 "nano" words in the titles of these 180 books. Nanotechnology is most common, appearing 94 times. Nanostructure (or a variant like nanostructured) appeared 28 times, and nano, 18 times. These words appeared five times: nanocomposite, nanofabrication, nanomaterials, nanophase, nanotribology, nanoscale, and nanoscience.

Nanosystems appeared four times, and nanoengineering, nanoindentation, nanomeeting, and nanoparticles appeared three times each. Bionanotechnology appeared twice, as did nanocrystalline, nanoelectronics, nanometer, nanophotonics, nanotech, and nanoworld. Sixteen other words appeared once in the titles: nanobelts, nanobiology, nanocosm, nanodevices, nanoelectromechanics, nanolithography, nanomechanics, nanomedicine, nanometric, nanometrology, nanoporous, nanopositioning, nanoscopy, nanosources, nanotubes, and nanowires. Clearly, we are facing a nanocraze, nanofad, or nanohype.

This welter of words may bring pure nano into disrepute, because it seems to be claiming too much scope for the field. Nevertheless, it would be a mistake to think that nanotechnology is a specific technical approach, such as the fabled nanoscale robots that some visionaries imagine. Rather, the nanoscale is the region where many technologies meet, combine, and creatively generate a world of possibilities. The official website of the National Nanotechnology Initiative (NNI; www.nano.gov) defines the field as follows:

> Nanotechnology is the understanding and control of matter at dimensions of roughly 1 to 100 nanometers, where unique phenomena enable novel applications. Encompassing nanoscale science, engineering, and technology, nanotechnology involves imaging, measuring, modeling, and manipulating matter at this length scale. At the nanoscale, the physical, chemical, and biological properties of materials differ in fundamental and valuable ways from the properties of individual atoms and molecules or bulk matter. Nanotechnology R&D is directed toward understanding and creating improved materials, devices, and systems that exploit these new properties.

For NNI leader Mike Roco (Figure 1–1), the scientific challenges of this length scale are as immense as the technical opportunities:

> We know most about single atoms and molecules at one end, and on bulk behavior of materials and systems at the other end. We know less about the intermediate length scale—the nanoscale, which is the natural threshold where all living systems and manmade systems work. This is the scale where the first level of organization of molecules and atoms in nanocrystals, nanotubes, nanobiomotors, etc., is established. Here, the basic properties and functions of material structures and systems are defined, and even more importantly can be changed as a function of organization of matter via "weak" molecular interactions.[3]

Figure 1–1 Mihail C. Roco, Senior Advisor for Nanotechnology to the Directorate for Engineering, National Science Foundation. Mike has not only been the most forceful advocate for nanoscience and technology, but also originated many of the key ideas in NBIC convergence on the basis of considering the societal implications of nanotechnology.

When I first became professionally involved with nanotechnology, I was a member of the scientific staff of the Directorate for Social, Behavioral, and Economic Sciences of the National Science Foundation (NSF). Since 1993, I had been representing the directorate on computer-oriented cross-cutting initiatives, such as High-Performance Computing and Communications, the Digital Library Initiative, and Information Technology Research. I was a lifelong technology enthusiast, having written three books about the space program, experimented with musical technologies from harpsichords to electronic tone generators, and programmed a good deal of educational and research software. Thus, when Mike Roco approached the directorate in 1999, seeking someone to represent the social sciences on the nanotechnology initiative he was organizing, I was excited to volunteer.

NANOTECHNOLOGY AND SCIENTIFIC PROGRESS

Unwittingly, I first encountered nanotechnology when I was a very small child. When I was four years old, I had the opportunity to visit the laboratory of multimillionaire and nuclear scientist Alfred Lee Loomis in his mansion at Tuxedo Park, New York. He showed me secrets that were too highly classified for an adult who might understand their importance. Loomis was a financier with some connection to my maternal grandfather's Wall Street law firm, but he was also a practicing physicist who played major roles in two high-tech programs that helped the Allies win World War II: the Manhattan Project, which developed the atomic bomb, and the Radiation Laboratory at Massachusetts Institute of Technology (MIT), which developed radar.[4] In his lab, Loomis first showed me a cup and then poured water into it; I was astonished to see that the water poured out again magically through the solid ceramic material. Only decades later did I realize that I had seen the fundamental secret of gas diffusion uranium isotope separation. It was my first introduction to nanotechnology.

There are several ways to obtain the fissionable material necessary to make an atom bomb. One of the first means developed relied on the separation of U235, the isotope of uranium suited for a bomb, from the unsuitable but much more common U238, using gas diffusion. Because they are isotopes of the same chemical element, the two cannot be separated by means of any chemical reaction. Instead, their slightly different physical properties need to be exploited to carry out the separation.

In this technique, uranium composed of both isotopes is chemically combined with fluorine to make uranium hexafluoride, which when heated becomes a gas. This gas is extremely corrosive and must be handled very carefully because of both its chemical properties and its radioactivity. For example, when uranium hexafluoride meets water, it generates hydrofluoric acid, which is so corrosive it can eat through glass.

