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Perspectives

Societal implications of nanoscience and nanotechnology: Maximizing human benefit

M.C. Roco and W.S. Bainbridge
National Science Foundation, 4201Wilson Blvd., Arlington, VA 22101, USA
(E-mail: mroco@nsf.gov)

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Abstract

The balance between the potential benefits and risks of nanotechnology is discussed based on judgments expressed by leading industry, academe and government experts at a U.S. National Nanotechnology Initiative (NNI) sponsored meeting. The results are summarized in various themes related to: economic impacts and commercialization; social scenarios; technological convergence; quality of life; ethics and law; governance, public perceptions, and education.

Introduction

Nanotechnology offers rapid advances across many areas of science and engineering crucial to society. This paper is an overview that synthesizes opinions expressed in a report on societal implications as input to the U.S. National Nanotechnology Initiative (NNI). The resultant report (Roco & Bainbridge, 2005) grew out of a major workshop held on December 3–5, 2003, at which leading representatives of industry, government, and a wide range of scientific and engineering disciplines shared information and analyzed the increasing societal importance of nanotechnology. These opinions were sought as part of preparation of the five-year R&D plan by the Nanoscale Science, Engineering and Technology (NSET) Subcommittee of the National Science and Technology Council (NSTC) to identify long term research directions for nanoscience and nanotechnology in 2004. The first long-term vision for NNI was developed in 1999 (Roco et al., 1999). The aim of the report is to identify future trends, opportunities, uncertainties and potential breakthroughs, and to prepare the relevant scientific communities to ensure that nanoscience and nanotechnology will provide maximum benefit to humanity while considering and limiting potential risks. It surveys the current state of knowledge about societal implications and explores potential developments over the next 10 years and beyond. It explores the areas of research, education and infrastructure development that would be most valuable for society, and suggests what methods of investigation are most appropriate both for research and for evaluation of programs. Based on the extensive professional expertise of the dozens of scientists, engineers and policy leaders who contributed, this report recommends the actions and anticipatory measures needed to take prompt but responsible advantage of the new technology.

The first significant effort to understand the societal implications of nanoscience and nanotechnology was an earlier workshop held on September 28–29, 2000 (and republished by Kluwer; Roco & Bainbridge, 2001), at the request of the NSET, and organized by the National Science Foundation. During the intervening three years, nanoscience and nanotechnology have progressed more rapidly than was expected (Roco, 2004), and a consensus has emerged in the scientific and non-technical communities about the importance of nanotechnology and its unintended consequences. Several reports on societal implications, including potential unexpected consequences have been completed in the last years (EU-US Meeting Report, 2002; ETC Report, 2003; Greenpeace, 2003; Swiss Bank, 2003; VDI, 2004; Meridian Institute, 2004, Report on International Dialogue on Responsible Nanotechnology Research and Development, sponsored by the NSF). Also, several working groups have been established, including "Nanotechnology Environmental and Health Implications" within the U.S. NSET, the Consultative Board for Advancing Nanotechnology (CBAN) between NSET and various industry sectors in the US; the International Council on Nanotechnology (ICoN); the International Risk Governance Council (IRGC); by the Royal Society in the UK; and in Switzerland. Two other NNI-sponsored reports complement this report: one on environmental aspects (Nanoscale Processes for Environmental Improvement, Arlington, VA, May 8–10, 2003a) and another on nanobiology and nanomedicine (Nanobiotechnology, Arlington, VA, October 9–11, 2003b).

Nanotechnology has entered the mainstream of industry, and many companies have shown their confidence in its future by committing substantial resources to its development. For example, all Fortune 500 companies in advanced materials, electronics, chemicals and pharmaceuticals have activities in nanotechnology in the last couple of years. It already pervades many products, both improving everyday goods and offering potentially transformational new ones. At a minimum, the workshop participants including large and small industry leaders estimated that 50% of new products in manufacturing and medical approaches in 2015 will be affected by nanotechnology. Unexpected consequences of working at the foundation of all biological and man-made systems need to be addressed differently in each application area.

