1. INTRODUCTION

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.

The nanoscale is not just another step toward miniaturization, but a qualitatively new scale. The new behavior is dominated by quantum mechanics, material confinement in small structures, large interfacial volume fraction, and other unique properties, phenomena and processes. Many current theories of matter at the microscale have critical lengths of nanometer dimensions. These theories will be inadequate to describe the new phenomena at the nanoscale.

As knowledge in nanoscience increases worldwide, there will likely be fundamental scientific advances. In turn, this will lead to dramatic changes in the ways materials, devices, and systems are understood and created. Innovative nanoscale properties and functions will be achieved through the control of matter at its building blocks: atom-by-atom, molecule-by-molecule, and nanostructure-by-nanostructure. Nanotechnology will include the integration of these nanoscale structures into larger material components, systems, and architectures. However, within these larger scale systems the control and construction will remain at the nanoscale.

Today, nanotechnology is still in its infancy, because only rudimentary nanostructures can be created with some control. However, among the envisioned breakthroughs are orders-of-magnitude increases in computer efficiency, human organ restoration using engineered tissue, “designer” materials created from directed assembly of atoms and molecules, as well as emergence of entirely new phenomena in chemistry and physics.

Nanotechnology has captured the imaginations of scientists, engineers and economists not only because of the explosion of discoveries at the nanoscale, but also because of the potential societal implications. A White House letter (from the Office of Science and Technology Policy and Office of Management and Budget) sent in the fall of 2000 to all Federal agencies has placed nanotechnology at the top of the list of emerging fields of research and development in the United States. The National Nanotechnology Initiative was approved by Congress in November 2000, providing a total of $422 million spread over six departments and agencies.

Nanotechnology’s relevance is underlined by the importance of controlling matter at the nanoscale for healthcare, the environment, sustainability, and almost every industry. There is little doubt that the broader implications of this nanoscience and nanotechnology revolution for society at large will be profound.

National Nanotechnology Initiative

The National Nanotechnology Initiative (NNI, http://nano.gov) is a multi-agency effort within the U.S. Government that supports a broad program of Federal nanoscale research in materials, physics, chemistry, and biology. It explicitly seeks to create opportunities for interdisciplinary work integrating these traditional disciplines. The NNI will accelerate the pace of fundamental research in nanoscale science and engineering, creating the knowledge needed to enable technological innovation, training the workforce needed to exploit that knowledge, and providing the manufacturing science base needed for future commercial production. Potential breakthroughs are possible in areas such as materials and manufacturing, medicine and healthcare, environment and energy, biotechnology and agriculture, electronics and information technology, and national security. The effect of nanotechnology on the health, wealth, and standard of living for people in this century could be at least as significant as the combined influences of microelectronics, medical imaging, computer-aided engineering, and man-made polymers developed in the past century.

The NNI is balanced across five broad activities: fundamental research; grand challenges; centers and networks of excellence; research infrastructure; and societal/workforce implications. Under this last activity, nanotechnology’s effect on society – legal, ethical, social, economic, and workforce preparation – will be studied to help identify potential concerns and ways to address them. As the NNI is commencing, there is a *rare opportunity to integrate the societal studies and dialogues from the very beginning and to include societal studies as a core part of the NNI investment strategy.*

NSET Workshop on “Societal Implications of Nanoscience and Nanotechnology”

Research on societal implications will boost the NNI’s success and help us to take advantage of the new technology sooner, better, and with greater confidence. Toward this end, the National Science and Technology Council (NSTC), Committee on Technology (CT), Subcommittee on Nanoscale Science, Engineering, and Technology (NSET) — the Federal interagency group that coordinates the NNI — sponsored a workshop on “Societal Implications of Nanoscience and Nanotechnology.” Held September 28–29, 2000 at the National Science Foundation, this workshop brought together nanotechnology researchers, social scientists, and policy makers representing academia, government, and the private sector. It had four principal objectives:

- Survey current studies on the societal implications of nanotechnology (educational, technological, economic, medical, environmental, ethical, legal, cultural, etc.).
- Identify investigative and assessment methods for future studies of societal implications.
- Propose a vision and alternative pathways toward that vision integrating short-term (3 to 5 year), medium-term (5 to 20 year), and long-term (more than 20 year) perspectives.
- Recommend areas for research investment and education improvement.

This report addresses issues far broader than science and engineering, such as how nanotechnology will change society and the measures to be taken to prepare for these transformations. The conclusions and recommendations in this report will provide a basis for the NNI participants and the public to address future societal implications issues.

Chapters 2 through 5 of this report present the conclusions and recommendations that arose from the workshop. The participants' statements on societal implications are in Chapter 6, and a list of participants and contributors is in Appendix A. Selected endorsements of the NNI are provided as a reference (Appendix B).