The uranium hexafluoride is then passed through a porous barrier—a sheet of something with holes to allow the gas through—that slows the U238 down slightly, because it is slightly heavier. Although the exact details remain classified, the ideal average size of the pores is about 10 nanometers.[5] This is not just a matter of having holes that are exactly the right size to let U235 through yet block U238. A uranium atom is slightly less than one nanometer in diameter, and clustering six fluorine atoms around it does not produce a big molecule. The efficiency of the separation process is low, so it is necessary to cascade a large number of separation steps to enrich the uranium sufficiently for use in a bomb, and other methods are used today.

When Loomis showed me his sample of the gas diffusion barrier, in the form of a cup that could not hold its water, the first atomic bomb had not been detonated yet, and the word "nanotechnology" had not been coined. Nevertheless, even a child could see that his laboratory held secrets of the utmost importance. A sense of how far nano has come since those bygone days can be gained from the speeches given by six scientists when they accepted the Nobel Prize for great advances that enabled rapid development in nanoscience. The NNI website notes, "Nanoscale science was enabled by advances in microscopy, most notably the electron, scanning tunneling, and atomic force microscopes, among others. The 1986 Nobel Prize for Physics honored three of the inventors of the electron and scanning tunnel microscopes: Ernst Ruska, Gerd Binnig, and Heinrich Rohrer."[6]

The first electron microscope, which was built in 1931 by Ruska and Max Knoll, was hardly more powerful than a student's optical microscope, magnifying objects 400 times their diameter. Optical microscopes, however, remain limited by the rather long wavelengths of visible light (400–700 nanometers). In contrast, over a period of years, the resolving power of electron microscopes gradually sharpened until it reached deep into the nanoscale. The research by Ruska and Knoll was initially intended to refine oscilloscopes—devices used to measure fluctuating electric currents and signals, which were based on the same kind of cathode ray tube used as the picture tube in television sets before the introduction of flat screens. A cathode ray tube draws a picture on a fluorescent screen by scanning an electron beam over it. In 1929, Ruska became the first person to carry out experiments in which a well-focused electron beam actually cast images of a physical object in the beam's path. Two years later he developed an arrangement of focusing coils that permitted enlargement of the image—that is, the first electron microscope.[7]

Gerd Binnig and Heinrich Rohrer did not set out to develop a new kind of microscope, but rather sought to perform spectroscopic analysis of areas as small as 10 nanometers square. Interested in the quantum effect called tunneling, they were aware that other scientists were studying this phenomenon in connection with spectroscopy, and they began to think about how they might apply it in their own work. Binnig and Rohrer considered studying a material by passing a small probe with a very tiny tip over the surface so that electrons would tunnel across the gap. As they noted in their lecture accepting the Nobel Prize: "We became very excited about this experimental challenge and the opening up of new possibilities. Astonishingly, it took us a couple of weeks to realize that not only would we have a local spectroscopic probe, but that scanning would deliver spectroscopic and even topographic images, i.e., a new type of microscope."[8]

New measurement instruments and research methodologies are fundamental to the development of new fields of science and engineering. Once methods of research exist, then discoveries naturally follow. In 1985, Robert F. Curl, Jr., Sir Harold W. Kroto, and Richard E. Smalley discovered that carbon atoms can assemble into ball-shaped structures rather like the geodesic domes designed by architect Buckminster Fuller in the 1960s.[9] In recognition of the similarity, these assemblies of carbon atoms came to be called "buckyballs" or, more formally, buckminsterfullerenes (usually shortened to fullerenes). The

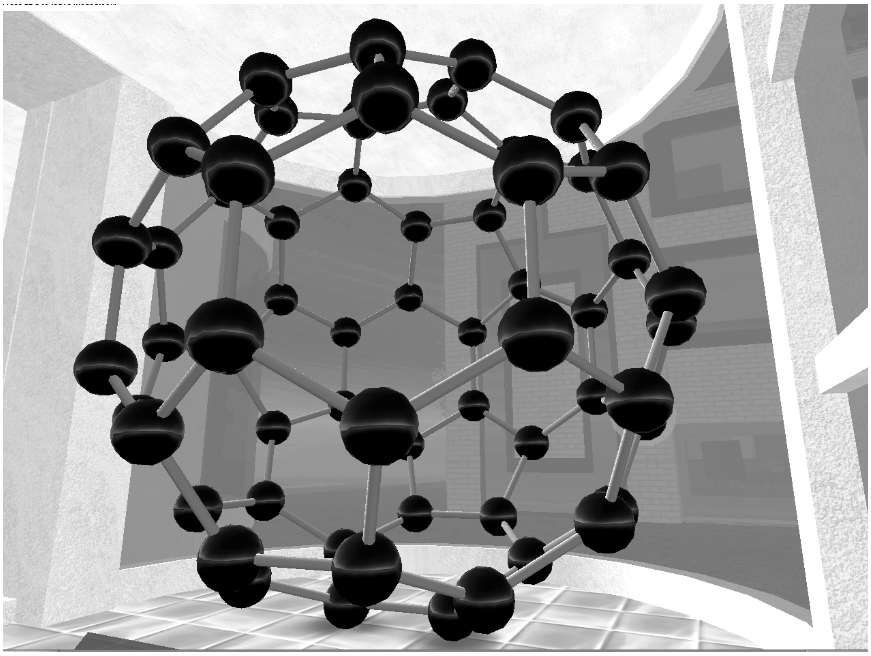

Figure 1–2 Superscale model of a fullerene, built by Troy McLuhan, on display in a virtual world. This nanoscale structure appears twice the height of a human being in the Science Center in the online environment called Second Life (http://www.secondlife.com/), illustrating the many convergences between nanotechnology and information technology.