As technology and society are complex, interacting systems, it is difficult to predict the long-term consequences of particular innovations. Therefore, rational management of nanotechnology must involve a variety of stakeholders as well as experts in the decision process, as new technologies are developed and deployed, including representatives of the general public and mechanisms that adequately reflect the public interest. The aim must be to maximize benefit while guarding against potential harm, based on a realistic assessment of technical facts in the light of human values. Delaying the introduction of life-saving or life-enhancing technologies can be as harmful as prematurely releasing dangerous technologies, so policy must be both well-informed and agile. Unexpected consequences need to be addressed by an anticipatory and corrective system approach.

Feedback from a well-informed public and international partners has become essential for progress. More interactions between scientists, economists, and the public are needed to identify and reach the robust balance between benefits and limiting factors of nanotechnology. Media analyses show that groups with views at the extremes of the spectrum of opinions, either exaggerating the benefits of or mistrusting nanotechnology, have a disproportionate voice in the mass media, which impedes public understanding of both potential benefits and possible risks. Appropriately, increasing attention is being given to possible risks of particular applications based on innovations at the nanoscale, which will provide the general public and policy leaders with correct information.

Ten transformative themes

The group of experts developed well-grounded analyses and recommendations in 10 thematic areas: productivity and equity; future economic scenarios; the quality of life; future social scenarios; converging technologies; national security and space exploration; ethics, governance, risk and uncertainty; public policy, legal and international aspects; interaction with the public; and education and human development. The first five of these themes primarily concern the benefits nanotechnology could provide to humanity, and some of the conceivable problems it might cause if not developed wisely. National security and space exploration are combined because they are likely to make use of similar nanotechnology technical innovations. Three of the themes concern the broad issue of investment and risk governance of nanotechnology, including ethical and legal issues, policy-making institutions, and appropriate ways to include the general public in the decision process. The final theme, education and human resources, is in many ways the most fundamental. Without enough well-trained scientists and engineers, we will not be able to take advantage of the benefits of nanotechnology. Without a widespread, accurate awareness of the basic facts of nanoscience, the public and policy-makers will not have the knowledge to make informed decisions about nanotechnology and its products.

About 50 of the participants in the workshop contributed individual essays, which are included in the published volume, offering an examination of many important issues and approaches. Each of the 10 panels provided a summary of its deliberations, and here are very brief abstracts of those summaries.

Productivity and equity

The effects of nanotechnology are expected to stimulate improvements in work efficiency in almost all sectors involving material work (see Chapters 1 to 4 in the report, Roco and Bainbridge, 2005). Major national efforts should be focused on how nanotechnology can improve efficiency in manufacturing, energy resources and utilization, reduce environmental impacts of industry and transportation, enhance healthcare, produce better pharmaceuticals, improve agriculture and food production, and expand the capabilities of information technologies. A programmatic approach should be developed to prepare productive units and to increase synergy in nanotechnology development by creating partnerships earlier in the research and development processes between venture capitalists, industry, academia, national laboratories, and funding agencies. Social scientists, economists and public exponents must be involved from the beginning of major projects, in order to ensure equitable distribution of contributions and benefits, and to improve potential applications so they can better serve people and thus better achieve success in the market.

Future economic scenarios

Breakthroughs in nanoscale science and engineering can launch and sustain systemic economic progress (see Chapters 5 in the report). Nanotechnology will lower input costs in some industries, dramatically improve productivity in others, create entirely new industries, increase demand for some goods and lower demand for others. The net result will be significantly increased real wages and improved standard of living, with only a transitional increase in unemployment as labor and capital are shifted to new, more valuable uses from those that have been superseded or made less valuable. A new research effort is needed, examining the complex effects of nanotechnology from viewpoints as diverse as macroeconomics, industrial organization, and labor economics. Appropriate research methods include econometric analysis, case studies, surveys, economic models, and input-output analysis of impact on sectoral productivity that requires a concerted effort to collect data detailing the use of nanotechnology by industry and geographic area. International competition is an important area for economic research, on such topics as achieving national energy independence, the potential effect of different laws regulating nanotechnology across nations, and the potential national return to investment of government support for nanoscience and nanotechnology research.