2. NANOTECHNOLOGY GOALS

Nanoscale science and engineering will lead to better understanding of nature; advances in fundamental research and education; and significant changes in industrial manufacturing, the economy, healthcare, and environmental management and sustainability. Examples of the promise of nanotechnology, with projected total worldwide market size of over $1 trillion annually in 10 to 15 years, include the following:

- *Manufacturing*: The nanometer scale is expected to become a highly efficient length scale for manufacturing once nanoscience provides the understanding and nanoengineering develops the tools. *Materials* with high performance, unique properties and functions will be produced that traditional chemistry could not create. Nanostructured materials and processes are estimated to increase their market impact to about $340 billion per year in the next 10 years (Hitachi Research Institute, personal communication, 2001).
- *Electronics*: Nanotechnology is projected to yield annual production of about $300 billion for the semiconductor industry and about the same amount more for global integrated circuits sales within 10 to 15 years (see R. Doering, page 74-75 of this report).
- *Improved Healthcare*: Nanotechnology will help prolong life, improve its quality, and extend human physical capabilities.
- *Pharmaceuticals*: About half of all production will be dependent on nanotechnology — affecting over $180 billion per year in 10 to 15 years (E. Cooper, Elan/Nanosystems, personal communication, 2000).
- *Chemical Plants*: Nanostructured catalysts have applications in the petroleum and chemical processing industries, with an estimated annual impact of $100 billion in 10 to 15 years (assuming a historical rate of increase of about 10% from $30 billion in 1999; "NNI: The Initiative and Its Implementation Plan," page 84).
- *Transportation*: Nanomaterials and nanoelectronics will yield lighter, faster, and safer vehicles and more durable, reliable, and cost-effective roads, bridges, runways, pipelines, and rail systems. Nanotechnology-enabled aerospace products alone are projected to have an annual market value of about $70 billion in ten years (Hitachi Research Institute, personal communication, 2001).

- *Sustainability*: Nanotechnology will improve agricultural yields for an increased population, provide more economical water filtration and desalination, and enable renewable energy sources such as highly efficient solar energy conversion; it will reduce the need for scarce material resources and diminish pollution for a cleaner environment. For example, in 10 to 15 years, projections indicate that nanotechnology-based lighting advances have the potential to reduce worldwide consumption of energy by more than 10%, reflecting a savings of $100 billion dollars per year and a corresponding reduction of 200 million tons of carbon emissions ("NNI: The Initiative and Its Implementation Plan," page 93).

Knowledge and Scientific Understanding of Nature

The study of nanoscale systems promises to lead to fundamentally new advances in science and engineering and in our understanding of biological, environmental, and planetary systems. It also will redirect our scientific approach toward more generic and interdisciplinary research. Nanoscience is at the unexplored frontiers of science and engineering, and it offers one of the most exciting opportunities for innovation in technology.

Nanotechnology will provide the capacity to create affordable products with dramatically improved performance. This will come through a basic understanding of ways to control and manipulate matter at the nanometer scale and through the incorporation of nanostructures and nanoprocesses into technological innovations. It will be a center of intense international competition when it lives up to its promise as a generator of technology.

Nanotechnology promises to be a dominant force in our society in the coming decades. Commercial inroads in the hard disk, coating, photographic, and pharmaceutical industries have already shown how new scientific breakthroughs at this scale can change production paradigms and revolutionize multibillion-dollar businesses. However, formidable challenges remain in fundamental understanding of systems on this scale before the potential of nanotechnology can be realized.

Today, nanotechnology is still in its infancy, and only rudimentary nanostructures can be created with some control. The science of atoms and simple molecules, on one end, and the science of matter from microstructures to larger scales, on the other, are generally established. The remaining size-related challenge is at the nanoscale — roughly between 1 and 100 molecular diameters — where the fundamental properties of materials are determined and can be engineered. A revolution has been occurring in science and technology, based on the recently developed ability to measure, manipulate and organize matter on this scale. Recently discovered organized structures of matter (such as carbon nanotubes, molecular motors, DNA-based assemblies, quantum dots, and molecular switches) and new phenomena (such as giant magnetoresistance, coulomb blockade, and those caused by size confinement) are scientific breakthroughs that merely hint at possible future developments.

The nanoscale is not just another step toward miniaturization, but a qualitatively new scale. The new behavior is dominated by quantum mechanics, material confinement in small structures, large interfaces, and other unique properties, phenomena and processes. Many current theories of matter at the microscale have critical lengths of nanometer dimensions; these theories will be inadequate to describe the new phenomena at the nanoscale.

Nanoscience will be an essential component in better understanding of nature in the next decades. Important issues include greater interdisciplinary research collaborations, specific education and training, and transition of ideas and people to industry.

Industrial Manufacturing, Materials and Products

The potential benefits of nanotechnology are pervasive, as illustrated in the fields outlined below.

Nanotechnology is fundamentally changing the way materials and devices will be produced in the future. The ability to synthesize nanoscale building blocks with precisely controlled size and composition and then to assemble them into larger structures with unique properties and functions will revolutionize materials and manufacturing. Researchers will be able to develop material structures not previously observed in nature, beyond what classical chemistry can offer. Some of the benefits that nanostructuring can bring include lighter, stronger, and programmable materials; reductions in life-cycle costs through lower failure rates; innovative devices based on new principles and architectures; and use of molecular/cluster manufacturing, which takes advantage of assembly at the nanoscale level for a given purpose.