best known, C_{60}, is a practically spherical structure of 60 carbon atoms; because it is hollow, it is therefore capable of holding other atoms inside. Figure 1–2 shows what one might look like—if atoms were like solid balls and you could shrink yourself down to nanoscale and still be able to see.

Fullerenes earned their discoverers the 1996 Nobel Prize in Chemistry and inspired many researchers to hunt for other remarkable structures at the nanoscale. As the Nanotech Facts webpage of the NNI notes, the development of practical applications is not automatic but can follow more or less quickly:

> The transition of nanotechnology research into manufactured products is limited today, but some products moved relatively quickly to the marketplace and already are having significant impact. For example, a new form of carbon—the nanotube—was discovered by Sumio Iijima in 1991. In 1995, it was recognized that carbon nanotubes were excellent sources of field-emitted electrons. By 2000, the "jumbotron lamp," a nanotube-based light

> source that uses these field-emitted electrons to bombard a phosphor, was available as a commercial product. (Jumbotron lamps light many athletic stadiums today.) By contrast, the period of time between the modeling of the semiconducting property of germanium in 1931 and the first commercial product (the transistor radio) was 23 years.[10]

After experiencing 60 years of progress since the Manhattan Project, is nanotechnology now ready to transform the world? Encouraged by science fiction writers and visionaries who wanted to turn sci-fi dreams into reality, a romantic mythology has arisen around nanotechnology. It prophesies that nanotechnology will make practically anything possible, from cost-free manufacturing of anything humans can imagine, to cure of all diseases including old age, to extinction of the human species by self-reproducing nanoscale robotic monsters. This vision imagines that "nanotech" or "nano" will be the ultimate magic, fulfilling all human wishes and fears. As such, it has helped science fiction sustain its traditional sense of wondrous possibilities, despite widespread disappointment about the original sci-fi plot device, which was space travel to other inhabited planets.

It is good to have hope, and creative individuals need unreasonable enthusiasm to overcome the resistance of the uncreative majority and to sustain their own energies when years of effort have not led to attainment of their goals. Much nano rhetoric is hyperbole, but a certain amount of nanohype may be necessary to achieve real progress. Probably the false impressions promulgated by science fiction writers and nontechnical visionaries have helped the real scientists and engineers receive greater funding from government and industry. Perhaps they also attract young people to the related professional fields, in an era when intellectually demanding careers in science and technology are not particularly popular among the wealthy citizens of postindustrial nations like the United States. However, investors, policy makers, and interested citizens deserve an accurate accounting of the real applications that nanotechnology is likely to have.

For the United States and other advanced postindustrial societies, a crucial part of the context for nanotechnology is the heavy reliance the economy places not only on existing technology, but also on technological innovation. If the United States stops innovating, other nations with lower labor costs will take away the business that supports American prosperity. A key ingredient for innovation is entrepreneurship, but enthusiasm and salesmanship can accomplish little if science fails to provide the technical basis for innovation.

In the early 1990s, when *Scientific American* journalist John Horgan interviewed many senior scientists about whether research in their field had passed the point of diminishing returns, several of them believed that all the big discoveries had been made.[11] It should be noted that many of the scientists Horgan interviewed were very elderly, and they had an alarming tendency to die soon after he had interviewed them. Many were at the ends of their careers, if not their lives, and such people often like to think that their generation made the great discoveries and to begrudge future generations their own achievements. Even so, these scientists may have been correctly reporting that their fields, as traditionally defined, had already accomplished most of what could be expected of them.

Thus nanoconvergence may be absolutely essential for continued technological progress. The danger of hyping nanotechnology on the basis of false impressions is that its actual revolutionary potential might unfairly be discounted. A correct understanding of nanoconvergence requires serious, collaborative analysis by experts in many fields.

Technological Convergence

In a sense, nanotechnology is based on a scientific and technological convergence of great importance that began early in the twentieth century as physicists elucidated the nature of atoms. This knowledge, in conjunction with chemists' growing understanding of how atoms combined into molecules, gave birth to modern materials science. One way to understand how these fields connect is to examine how they are organized at the National Science Foundation. NSF is divided into a number of directorates, each representing a major territory of discovery. The Directorate for Mathematical and Physical Science (MPS) consists of five divisions: Mathematical Sciences, Physics, Chemistry, Materials Research, and Astronomical Sciences. We will refer to the domain of astronomical sciences in Chapter 8 (covering "the final frontier"), while the first four divisions provide the basis for most of nanoscience. The Directorate for Engineering has played a special role in organizing the National Nanotechnology Initiative in cooperation with people in MPS, other directorates, and other government agencies. Nanotechnology is not simply the current phase in the evolution of MPS fields, but rather reflects a new departure, based on their convergence, with the broadest possible implications.