The quality of life

Research should indentify the qualities of work, life and the environment to which citizens give highest priority and identify branches of nanotechnology most relevant to them, Nanotechnology will help ensure that we can produce enough *food* by improving inventory storage and the ability to grow at high yield and a diversity of crops locally. Nanotechnology will also help with *water* resources, allowing low energy purification and desalination, and reducing water waste in manufacturing and farming. Nanoscale-related improvements in *energy* technology will reduce the dependence on fossil fuels, make photovoltaic energy production competitive with other sources, allow entrance into a potential hydrogen economy, and improve renewable energy systems like biomass. In order to preserve the *environment*, we would use nanotechnology to remediate waste and pollution, produce systems and materials that use resources most efficiently, recycle pollution into raw materials, and ensure safety and sustainability of new materials. Developments in cognitive sciences and humanities resulting from scientific and technological developments will increase their contribution to the quality of life. Potential risks and unexpected consequences need to be monitored and included in any assessment of overall changes of quality of life (Chapters 4 to 10 in the report).

Future social scenarios

New technologies do not merely have implications for society. Rather, they interact with society, and the impact is a resultant of technical facts with social factors (see Chapter 5 in the report). Thus, public opinion surveys and methods like market testing are important ways of charting the changing meaning of nanotechnology. Contributors to the socially-oriented panels identified a number of major trends already taking place in society that will interact with nanotechnology to determine its implications. Table 1 lists some of these trends, described in terms of the social problems associated with them, along with ideas about the ways nanotechnology could contribute to solutions. The broad societal consequences and particularly respect for the human condition must be addressed from the beginning.

Over the coming 10–20 years, civilization will transition from the relatively crude technologies society depends upon today to more efficient and environmentally friendly nano-enabled technologies. In one scenario, the transition will be smooth and benign, whereas in another scenario, the transition will be rough and marked by many different kinds of harm and conflicts with social values and institutions. It is essential to understand how adequate existing institutions are to deal with the changes inevitably brought by nanotechnology, and we need to know what institutional forms and processes will lead to the best balance of innovation, security, equity, health and environmental protection. An inventory should be undertaken of existing institutions and assessment of how they cope with change and uncertainty. Also valuable would be research to develop a future nanotech skills inventory for identifying best of breed competencies that will enable jobs, career development and competitiveness. Research is recommended to model possible scenarios, make comparisons with the history of other technologies, and better understand the processes of nanotechnology innovation, diffusion and adjustment.

Converging technologies

Much of the impact of nanotechnology will occur through its convergence with other fields, especially biotechnology, information technology, and new technologies based on cognitive science (Chapter 6 in the report). The unity of nature at the nanoscale provides the fundamental basis for the unification of science, because many structures essential to life, computation and communication and to human thought itself are based on phenomena that take place at this scale. Maximizing human benefit will require the development of transforming tools that can be shared across fields, such as new scientific instrumentation, overarching theoretical concepts, methods of interdisciplinary communication, and fresh techniques of production such as those bridging the gap between the organic and inorganic. Technological convergence is the wave of the future, but it cannot properly transform science and technology without the investment of considerable effort to achieve maximum human benefit. These technologies are likely to bring about and require fundamental change generating new science, new technologies, new industries, new manufacturing processes and capabilities, new services, new skills and knowledge. They also have the potential to disrupt existing industries and the current balance between societal institutions, so comprehensive convergence will require anticipatory measures.

National security and space exploration

In almost every phase of operations required for national security and for space exploration, nanotechnology provides advantages in the ability to gather, communicate, digest, and act upon information with advanced sensors, and to take requisite action with platforms that will have augmented capacity (see Chapters 3 and 4 in the report). In both arenas, there are also pressing needs for stronger, lighter, more durable structural

Table 1. Problematic social trends and ways nanotechnology could contribute to solutions (examples)