The Semiconductor Industry Association (SIA) has developed a roadmap for continued improvements in miniaturization, speed, and power reduction in information processing devices — sensors for signal acquisition, logic devices for processing, storage devices for memory, displays for visualization, and transmission devices for communication. The SIA roadmap projects the future of nanoelectronics and computer technology to approximately 2010 and to 0.1 micron (100 nanometer) structures, just short of fully nanostructured devices. The roadmap ends short of true nanostructured devices because the principles, fabrication methods, and techniques for integrating devices into systems at the nanoscale are generally unknown. New approaches such as chemical and biomolecular computing, and quantum computing making use of nanoscale phenomena and nanostructures, are expected to emerge.

The molecular building blocks of life — proteins, nucleic acids, lipids, carbohydrates, and their non-biological mimics — are examples of materials that possess unique properties determined by their size, folding, and patterns at the nanoscale. Biosynthesis and bioprocessing offer fundamentally new ways to manufacture chemicals and pharmaceutical products. Integration of biological building blocks into synthetic materials and devices will allow the combination of biological functions with other desirable materials properties. Imitation of biological systems provides a major area of research in several disciplines. For example, the active area of bio-mimetic chemistry is based on this approach.

Medicine and the Human Body

Living systems are governed by molecular behavior at the nanometer scale, where chemistry, physics, biology, and computer simulation all now converge. Recent insights into the uses of nanofabricated devices and systems suggest that today's laborious process of genome sequencing and detecting the genes' expression can be made dramatically more efficient through use of nanofabricated surfaces and devices. Expanding our ability to characterize an individual's genetic makeup will revolutionize diagnostics and therapeutics. Beyond facilitating optimal drug usage, nanotechnology can provide new formulations and routes for drug delivery, enormously broadening the drugs' therapeutic potential.

Increasing nanotechnological capabilities will also markedly benefit basic studies of cell biology and pathology. As a result of the development of new analytical tools capable of probing the world of the nanometer, it is becoming increasingly possible to characterize the chemical and mechanical properties of cells (including processes such as cell division and locomotion) and to measure properties of single molecules. These capabilities complement (and largely supplant) the ensemble average techniques presently used in the life sciences. Moreover, biocompatible, high-performance materials will result from the ability to control their nanostructure. Artificial inorganic and organic nanoscale materials can be introduced into cells to play roles in diagnostics (e.g., quantum dots in visualization), but also potentially as active components. Finally, nanotechnology-enabled increases in computational power will permit the characterization of macromolecular networks in realistic environments. Such simulations will be essential for developing biocompatible implants and for studying the drug discovery process. An open issue is how the healthcare system would change with such large changes in medical technology.

Sustainability: Agriculture, Water, Energy, Materials, and Clean Environment

Nanotechnology will lead to dramatic changes in the use of natural resources, energy, and water, as outlined in the following paragraphs. Waste and pollution will be minimized. Moreover, new technologies will allow recovery and reuse of materials, energy, and water.

Environment

Nanoscience and engineering could significantly affect molecular understanding of nanoscale processes that take place in the environment; the generation and remediation of environmental problems through control of emissions; the development of new "green" technologies that minimize the production of undesirable by-products; and the remediation of existing waste sites and streams. Nanotechnology also will afford the removal of the smallest contaminants from water supplies (less than 200 nanometers) and air (under 20 nanometers) and the continuous measurement and mitigation of pollution in large areas.

In order to hasten the integrated understanding of the environmental role of nanoscale phenomena, scientists and engineers studying the fundamental properties of nanostructures will need to work together with those attempting to understand complex processes in the environment. Model nanostructures can be studied, but in all cases the research must be justified by its connection to naturally occurring systems or to environmentally beneficial uses. Environments for investigations are not limited and might include terrestrial locations such as acid mines, subsurface aquifers, or polar environments.

Energy

Nanotechnology has the potential to significantly impact energy efficiency, storage, and production. Several new technologies that utilize the power of nanostructuring, but developed without benefit of the new nanoscale analytical capabilities, illustrate this potential:

- Increasing the efficiency of converting solar energy into useful forms.
- High efficiency fuel cells, including hydrogen storage in nanotubes.
- A long-term research program in the chemical industry on the use of crystalline materials as catalyst supports has yielded catalysts with well-defined pore sizes in the range of 1 nanometer to reduce energy consumption and waste; their use is now the basis of an industry that exceeds $30 billion a year (“NNI: The Initiative and Its Implementation Plan,” page 84).
- Developed by the oil industry, the ordered mesoporous material MCM-41 (known also as “self-assembled monolayers on mesoporous supports,” SAMMS), with pore sizes in the range of 10–100 nanometers, is now widely used for the removal of ultrafine contaminants (see work performed at Pacific Northwest National Laboratory in *Nanotechnology Research Directions*, Kluwer Academic Publishers, 2000, pp. 216-218).
- Several chemical manufacturing companies are developing a nanoparticle-reinforced polymeric material that can replace structural metallic components in automobiles; widespread use of those nanocomposites could lead to a reduction of 1.5 billion liters of gasoline consumption over the life of one year’s production of vehicles, thereby reducing carbon dioxide emissions annually by more than 5 billion kilograms (“NNI: The Initiative and Its Implementation Plan,” page 88).
- Significant changes in lighting technologies are expected in the next ten years. Semiconductors used in the preparation of light emitting diodes (LEDs) for lighting can increasingly be sculpted on nanoscale dimensions. In the United States, roughly 20% of all electricity is consumed for lighting, including both incandescent and fluorescent lights. In 10 to 15 years, projections indicate that such nanotechnology-based lighting advances have the potential to reduce worldwide consumption of energy by more than 10%, reflecting a savings of $100 billion dollars per year and a corresponding reduction of 200 million tons of carbon emissions (“NNI: The Initiative and Its Implementation Plan,” pages 92 - 93).