The first serious effort to envision the societal implications of nanotechnology was a conference organized at the request of the Subcommittee on Nanoscale Science, Engineering, and Technology (NSET) of the U.S. government's National Science and Technology Council (NSTC), and held at NSF on September 28–29, 2000. The result was a major scientific and engineering report, *Societal Implications of Nanoscience and Nanotechnology*, edited by Mike Roco and myself. The very first sentences of the introduction to this report recognized that nanotechnology's chief impact would be through partnerships with other fields:

> A revolution is occurring in science and technology, based on the recently developed ability to measure, manipulate, and organize matter on the nanoscale—1 to 100 billionths of a meter. At the nanoscale, physics, chemistry, biology, materials science, and engineering converge toward the same principles and tools. As a result, progress in nanoscience will have very far-reaching impact.[12]

This pioneering report had great impact, both immediate and indirect. Notably, NSF began supporting projects, both large and small, to explore the social, ethical, and economic implications of nanotechnology.[13] Centers were established across the country, including the Center for Nanotechnology in Society at the University of California, Santa Barbara (grant 0531184 for $2,095,000); the Center for Nanotechnology in Society at Arizona State University (grant 0531194 for $2,605,000); and "From Laboratory to Society: Developing an Informed Approach to Nanoscale Science and Technology" associated with the nanotechnology center at the University of South Carolina (grant 0304448 for $1,350,000). A graduate research and training program was set up at MIT, "Assessing the Implications of Emerging Technologies" (grant 0333010 for $1,737,806), to involve faculty members and graduate students in prospective analysis of the likely implications of nanotechnology, based on retrospective analogies with earlier emerging technologies. The University of California, Los Angeles, began developing a database called NanoBank, providing information for social-science studies of nanoscience and commercialization (grant 0304727 for $1,490,000), specifically incorporating a component charting the convergence of nanotechnology with other fields. Finally, Michigan State University established a major convergent program called "Social and Ethical Research and Education in Agrifood Nanotechnology" (grant 0403847 for $1,720,000), with three objectives:[14]

- Deriving lessons from the social conflict over agrifood biotechnology that may be useful to the entire range of researchers engaged in the new nanotechnology initiative
- Building a new multidisciplinary competence among a team of senior researchers with extensive experience in social and ethical issues associated with agrifood technology, who have collaborated to develop communication strategies in engineering applications, and relatively junior researchers starting research programs in social and economic dimensions of agrifood science

- Identifying the most likely applications of nanotechnology within the agrifood sector (including food distribution and consumption), and developing a proactive strategy for understanding and addressing social and ethical issues associated with them

In the influential nanotechnology review called *Small Wonders, Endless Frontiers*, the National Research Council reported, "Scientists and engineers anticipate that nanoscale work will enable the development of materials and systems with dramatic new properties relevant to virtually every sector of the economy, such as medicine, telecommunications, and computers, and to areas of national interest such as homeland security."[15] Note that this sentence implies convergence, speaking of "nanoscale work" that will "enable," rather than treating nanotechnology as a completely separate branch of engineering. The NRC based its three findings about societal implications largely on our pioneering report:[16]

- The development of radically new nanotechnologies will challenge how we educate our scientists and engineers, prepare our workforce, and plan and manage R&D.
- The social and economic consequences of nanoscale science and technology promise to be diverse, difficult to anticipate, and sometimes disruptive.
- Nanoscale science and technology provides a unique opportunity for developing a fuller understanding of how technical and social systems affect each other.

As soon as we had finished editing *Societal Implications of Nanoscience and Nanotechnology,* we organized a second major gathering for December 3–4, 2001. Sponsored by NSF and the Department of Commerce, this conference examined the progress that could be achieved by combining four NBIC fields: nanotechnology, biotechnology, information technology, and cognitive science (Figure 1–3). Nearly 100 contributors concluded that this technological convergence could vastly increase the scope and effectiveness of human activity, thereby improving human performance and well-being. As co-editor Mike Roco and I explained in the first paragraph of the introduction to the report emerging from this conference:

> We stand at the threshold of a new renaissance in science and technology, based on a comprehensive understanding of the structure and behavior of matter from the nanoscale up to the most complex system yet discovered, the human brain. Unification of science based on unity in nature and its holistic investigation will lead to technological convergence and a more efficient societal

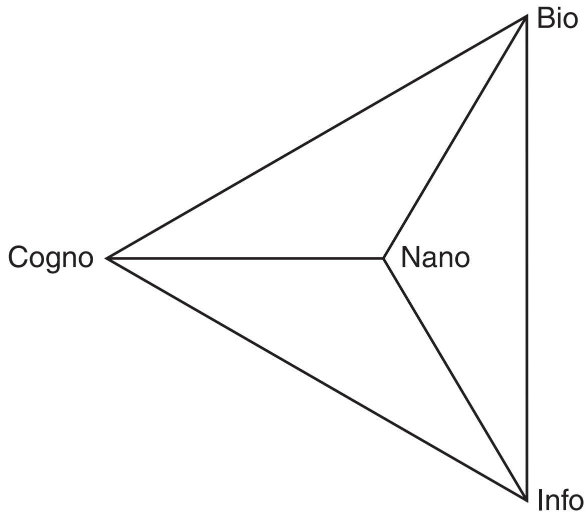

Figure 1–3 The NBIC tetrahedron combining nanotechnology, biotechnology, information technology, and new technologies based on cognitive science. Scientific and technological innovation can be stimulated through the convergence of two, three, or all four fields.