Social problem	Nanotechnology contribution to solution
Healthcare and working capacity of aging population	Convergence of nanotechnology with biotechnology, information technology and neurotechnology would address chronic illnesses, losing sensorial capacity, and maintaining work capacity
Collapse of birth rate in most advanced nations, below level required for population stability	Convergence of nanotechnology with biotechnology to overcome infertility
Poverty and inequality, most urgently in under developed nations	Economic progress, fueled by technological developments requiring systematic control of nanoscale processes and materials
Loss of jobs in advanced nations, as work goes to nations with lower wages, weaker worker benefits, and worse workplace safety	Progress in nanoscience will allow industrial nations to maintain quality of life, generating new domestic industries with high-quality jobs, even as poor nations benefit from globalization
Threatened exhaustion of natural resources	Nano-enabled technologies for improved efficiency in use of non-renewable resources, including energy production, water filtration, and invention of many high-quality nano-fabricated substitute materials
Environmental degradation, including global warming	Reduced pollution from more efficient use of materials; specific new pollution remediation nanotechnologies; improved environmental monitoring by means of nano-enabled sensor nets
World political instability threatens the gains achieved by newly democratic nations	Stability will require technology that can offer abundance to a majority of people in all societies with existing natural resources
Security issues within industrial nations	Numerous specific nanotechnology-based solutions, such as: sensors to detect bioterrorism substances; inexpensive "smart labels" to deter theft of valuable goods; armor and vehicle components from nano-structured materials
Cultural chaos in post-industrial, post-modern, pluralist society	Nanotechnology will permit rapid progress in technologies of computation, communication, and creativity to sustain a culture of connectivity, equal access to information and a myriad subcultures simultaneously
Medical: diminishing returns from research; rising cost of health care	Fresh approaches to disease diagnosis and treatment from nanotechnology; prevention of disease from better nutrition and from quick detection and treatment of conditions predisposing to disease
Medical: currently incurable illnesses, including cancer and AIDS	Molecular and nanobiosystems solutions for detection and treatment at the subcellular level
Possible slowing of progress in many fields of science and engineering (e.g., aviation and space, nuclear power; computers)	Fresh ideas, research methods, and design approaches generated by convergence and combination of many fields, made possible by the nanoscale science and technology platforms. It will support rapid advancements in biotechnology and information technology.

materials and reliable explosives or propellants that release greater energy. Nanotechnology can provide advanced materials for aircraft, armor for combat or re-entry vehicles, and ships or satellites that are less vulnerable to corrosive environments. Future possibilities include adaptive airframes built from smart skin materials, light-weight and highly intelligent nanoelectronic space probes, integrated smart nano-sensor systems that tolerate radiation and high temperatures, and systems for diagnosing and treating human injuries and illnesses both during combat missions and during long-duration human space flight.

Perhaps the most important strategic resources for national security are human resources. The adoption of nanotechnology, over the coming decades, will initiate an increase in demand for scientists and engineers globally. Programs must be established to provide awareness of the importance of nanotechnology for societal benefit and to stimulate interest in pursuing science education.

Ethics, governance, risk and uncertainty

The ''news model'' of public involvement, in which technical experts and the media impart information to a passive audience, fails to bring about an informed public. We need information systems that facilitate two-way conversation. Innovative technologies bring about unintended consequences. Instead of trying to predict the future, it will be more fruitful to try to shape the future by building institutions that can learn while preserving core values. A range of projects could develop infrastructures for balanced and inclusive public participation in decision making, with many different, innovative models used to assure two-way interchange between nano-engineers or scientists and their publics. There must be genuine respect for interdisciplinary discussion of ethical and social dimensions of nanoscale science, engineering, and technology (see Chapter 7 in the report). Research should be carried out to achieve better understanding of complex systems and uncertainty, and better understanding of how research directions themselves are decided. Risks and uncertainties are expected to increase with the transforming capabilities provided by nanotechnology, and must be evaluated by considering global factors in governance. Examples of projects supporting societal implications are given in Table 2.

Public policy, legal and international aspects

Although there has been a significant increase in funding for nanoscale science and engineering, the perception is that we are still under-investing. A careful and rigorous analysis of the adequacy of current funding levels is needed. Safety, legal aspects and other issues need to be addressed. Nanotechnology research has the potential to play a considerable role in the developing world, and many legal or policy issues will need to be addressed on a global rather than national scale. Nanotechnology impacts not only intellectual property, the commercialization and technology transfer of research results and products from laboratory to market, but also a wide integration of multiple legal practice areas (see Chapter 8 in the report). As nanotechnologies reach the commercial marketplace, the public should be confident that the government is taking appropriate steps to safeguard the environment and human health, while enabling new technologies and new industries to flourish. Therefore, government should support research to understand the human health and environmental consequences of nanostructured materials, and review the adequacy of the current regulatory environment for nanomaterials.