- The replacement of carbon black in tires by nanometer-scale particles of inorganic clays and polymers is a new technology that is leading to the production of environmentally friendly, wear-resistant tires.

Water

Global population is increasing while fresh water supplies are decreasing. The United Nations predicts that by the year 2025 that 48 countries will be short of fresh water accounting for 32% of the world's population ("NNI: The Initiative and Its Implementation Plan", page 95). Water purification and desalinization are some of the focus areas of preventative defense and environmental security since they can meet future water demands globally. Consumptive water use has been increasing twice as fast as the population and the resulting shortages have been worsened by contamination. Nanotechnology-based devices for water desalinization have been designed to desalt sea water using at least 10 times less energy than state-of–the art reverse osmosis and at least 100 times less energy than distillation. The critical experiments underpinning these estimations are underway now. This energy-efficient process is possible by fabricating of very high surface area electrodes that are electrically conductive using aligned carbon nanotubes, and by other innovations in the system design.

Agriculture

Nanotechnology will contribute directly to advancements in agriculture in a number of ways: (1) molecularly engineered biodegradable chemicals for nourishing plants and protecting against insects; (2) genetic improvement for animals and plants; (3) delivery of genes and drugs to animals; and (4) nano-array-based technologies for DNA testing, which, for example, will allow a scientist to know which genes are expressed in a plant when it is exposed to salt or drought stress. The application of nanotechnology in agriculture has only begun to be appreciated.

Space Exploration

The stringent fuel constraints for lifting payloads into earth orbit and beyond, and the desire to send spacecraft away from the sun for extended missions (where solar power would be greatly diminished) compel continued reduction in size, weight, and power consumption of payloads. Nanostructured materials and devices promise solutions to these challenges. Nanostructuring is also critical to the design and manufacture of lightweight, high-strength, thermally stable materials for aircraft, rockets, space stations, and planetary/solar exploratory platforms. The augmented utilization of miniaturized, highly automated systems will also lead to dramatic improvements in manufacturing technology. Moreover, the low-gravity, high-vacuum space environment may aid the development of nanostructures and nanoscale systems that cannot be created on Earth.

National Security

Defense applications include (1) continued information dominance through advanced nanoelectronics, identified as an important capability for the military; (2) more sophisticated virtual reality systems based on nanostructured electronics that enable more affordable, effective training; (3) increased use of enhanced automation and robotics to offset reductions in military manpower, reduce risks to troops, and improve vehicle performance; (4) achievement of the higher performance (lighter weight, higher strength) needed in military platforms while providing diminished failure rates and lower life-cycle costs; (5) needed improvements in chemical/biological/nuclear sensing and in casualty care; (6) design improvements in systems used for nuclear non-proliferation monitoring and management; and (7) combined nanomechanical and micromechanical devices for control of nuclear defense systems.

In many cases economic and military opportunities are considered to be complementary. Strong applications of nanotechnology in other areas would provide support for national security in the long term, and vice versa.

Moving into the Market

Since economists have not yet really begun research on nanotechnology, their insights are somewhat tentative and based on experience with earlier technologies. A common paradigm is that new applications will be initially more costly than existing technologies, but will achieve better performance. However, completely new technologies may be cheaper, such as chemical manufacturing to mass produce nanoelectronic circuits as opposed to current methods using lithography in microelectronics. Overall, nanotechnology will offer substantial advantages, being smaller, faster, stronger, safer, and more reliable. At the same time, it will require investments in new production facilities and in a host of ancillary industries supplying the raw materials, components, and manufacturing machines. Because it will take time to achieve economies of scale and to develop the most efficient fabrication methods, costs are likely to be relatively high in the beginning.

For this reason, nanotechnology-based goods and services will probably be introduced earlier in those markets where performance characteristics are especially important and price is a secondary consideration. Examples are medical applications and space exploration. The experience gained will reduce technical and production uncertainties and prepare these technologies for deployment into the market place. Similarly, in the private sector, technology transfer is likely to occur from performance-oriented areas (such as medicine) to price-oriented ones (such as agriculture). As a given technology matures, its cost may decline, leading to greater penetration of the market even where performance is not decisive.

The displacement of an old technology by a new one tends to be both slow and incomplete. Displacement of older methods will accelerate to the extent that nanotechnology extends its technical range and perhaps lowers its relative price. However, nanotechnology also is likely to stimulate innovations in older technologies that make them better able to compete — an ironic but potentially beneficial second-order effect.

The diffusion and impact of nanotechnology will be partly a function of the development of complementary technologies and of a network of users. Whole new industries may have to be developed — along with the trained scientists and technicians to staff them.