> structure for reaching human goals. In the early decades of the twenty-first century, concentrated effort can bring together nanotechnology, biotechnology, information technology, and new technologies based in cognitive science. With proper attention to ethical issues and societal needs, the result can be a tremendous improvement in human abilities, new industries and products, societal outcomes, and quality of life.[17]

Word-play is not a serious form of analysis, but fortuitous coincidences can express valid symbolisms. For example, NSF says it is the place where discoveries begin, based on its support for all forms of fundamental science. Thus it is not surprising that NSF supported the first NBIC conference. NBIC will transform the world, and the letters "NSF" are at the heart of the word "traNSForm"! Converging technologies seek to combine the powers of all sciences, and the letters "NBIC" are found in "ComBINe." They are also found in "BioNIC," the combination of biotechnology and information technology to enhance human performance.

Many perceptive observers have noticed the progressing convergence. In his massive study of the Information Society, Manuel Castells writes, "Technological convergence increasingly extends to growing interdependence between the biological and micro-electronics revolutions, both materially and methodologically. . . . Nanotechnology may allow sending tiny microprocessors into the systems of living organisms, including humans."[18] Leading scientists have actively promoted convergence throughout their careers—most notably sociobiologist Edward O. Wilson, who called convergence "consilience" in his 1998 book of that title.[19]

The challenge of integrating fields, disciplines, and subdisciplines will stimulate both theoretical creativity and empirical discovery. Measurement techniques developed in one area will accelerate progress elsewhere, as will innovative tools of all kinds, from nanoscale sensors to cyberinfrastructure. Investment by government and industry cannot be entirely justified by the anticipated intellectual benefits, however. The great promise of technological convergence must attract the interest of policy makers and ordinary citizens through the practical applications it can achieve. Converging technologies will make people healthier, stronger, smarter, more creative, and more secure. In their group deliberations and individual essays, the prominent scientists and engineers at the NBIC conference identified a variety of practical possibilities associated with this trend:[20]

- Comfortable, wearable sensors and computers will enhance every person's awareness of his or her health condition, environment, chemical pollutants, potential hazards, and information of interest about local businesses, natural resources, and the like.
- Machines and structures of all kinds, from homes to aircraft, will be constructed of materials that have exactly the desired properties, including the ability to adapt to changing situations, high energy efficiency, and environmental friendliness.
- A combination of technologies and treatments will compensate for many physical and mental disabilities and will eradicate altogether some handicaps that have plagued the lives of millions of people.
- Robots and software agents will be far more useful for people, because they will operate on principles compatible with human goals, awareness, and personality.
- People from all backgrounds and of all ranges of ability will learn valuable new knowledge and skills more reliably and quickly, whether in school, on the job, or at home.
- Individuals and teams will be able to communicate and cooperate profitably across traditional barriers of culture, language, distance, and professional specialization, thereby greatly increasing the effectiveness of groups, organizations, and multinational partnerships.

- The human body will be more durable, healthier, more energetic, easier to repair, and more resistant to many kinds of stress, biological threats, and aging processes.
- National security will be greatly strengthened by lightweight, information-rich war-fighting systems, capable uninhabited combat vehicles, adaptable smart materials, invulnerable data networks, superior intelligence-gathering systems, and effective measures against biological, chemical, radiological, and nuclear attacks.
- Anywhere in the world, an individual will have instantaneous access to needed information, whether practical or scientific in nature, in a form tailored for most effective use by that particular individual.
- Engineers, artists, architects, and designers will experience tremendously expanded creative abilities, both with a variety of new tools and through improved understanding of the wellsprings of human creativity.
- The ability to control the genetics of humans, animals, and agricultural plants will greatly benefit human welfare; widespread consensus about ethical, legal, and moral issues will be built in the process.
- The vast promise of outer space will finally be realized by means of efficient launch vehicles, robotic construction of extraterrestrial bases, and profitable exploitation of the resources of the Moon, Mars, or near-Earth-approaching asteroids.
- New organizational structures and management principles based on fast, reliable communication of needed information will vastly increase the effectiveness of administrators in business, education, and government.
- Both average persons and policy makers will have a vastly improved awareness of the cognitive, social, and biological forces operating their lives, enabling far better adjustment, creativity, and daily decision making.
- The factories of tomorrow will be organized around converging technologies and increased human–machine capabilities as "intelligent environments" that achieve the maximum benefits of both mass production and custom design.
- Agriculture and the food industry will greatly increase yields and reduce spoilage through networks of cheap, smart sensors that constantly monitor the condition and needs of plants, animals, and farm products.
- Transportation will be safe, cheap, and fast owing to ubiquitous real-time information systems, extremely high-efficiency vehicle designs, and the use of synthetic materials and machines fabricated from the nanoscale for optimal performance.