Table 2. NNI projects supporting social implications (examples)

Project	Funding agency, Awarded institution
Nanotechnology and its Publics	NSF, Pennsylvania St. U.
Public Information, and Deliberation in Nanoscience and Nanotechnology Policy (SGER)	Interagency, North Carolina St. U.
Social and Ethical Research and Education in Agrifood Nanotechnology (NIRT)	NSF, Michigan St. U.
From Laboratory to Society: Developing an Informed Approach to NSE (NIRT)	NSF, U. of South Carolina
Data base and innovation timeline for nanotechnology	NSF, UCL
Social and ethical dimensions of nanotechnology	NSF, U. Of Virginia
Undergraduate Exploration of Nanoscience, Applications and Societal Implications (NUE)	NSF, Michigan Technological U.
Ethics and belief inside the development of nanotechnology (CAREER)	NSF, U. Of Virginia
All centers, NNIN and NCN have societal implications components	NSF, DOE, DOD and NIH All nano centers and networks

Interaction with the public

The National Nanotechnology Initiative can play an important role as an honest broker in coordinating research and development in nanotechnology with public hopes and fears, and it should embrace the goal of building capacity for public dialog (see Chapter 9 in the report). It is imperative that genuine risks be dealt with in an expeditious, open and honest manner. Negative public attitudes toward nanotechnology could impede research and development, leaving the benefits of nanotechnology unrealized and the economic potential, untapped, or worse, leaving the development of nanotechnology to countries and researchers who are not constrained by regulations and ethical norms held by most scientists worldwide. Research on how to achieve an informed population will be important for establishing best practices for educating, communicating and engaging diverse publics about nanotechnology. We need to develop survey data about understanding and attitudes, information about audience response to various media products, and effective training methods to prepare scientists and engineers to engage in public dialog about nanotechnology.

Education and human development

The Nanotechnology Revolution will be social and cultural as well as scientific and technological, because it creates an opportunity to integrate education across science, technology, social sciences and even humanities (see Chapter 10 in the report). It is emblematic of new ways of thinking about the future and the workforce. Students will be motivated by problems that combine the social and the technical, for example, the potential for new environmental technologies. Nanotechnology will fulfill the mission of liberal education to make students into critical thinkers, capable of participating in intelligent debates about how societies ought to be transformed. The end-result will be informed, educated publics emerging from our high schools and colleges, able to shape the direction of nanotechnology in beneficial ways. Research needs to focus on the viability and transferability of strategies to integrate across disciplines, including curriculum test-beds where students and teachers could work with nanoscientists. Disciplinary education is going to have to be complemented by training in how to work in interdisciplinary teams, and worker transition programs should be framed as opportunities to get in on the ground floor of a growing field. Societal dimensions of nanotechnology create an opportunity for training postdoctoral and other advanced students in areas of technology that will be in demand from society.

Each of the 10 panels was asked to address five general questions: What is the current state of knowledge about the societal implications of nanoscience and nanotechnology? What major developments are anticipated over the next five, 10 or twenty years, as their direct or significant indirect effect? Which methods of research and evaluation would be most appropriate for answering important questions within the theme? What kinds of resources or infrastructure should be developed for research and education, either in nanoscience and nanotechnology themselves, or in understanding and addressing their societal implications? Finally, what specific action recommendations should be presented to the major relevant societal institutions, including government, industry, and education.

Current state of knowledge

It is crucial to realize that the term *nanotechnology* covers a very wide range of actual approaches and applications, so there cannot be only one kind of societal implication or one policy to promote or to regulate nanotechnology. Science and engineering at the nanoscale are already contributing significantly to many industries, such as catalysts, coatings, paints, rubber and tire products, microprocessor manufacturing, heavy equipment manufacturing, and aerospace. Thus, the early implications of nanotechnology are mediated through the numerous other technologies where control over nanoscale structures and processes is advantageous. In the short-term, the chief effect of these developments is continued economic growth and improvement in the performance of a variety of products.