There may be many obstacles along this road that ordinary market processes cannot easily overcome. An important role for the government will be to invest in the long-term, high-risk, high-gain research needed to create these new industries and to ensure that they are consistent with broader societal objectives.

Federal support of the nanotechnology initiative is necessary to enable the United States to take advantage of this strategic technology and remain competitive in the global marketplace well into the future. Focused research programs on nanotechnology have been initiated in other industrialized countries. Currently, the United States has a lead on synthesis, chemicals, and biological aspects; it lags in research on nanodevices, production of nano-instruments, ultra-precision engineering, ceramics, and other structural materials. Japan has an advantage in nanodevices and consolidated nanostructures; Europe is strong in dispersions, coatings, and new instrumentation.

3. NANOTECHNOLOGY AND SOCIETAL INTERACTIONS

The Interactive Process of Innovation and Diffusion

New technologies come into being through a complex interplay of technical and social factors. The process of innovation that will produce nanotechnology and diffuse its benefits into society is complex and only partially understood. Economists, as well as scholars in other fields, have long studied the generation, diffusion, and impact of scientific and technological innovation. These studies outline the variables likely to determine the rate and direction of these impacts, and to identify relevant research questions. They provide a foundation on which to build studies of societal implications of nanotechnology.

Scientific discoveries do not generally change society directly; they can set the stage for the change that comes about through the confluence of old and new technologies in a context of evolving economic and social needs. The thorough diffusion of even major new developments rarely happens all at once. Nanotechnologies are so diverse that their manifold effects will likely take decades to work their way through the socio-economic system. While market factors will determine ultimately the rate at which advances in nanotechnology get commercialized, sustained support for nanoscience research is necessary in this early stage of development so as not to become a rate-limiting factor. Expediting research (innovation) and its incorporation into beneficial technology is a major challenge to the NNI.

Unintended and Second-order Consequences

Perhaps the greatest difficulty in predicting the societal impacts of new technologies has to do with the fact that once the technical and commercial feasibility of an innovation is demonstrated, subsequent developments may be as much in the hands of users as in those of the innovators. The diffusion and impact of technological innovations often depends on the development of complementary technologies and of the user network. As a result, new technologies can affect society in ways that were not intended by those who initiated them. Often these unintended consequences are beneficial, such as spin-offs with valuable applications in fields remote from the original innovation. For instance, consider how the Internet has progressed from a technology supported by the Department of Defense's Advanced Research Projects Agency (DARPA) to facilitate digital communications among universities with DARPA contracts, to a means by which teenagers and college students exchange music files. In another example, intended benefits may also have unintended or "second-order consequences." Nanotechnology-based medical treatments, for example, may significantly improve life span and quality of life for elderly people; a second-order consequence would be an increase in the proportion of the population that is elderly, which might require changes in pensions or health insurance, an increase in the retirement age, or a substantial increase in the secondary careers undertaken by older people. Another potential consequence that would need to be addressed is the potential increase of inequality in the distribution of wealth that we may call the "nano divide." Those who participate in the "nano revolution" stand to become very wealthy. Those who do not may find increasingly difficult to afford the technological wonders that it engenders. One near-term example will be in medical care: nanotech-based treatments may be initially expensive, hence accessible only to the very rich. Other consequences are not so desirable, such as the risk of closing old industries and environmental pollution, which sometimes becomes a problem, especially for large-scale technologies.

To assess a nanotechnology (or any technology) in terms of its unintended consequences, researchers must examine the entire system of which the technology is a part through its entire life cycle. As the case of electric automobiles illustrates, without a careful analysis of the entire set of activities that produce, operate, and eventually dispose of a technology, people may leap to false conclusions about the extent to which the technology pollutes. For example, manufacture and disposal of an electric vehicle's battery may release more lead into the environment than if the vehicle had been fueled throughout its working life by leaded gasoline.

One concern about nanotechnology's unintended consequences raises the question of the uncontrolled development of self-replicating nanoscale machines. A number of very serious technical challenges would have to be overcome before it would be possible to create nanoscale machines that could reproduce themselves in the natural environment. Some of these challenges appear to be insurmountable with respect to chemistry and physical principles, and it may be technically impossible to create self-reproducing mechanical nanoscale robots of the sort that some visionaries have imagined. A new form of life different from that known (i.e., carbon-based) would be a dramatic change that is not foreseen in the near future.

Initially, the impact of nanotechnology will likely be limited to a few specific products and services. Nanotechnology-based goods and services will probably be introduced earlier to those markets where consumers are willing to pay a premium for new or improved performance. Such primary effects would be to make things work better, cheaper, with more features, etc. This might, for example, increase food yields, generate new textiles for clothing, improve power production, or cure a certain disease. As mentioned above, by and large, the displacement of an old technology by a new one tends to be both slow and incomplete. As a result, nanotechnology will coexist for a long time with older technologies rather than suddenly displacing them. During that time it will affect the further development of those competing technologies. Other secondary effects might be shifts in demand for products and services, so that people come to expect different kinds of food, medical care, entertainment, etc. This shift in demand may also initiate a tertiary effect, the need for augmented nanotechnology infrastructure — interdisciplinary research centers, new educational programs to supply nanoscientists and nanotechnologists, etc. Other tertiary effects would move upstream in our social structures and cultural patterns, such as shifts in education and career patterns, family life, government structure, and so forth. *While there is no way of knowing, a priori, the unintended and higher order consequences of nanotechnology, the participation of social scientists in the NNI may allow for important issues to be identified earlier, the right questions to be raised, and necessary corrective actions taken.*

An effective and cost-efficient way to protect the public and deal with nanotechnology's potential negative consequences is to develop a tradition of social-science-based countermeasures — and to support research in publicly recognized institutions on the processes that develop nanotechnology and apply it in diverse areas of life.