- The work of scientists will be revolutionized by importing approaches pioneered in other sciences—for example, genetic research employing principles from natural language processing and cultural research employing principles from genetics.
- Formal education will be transformed by a unified but diverse curriculum based on a comprehensive, hierarchical intellectual paradigm for understanding the architecture of the physical world from the nanoscale through the cosmic scale.
- Fast, broadband interfaces directly between the human brain and machines could transform work in factories, control automobiles, ensure military superiority, and enable new sports, art forms, and modes of interaction between people.

Since the original Converging Technologies conference, there have been three others—in Los Angeles, New York, and Kona, Hawaii—plus a second NSF-organized conference on the societal implications of nanotechnology that confirmed the centrality of nanoscience for convergence, and of convergence for the impacts of nanotechnology. I had the privilege of co-editing five of the book-length reports that grew out of these conferences and contributing two chapters to the sixth report; I also had the pleasure of attending all of these historic gatherings. In addition, the European Commission (EC) published a report in reaction to the U.S. work in this field; the EC report, called *Converging Technologies: Shaping the Future of European Societies*, urged concerted efforts in this area.[21]

Application Areas

At the first Converging Technologies conference, five workshop groups of experts in appropriate fields considered the research challenges associated with highly valuable applications that could enhance human performance along five different dimensions. Their conclusions follow.[22]

Expanding Human Cognition and Communication. The human mind can be significantly enhanced through technologically augmented cognition, perception, and communication. Central to this vital work will be a multidisciplinary effort to understand the structure and function of the mind, which means research not only on the brain, but also on the ambient sociocultural milieu, which both shapes and is shaped by individual thought and behavior. Specific application areas include personal sensory device interfaces and enhanced tools for creativity. A fundamental principle is putting people fully in command of their technology, which will require sociotechnical design to humanize computers, robots, and information systems.

Improving Human Health and Physical Capabilities. In the absence of new approaches, medical progress is widely expected to slow markedly during the coming century. To increase longevity and well-being throughout the life span, we will need to innovate in fresh areas. Nanoscale biosensors and bioprocessors can contribute greatly to research and to development of treatments, including those resulting from bioinformatics, genomics, and proteomics. Implants based on nanotechnology and regenerative biosystems may replace human organs, and nanoscale machines might unobtrusively accomplish needed medical interventions. Advances in cognitive science will provide insights to help people avoid unhealthy lifestyles, and information technology can create virtual environment tools both for training medical professionals and for enlisting patients as effective partners in their own cure.

Enhancing Group and Societal Outcomes. Peace and economic progress require vastly improved cooperation in schools, corporations, government agencies, communities, and nations, as well as across the globe. Unfortunately, communication is too often blocked by substantial barriers caused by physical disabilities, language differences, geographic distances, and variations in knowledge. These barriers can be overcome through the convergence of cognitive and information science to build a ubiquitous, universal web of knowledge, which is automatically translated into the language and presentation media desired by diverse users. Nano-enabled microscale data devices will identify every product and place, and individuals will merge their personal databases as they choose which groups and interaction networks to join. Group productivity tools will radically enhance the ability of people to imagine and create revolutionary new products and services based on the integration of the four technologies from the nanoscale.

National Security. The rapidly changing nature of international conflict demands radical innovations in defense technology, strategic thinking, and the capabilities of professional war fighters. Both mental and physical enhancement of human abilities can achieve significant gains in the performance of individual military personnel, and new battlefield communication systems employing data linkage and threat anticipation algorithms will strengthen armies and fleets. The combination of nanotechnology and information technology will produce sensor nets that are capable of instantly detecting chemical, biological, radiological, and explosive threats and can direct immediate and effective countermeasures. Uninhabited combat vehicles and human–machine interfaces will enhance both attack capabilities and survivability. As was true historically in the development of computer technology, developments initially achieved at high cost for defense purposes will be transferred over time to low-cost civilian applications, for the general benefit of society.

Unifying Science and Education. To meet the coming challenges, scientific education needs radical transformation at all stages, from elementary school through postgraduate training. Convergence of previously separate scientific disciplines and fields of engineering cannot take place without the emergence of new kinds of people who understand multiple fields in depth and can intelligently work to integrate them. New curricula, new concepts to provide intellectual coherence, and new forms of educational institutions will be necessary.

Radical Transformations

Revolutionary advances at the interfaces between previously separate fields of science and technology are ready to create key *transforming tools* for NBIC technologies. These tools include scientific instruments, analytical methodologies, radically new materials, and data-sharing systems. The innovative momentum achieved in these interdisciplinary areas must not be lost, but rather should be harnessed to accelerate unification of the various disciplines. Progress can become self-catalyzing if we press forward aggressively; if we hesitate, however, the barriers to progress may crystallize and become harder to surmount.