Ethical Issues and Public Involvement in Decision Making

An important aim of a societal impact investigation of nanotechnology is to identify harms, conflicts over justice and fairness, and issues concerning respect for persons. For example, changes in workforce needs and human resources are likely to bring benefits to some and harm to others. Other examples of potential issues include safeguards for workers engaged with hazardous production processes, equity disputes raised by intellectual property protection, and questions about relationships between government, industry, and universities.

Scientists and engineers bring to their work a laudable concern for the social value of their labors. However, those working in a particular technical field may be focused on the immediate technical challenges and not see all of the potential social and ethical implications. It is important to include a wide range of interests, values, and perspectives in the overall decision process that charts the future development of nanotechnology. Involvement of members of the public or their representatives has the added benefit of respecting their interests and enlisting their support.

The inclusion of social scientists and humanistic scholars, such as philosophers of ethics, in the social process of setting visions for nanotechnology is an important step for the NNI. As scientists or dedicated scholars in their own right, they can respect the professional integrity of nanoscientists and nanotechnologists, while contributing a fresh perspective. Given appropriate support, they could inform themselves deeply enough about a particular nanotechnology to have a well-grounded evaluation. At the same time, they are professionally trained representatives of the public interest and capable of functioning as communicators between nanotechnologists and the public or government officials. Their input may help maximize the societal benefits of the technology while reducing the possibility of debilitating public controversies.

In addition, attention needs to be given to the individual responsibility of engineers, scientists, and others involved in the processes of generating powerful new nanotechnologies. Professional societies have a role to play in providing opportunities for discussing and devising guidelines that incorporate relevant ethical principles into emerging issues. Perhaps most importantly, ethics must be incorporated effectively into the curriculum for training new nanoscientists, nanotechnologists, and nanofabrication technicians.

Education of Nanoscientists, Nanotechnologists, and Nanofabrication Technicians

The United States faces the daunting challenge of attracting enough of the best graduate students to the physical sciences and engineering disciplines. Under present conditions, far too few good students are attracted to the fields relevant to nanotechnology. To some extent, this is a problem faced by all of the sciences, but the problem is especially acute for nanotechnology because a very large number of talented scientists, engineers, and technicians will be needed to build the nanotechnology industries of the future, and these professionals will require an interdisciplinary perspective.

Development of nanotechnology will depend upon multidisciplinary teams of highly trained people with backgrounds in biology, medicine, applied and computational mathematics, physics, chemistry, and in electrical, chemical, and mechanical engineering. Team leaders and innovators will probably need expertise in multiple subsets of these disciplines, and all members of the team will need a general appreciation of the other members' fields. Developing a broadly trained and educated workforce presents a severe challenge to our four-year degree and two-year degree educational institutions, which favor compartmentalized learning. Because current educational trends favor specialization, there must be fundamental changes in our educational systems. However, introducing new degree programs in nanotechnology that provide a shallow overview of many disciplines, none in sufficient depth to make major contributions, may not give students the training that is needed to meet the future challenges. The right balance between specialization and interdisciplinary training needs to be worked out through innovative demonstration programs and research on the education process and workforce needs.

Education in nanoscience and nanotechnology requires special laboratory facilities that can be quite expensive. Given the cost of creating and sustaining such facilities, their incorporation into nanotechnology workforce development presents a considerable challenge. Under the present education system, many engineering schools, let alone the two-year-degree colleges, cannot offer students any exposure to the practice of nanofabrication. Innovative solutions will have to be found, such as new partnerships with industry and the establishment of nanofabrication facilities that are shared by consortia of colleges, universities, and engineering schools. Web-based, remote access to those facilities may provide a powerful new approach not available previously.

Despite the tremendous educational challenges, the exciting intellectual, economic, and social opportunities of nanotechnology might become a major factor in reinvigorating our nation's youth for careers in science and technology.

Education of Social Scientists

A related educational challenge is the very small number of social scientists who have the technical background and research orientation that would allow them to conduct competent research on the societal implications of nanotechnology. At the university level, liberal arts education gives far too low a priority to scientific literacy. Social science professional societies, universities, and government agencies will have to make a long-term commitment to attract talented young social scientists to this area of research and to encourage them to gain the necessary professional skills and awareness of nanotechnology. This will require research on the societal implications of nanotechnology at a consistent and high enough level to establish this as a viable field of social science research.

4. SOCIAL SCIENCE APPROACHES FOR ASSESSING NANOTECHNOLOGY'S IMPLICATIONS

Social Science Research Approaches and Methodologies

It is important to have social scientists study the processes by which nanoscience is conducted and nanotechnology is developed — even at this early stage. The knowledge gained will help policymakers and the public understand how nanoscience and nanotechnology are advancing, how those advances are being diffused, and how to make necessary course corrections. Insight into the innovation process will also grow.

Social scientists and scholars possess many effective ways of studying the development of new technology and its implications for society. Some methodologies suitable for studying nanotechnology are known; others will have to be identified or developed. Ethnographic techniques, such as those traditionally employed by anthropologists, are appropriate for some of this work. Also useful will be interviews of research and development teams, conducted over time and augmented by surveys and historical methods, to document the evolution of the knowledge and technology. Interviews, social network techniques, studies of communication patterns, and citation analysis of publications more generally can offer insights into the diffusion of scientific discoveries and ideas. Application of a scientific idea to a technical problem, technology transfer, and introduction of products into the marketplace can be tracked through statistics on research and development investments, patent applications, and new products and services.

With concerted effort, it will be possible to develop a number of indicators that provide early signs of change. One challenge to social science research will be to identify “bellwethers,” “early adopters,” or “first movers.” For example, some geographic areas and strata of society experience technological change earlier than others do. Incipient transformations may reveal themselves first in start-up companies, university labs, and Internet communications.

Innovating activity takes place in academe, industry, government laboratories, Federal agencies, and professional societies. For each group, measures and methodologies for studying the process and content of change must be developed. In academe, key indicators might include interdisciplinary work, new courses, fellowships, information flow, and regional coalitions. In the private sector, key indicators might include investments, startups, and corporate partnerships. For government laboratories, data would cover budgets, equipment, standards, and coalitions, and for agencies, examination might be given to new initiatives, databases, and centers. The professions will create some number of new forums, symposiums, journals, and job fairs where interdisciplinary topics and careers would flourish. Social science research areas relevant to the process of discovery, invention, and development include appearance of new ideas and innovations, change in societal goals, and shift in commercial investment.

The societal impacts of nanotechnology may be of great scope and variety. A second research challenge is to address both short- and long-term impacts, intended and unintended, and first-order through Nth-order consequences. Because nanotechnology presents a highly diverse set of novel technical possibilities, accurate prediction of even the immediate consequences of individual innovations may be impossible. Some impacts will be surprising, and others will have emergent implications that will reveal themselves only over a long period of time. Ultimately, both technology and society are elaborate systems with the potential for chaotic and variable feedback mechanisms. Nanotechnology has such promise to impact so many aspects of society that predictions will be uncertain and difficult to validate empirically. This observation should not discourage researchers, however, but should inspire them to invest considerable sophistication and effort in their work. The domains and measures of potential social impacts include: economic growth, employment statistics, social transformations and medical statistics.

A third challenging, but important, area for social science research is the social acceptance, resistance, or rejection of nanotechnology. Representative sample surveys, supplemented by focus groups and open-ended interviews, can measure affective, cognitive, and psychosocial parameters. In recent years, political scientists and sociologists have developed new computation-intensive techniques for studying coverage by the news media; they have been tested in research on public controversies and are ready to track the changing public perceptions of nanotechnology. These and more traditional methods can also be applied to charting the process of regulatory review and approval, court decisions that actively sanction the use of the technology, mobilization of political support and opposition, and the activities of relevant social movements. There are multiple feedback loops in which society responds to new innovations and in so doing transforms the context in which innovation occurs. As more and more new nanotechnologies are publicized and actually appear in the marketplace, the variable degree of social acceptance will become ever more important. Indicators to measure social acceptance of nanotechnology will be needed in the following areas: economic, political, religious and cultural.

Institutional Infrastructure for Societal Implications Research

Nanotechnology's vast scope and the necessity of bringing together researchers from different disciplines may require that some of the important social science research be carried out by large teams, housed in research centers set up for this purpose. At the same time, many of the research methodologies require social scientists to be on site where nanoscientists, nanotechnologists, and decision-makers are doing their work. One model that meets both of these requirements is the virtual distributed research center (VDRC). Under this approach, each VDRC would be organized around a specific but somewhat broad set of scientific questions and research methods, so that the members would have a common framework for designing, carrying out, and communicating their research. To ensure that results reflect the wide diversity of nanotechnology, social scientists would have to examine a range of empirical settings — for example, by conducting ethnographic research in a variety of nanotechnology laboratories. Thus many individual members of the VDRC would be situated, or would spend large blocks of time, at the geographically dispersed sites where they are studying. However, the VDRC would have a physical center that coordinates the work, develops and maintains funding and institutional partnerships, and supports effective communications among the far-flung team, both electronically and face-to-face in periodic meetings.

Many important nanotechnology-related questions could best be examined by more traditional centers, teams, and individual investigators. For example, survey research on public attitudes might best be done by a conventional team of researchers connected to one of the existing social survey organizations. Some research on economic trends, changing labor markets, and publication patterns could be done by individual investigators with access to data already available. Finally, there will always be a need for innovative projects carried out by individual scientists or small teams to develop new theories and methodologies and to carry out reconnaissance studies of emerging social phenomena.