Developments in systems approaches, mathematics, and computation in conjunction with NBIC allow us for the first time to understand the natural world, human society, and scientific research as closely coupled, complex, hierarchical systems. At this moment in the evolution of technical achievement, improvement of human performance through integration of technologies becomes possible. When applied both to particular research problems and to the overall organization of the research enterprise, this complex systems approach provides holistic awareness of opportunities for integration, thereby allowing us to obtain the maximum synergy along the main directions of progress.

One reason sciences have not merged in the past is that their subject matter is so intellectually complex. It will often be possible to rearrange and connect scientific findings, based on principles from cognitive science and information theory, so that scientists from a wider range of fields can comprehend and apply those findings within their own work. Researchers and theorists must look for promising areas in which concepts developed in one science can be translated effectively for use in another science. For example, computational principles developed in natural language processing can be applied to work in genomics and proteomics, and principles from evolutionary biology can be applied to the study of human culture.

The aim of NBIC convergence is to offer individuals and groups an increased range of attractive choices while preserving such fundamental values as privacy, safety, and moral responsibility. It can give us the means to deal successfully with the often unexpected challenges of the modern world by substantially enhancing our mental, physical, and social abilities. Most people want to be healthier and to live longer. Most people want prosperity, security, and creativity. By improving the performance of all humans, technological convergence can help all of us achieve these goals together.

As the challenge posed by national security illustrates, human performance is often competitive in nature. In this arena, what may matter is the *relative* military power of two contending armies or the *relative* economic power of two competing corporations, not their *absolute* power. At the present time, technologically advanced nations such as the United States, Japan, and the countries of Western Europe maintain their positions in the world order in significant part through their rate of technical progress. Conversely, "developing countries" provide raw materials and relatively low-tech manufactured commodities in exchange for the cutting-edge products and services that the advanced nations can offer. If a rich nation were to cease moving forward technologically, a much poorer nation could quickly match the quality of its exports at lower cost. Although this reversal of fortune would be fine for businesses in the poorer nation, the rich nation could see its standard of living drop rapidly toward the world average. The result in such a case might be not merely disappointment and frustration, but deep social unrest.

For example, a significant fraction of the prosperity of the United States depends on the continuing superiority of its information technology, including the components manufactured by its semiconductor industry. In 1965, Gordon Moore, the co-founder of the Intel Corporation, observed that the density of transistors on the most advanced microchip doubles about every 18 months. Dubbed *Moore's law,* this observation has proven to be true ever since. Now, however, the transistors on conventional chips are nearing physical size limits that could repeal this "law" within a decade. If that happens, the U.S. semiconductor industry may evaporate, as other nations catch up to the current U.S. technical lead and produce comparable chips at lower cost. Not surprisingly, both U.S. government and industry have recently developed intense interest in nanotechnology approaches that could potentially extend the life of Moore's law by another decade or two—most notably, molecular logic gates and carbon nanotube transistors.

The realization of these radically new approaches will require the development of an entire complex of fresh technologies and supporting industries, so the cost of shifting over to them may be huge. Only the emergence of a host of new applications could justify the massive investments, by both government and industry, that will be required to make this transition. Already, there is talk in the computer industry of "performance overhang"—that is, the possibility that technical capabilities have already outstripped the needs of desirable applications. For example, the latest models of home computers are finally able to handle the speed and memory demands of high-quality video, but no more-demanding application is currently on the horizon that would require a new generation of hardware.

During the twentieth century, several major technologies essentially reached maturity or ran into social, political, or economic barriers to progress. Aircraft and automobiles, for example, have changed little in recent years. The introduction of high-definition television has been painfully slow, and one would predict that consumers will be content to stick with the next generation of television sets for many years. The evolution of spaceflight technology has apparently stalled at about the technical level of the 1970s, and the advance of nuclear technology has either halted or been blocked by political opposition. In medicine, the rate of introduction of new drugs has slowed, and the great potential of genetic engineering is threatened by increasing popular hostility. In short, technological civilization faces the very real danger of stasis or decline unless something can rejuvenate progress.

The *Converging Technologies* report suggests that the unification of nanotechnology, biotechnology, information technology, and cognitive science could launch a New Renaissance. Five centuries ago, the Renaissance energized all fields of creative endeavor by infusing them with the same holistic spirit and shared intellectual principles. It is time to rekindle the spirit of the Renaissance, returning to the holistic perspective on a higher level, with a new set of principles. In the first Renaissance, a very few individuals could span multiple fields of productivity and become "Renaissance men." Today, technological convergence holds out the very real hope that all people on the planet could become "Renaissance people" by taking advantage of enhanced abilities, tools, materials, knowledge, and humane institutions.

THE PLAN OF THIS BOOK

This chapter has reported the conclusions of the scores of leading scientists who participated in the Societal Implications and Converging Technologies workshops: Nanoscience and nanotechnology will have immense implications for human society. Although nano will generate distinctive materials and products, its chief impact will be felt through collaboration with other fields. Convergence at the nanoscale will unite nanotechnology with biotechnology, information technology, and new technologies based on cognitive science. Without this unification, scientific, technological, and economic progress would be greatly in doubt. This chapter has also described some of the research carried out at the nanoscale and hinted at likely applications of nanoconvergence that may emerge over the coming decade or two.