5. RECOMMENDATIONS

Given the tremendous potential benefits of nanotechnology, and the concern that it be developed with sensitivity to potential negative implications, the workshop participants offered the following recommendations:

- Make support for social and economic research studies on nanotechnology a high priority. Include social science research on the societal implications in the nanotechnology research centers, and consider creation of a distributed research center for social and economic research. Build openness, disclosure, and public participation into the process of developing nanotechnology research and development program direction.
- The National Nanotechnology Coordination Office should establish a mechanism to inform, educate, and involve the public regarding potential impacts of nanotechnology. The mechanism should receive feedback from the nanotechnology

community, social scientists, the private sector, and the public with the goals of (a) continuously monitoring the potential societal opportunities and challenges; and (b) providing timely input to responsible organizations.

- Create the knowledge base and institutional infrastructure to evaluate nanotechnology's scientific, technological, and societal impacts and implications from short-term (3 to 5 year), medium-term (5 to 20 year), and long-term (over 20 year) perspectives. This must include interdisciplinary research that incorporates a systems approach (research-technology development-societal impacts), life cycle analysis, and real time monitoring and assessment.

- Educate and train a new generation of scientists and workers skilled in nanoscience and nanotechnology at all levels. Develop specific curricula and programs designed to:

  (a) introduce nanoscale concepts into mathematics, science, engineering, and technological education;

  (b) include societal implications and ethical sensitivity in the training of nanotechnologists;

  (c) produce a sufficient number and variety of well-trained social and economic scientists prepared to work in the nanotechnology area;

  (d) develop effective means for giving nanotechnology students an interdisciplinary perspective while strengthening the disciplinary expertise they will need to make maximum professional contributions; and

  (e) establish fruitful partnerships between industry and educational institutions to provide nanotechnology students adequate experience with nanoscale fabrication, manipulation, and characterization techniques.

- Encourage professional societies to develop forums and continuing education activities to inform, educate, and involve professionals in nanoscience and nanotechnology.

Other Measures

- Involve social scientists at the onset of major nanotechnology R&D activities, while the technology is still in an early stage of development, from vision setting to development projects. Extend the NNI grand coalition of academe, the private sector, and government to include the social, behavioral and economic science communities. Coordinate this activity through the National Nanotechnology Coordination Office.

- Prepare corresponding management plans and policies to ensure that we can respond flexibly to implications as they appear on the horizon.

- Integrate short-, medium-, and long-term objectives and ensure intermediate outcomes.

Specific Areas for Research and Education Investment

- Invest in significant new innovative efforts to educate and train the nanoscience and nanotechnology workforce, including the sensitivity to societal implications and the introduction of nanoscale concepts in mathematics, science, engineering, and technological education. Conduct a comprehensive study to determine the distinctive educational and workforce issues related to nanotechnology and seek potential solutions for problems that are identified in that study.

- Support interdisciplinary research that includes a systems approach (research-technology-society), life cycle analysis, and real-time monitoring and assessment. Study the evolution of disruptive technologies, the winners and losers in major technological transformations, and the implications for the economy. From those studies, project the social purpose, social equity implications, and social enterprise dynamics of anticipated nanotechnologies

Recommendations to Organizations

Academe:

- Focus on multidisciplinary work on key research and education issues concerning socio-economic implications. Support interdisciplinary interactions between the physics, chemistry, biology, materials, and engineering communities on one hand, and the social sciences and economic science research communities on the other hand.

- Educate and train a new generation of scientists and workers for nanoscience and nanotechnology at all levels.

- Create local information centers for the public, teachers, industry, and scholars.

Private Sector:

- Provide intellectual input and seed funding of activities aimed at assessing the societal implications of nanotechnology.

- Develop partnerships with academic institutions and other sectors.

- Offer accessibility to social science researchers and provide feedback on societal implications studies.

Government R&D Laboratories:

- Establish interdisciplinary teams for major grand challenges in nanotechnology including socio-economic perspectives, including social scientists.

- Develop databases for evaluation and continuously update scenarios for the future.

- Establish user facilities available to industry and academe that enable integration of basic and applied research.
- Support nanotechnology research within laboratories emphasizing national defense mission.

Government Funding Agencies:

- Support nanotechnology researchers and social scientists to study the societal implications of nanotechnology.
- Support NNCO or an advisory group to monitor developments and examine the socio-legal implications of nanoscience and nanotechnology and take appropriate actions. Communicate the resulting activities to the public.
- Provide coordinated support for long-term basic research and shorter-term technological developments to create the technological base and prove the potential of the new technology.
- Establish dialog between NNCO and information technology (NSO) and biotechnology (BECON) coordinating groups elsewhere in the Federal Government.

Professional Societies:

- Develop forums and continuing education activities to inform, educate, and involve professionals and the public.
- Provide suggestions for grand challenges and suggest warning signs of potential risks.

With an Eye to the Future

Nanotechnology will fundamentally transform science, technology, and society. In 10 to 20 years, a significant proportion of industrial production, healthcare practice, and environmental management will be changed by the new technology. Economic growth, personal opportunities, sustainable development and environmental preservation will be affected. To take full advantage of the new technology, the entire scientific and technology community must involve all participants, including the general public; creatively envision the future; set broad goals; and work together to expedite societal benefits.