Chapter 2 deals with the fantasies and illusions that have both popularized the nano concept and given many investors, policy makers, and ordinary citizens a seriously distorted picture of the field. We cannot properly understand how nanotechnology will converge with the other fields if we have a false impression of the field itself. Also, nanofantasies would prevent us from seeing the real importance of convergence at the nanoscale, because we would falsely imagine that nano alone would remake the world without need of all the rest of the sciences and technologies. Chapter 2 uses a pair of parables plus sci-fi storytelling to show how science fiction literature has long promulgated inspiring but factually false impressions of the nanoscale. Some of these illusions involve convergence, especially Eric Drexler's original conception that nanotechnology is mechanical engineering applied to chemistry on the molecular scale.

Chapter 3 focuses on information technology and its convergence with nanotechnology. Already, the smallest transistors on computer chips are less than 100 nanometers across, and hard-disk memory storage exploits nanoscale magnetic phenomena. Moore's law has driven progress across all domains of information technology, but we may have reached the point at which this decades-long period of computer chip performance progress comes to a close, unless nanotechnology can take us further. Other promising areas of research, notably in nano-enabled microscale sensors and in quantum computing, could benefit from progress in nanotechnology. At the same time, information technology contributes directly to progress in all fields of science and engineering, and we may have entered a period in which the most important tool of research and development is cyberinfrastructure.

Chapter 4 focuses on the interface between nanotechnology and biotechnology, a tremendously active area of research at the present time. Both the National Institutes of Health (NIH) and NSF have aggressively supported research in nanobiotechnology (also known as bionanotechnology). The fundamental structures inside living cells that do all the work of metabolism and reproduction are nanoscale "machines" composed of complex molecular structures, and the methods of nanoscience are needed to understand them. For a century, biologists and medical researchers have sought to solve the problem of cancer, and nanobioconvergence offers new hope that this effort will finally succeed. Concepts from biology have been applied to information technology, and new biotechnologies enabled by both nano and info promise to improve human physical and mental performance.

Cognitive science, the subject of Chapter 5, is itself a convergence of disciplines, combining artificial intelligence, linguistics, psychology, philosophy, neuroscience, anthropology, and education. "Cog-sci" was initially dominated by the paradigm espoused by classical artificial intelligence, which modeled human thought processes in terms of logical manipulations of clearly defined, high-level concepts. More recently, a wide range of other paradigms have been introduced by this field's convergence with other branches of information technology and with biotechnology and nanotechnology. Society faces a number of challenges if it is to digest the cultural implications of cognitive science, notably the emerging controversies about the future viability of religion and neurotechnologies that could transform human cognition. An NBIC task force suggested that the greatest near-term development coming out of a union of cognitive science with other fields would be an information technology system, called *The Communicator*, that might transform human interaction.

Chapter 6 considers how we could accomplish full convergence of the NBIC fields as well as their convergence with reformulated social sciences. I suggest a system of theoretical principles—conservation, indecision, configuration, interaction, variation, evolution, information, and cognition—that could help connect similar natural laws, research methods, and technological applications across all these fields. Policy decisions about investment in various technologies require serious consideration of the ethical principles at stake and the likely social effects of those decisions. However, we cannot examine those issues rigorously without benefit of social science, and many knowledgeable people doubt that the social sciences are equal to the task, at least as currently constituted. To illustrate this crucial point, Chapter 6 describes a linked pair of failed attempts to accomplish convergence across the social sciences half a century ago, coming to the ironic conclusion that both were headed in the right direction but premature. A fresh attempt to unify and strengthen the social sciences could succeed, if it were based on solid cognitive science in convergence with the other NBIC fields.

Chapter 7 acknowledges that the social sciences cannot give us definitive answers to vital questions at the present time, but collects together a wealth of ideas about how convergence might affect human society. Already having surveyed the views of scientists in earlier chapters, we consider the harshest critics of convergence and the notions of ordinary citizens about the future of the world. A dozen years ago, social scientists proposed a major initiative to strengthen their disciplines so as to better understand the nature of our rapidly changing world, and it is not too late to follow their advice. More recently, key participants in the convergence movement have urged the creation of a new branch of social science focusing on service industries, an idea that is fully compatible with the decade-delayed hope to develop a convergent science of democratic institutions. Standing still is not an option, because uncontrolled sociopolitical forces will harness new technologies to divergent forces ripping humanity apart. The only hope is unification of the world on the basis of the unification of science.

The final chapter offers a visionary but scientifically based vision of how nanoconvergence might transform human potentialities by enabling vigorous exploration and colonization of outer space. Although convergence has vast terrestrial implications, it is easier to see clearly how NBIC fields could combine to create a revolution in astronautics. Specifically, they could revolutionize human access to the solar system, thereby leading to exploitation of the environments and resources that exist beyond the Earth. Current technologies are not potent enough to build an interplanetary society. By enabling moderate improvements across all space-related technologies, however, nanoconvergence could potentially help humans enter the final frontier with the powers needed to accomplish previously unimaginable goals. On new worlds, we could reinvent ourselves, our society, and our destiny.

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