From consideration of the early applications of nanotechnology, in light of the research on other technological developments of the past,

Figure 1. A culture of connectivity increasingly facilitated by nanotechnology (courtesy G. Whitesides).

economists and other social scientists are able to project some very general trends. With the passage of time, progressively more advanced nanotechnology applications can be expected to lower manufacturing cost in some industries, improve productivity in others, and even create entirely new industries. The result will be increased demand for some goods and skills, and reduced demand for others. While the short-term result may mean disruption of some specific corporations and careers, the free market system ensures that capital and labor will shift to new uses, and the disruption will be limited to a transition period in narrow sectors of the economy. On balance, technological development improves the standard of living, both through economic growth and through the new capabilities provided by the technology.

Apart from this general confidence, there are many specific areas in which our knowledge is limited and research therefore is needed. Scientists, engineers, corporate management and societal policy-makers do not know very much about how best to implement many of the possible technological developments, nor about what the indirect or second-order societal effects might be, for example at the intersection of nanomaterials and nanosystems with biological and ecological systems. Fresh ways of thinking, perhaps amounting to major paradigm shifts, may be required.

We do not know the extent to which nanotechnology's impacts will be felt through convergence with other, more traditional technologies, or will be distinctive to nanotechnology itself. We also do not know how much the introduction of its benefit will exacerbate or ameliorate inequality among groups in society or how broadly the benefits will be enjoyed either in the short-term or long-term. Among knowledgeable experts, there does seem to be a consensus that there will be really profound consequences of the convergence of nanotechnology with biotechnology, information technology, and new technologies based on cognitive science. In the areas of national defense and space exploration, near-term advances can be expected in the capabilities of equipment, but the most important issue is probably the development of sufficient human resources in the form of trained scientists, engineers, and technicians.

Knowledge about how to govern nanotechnology is in the very early stages of development. Some multidisciplinary research and theorizing has begun, bringing together experts from the social sciences and humanities, as well as engineering and physical science disciplines. We know that issues of power and trust are central to public debates, and merely informing the general public about the conclusions of experts is insufficient; the public or their representatives must be active parties to the deliberations. Three immediate policy questions concern the necessary funding level for nanotechnology research and development, the implications of nanotechnology for the developing world, and the environmental and human health effects of nanostructured materials. There is some evidence that the general public is losing trust in science and scientists, and a few very vocal special interest groups are raising alarms about nanotechnology. Negative public attitudes toward nanotechnology could impede research and development, leaving the benefits of nanotechnology unrealized, even if those attitudes were based upon misconceptions.

Nanotechnology presents both the need and the opportunity for transformation of our educational system. Teaching of the sciences is highly fragmented today, whereas nanotechnology bridges across physics, chemistry, and biology. Some believe that if we first integrate science teaching around phenomena at the nanoscale, it will also be possible to integrate education across science, technology, social sciences and even humanities. The challenges are immense, but it is widely recognized that a new model of education is sorely needed.

Anticipated developments

Many writers have tried to imagine what new accomplishments nanotechnology will make possible, and previous reports have listed many intended benefits (e.g. Roco & Bainbridge, 2001). A relatively small number of risks have been identified, some of them only conjectural, and awareness has grown that research needs to evaluate the conceivable disadvantages of some particular nanotechnologies and seek countermeasures for them. Recently, careful analysts have begun to see ways in which the fruits of nanoscience may require changes in our institutions and culture, changes that need not be disadvantageous but may represent progress toward a higher level of societal development.

Thus, the list of anticipated developments is quite varied, including possible technical breakthroughs, beneficial applications, possible risks, and social changes. The following illustrate the wide range of expected innovations:

- Nano-enabled improvements to computing, sensing, communications, data storage, and display capacities promises to transform the information technology industries, finally achieving long-standing dreams such as automatic extraction of information from raw data, artificial intelligence and virtual reality. Nanotechnology will enable increased social connectivity (see Figure 1).
- Nanotechnology promises to achieve energy independence for major industrial nations, both from ecologically sound production of energy and from a reduction in the demand for energy caused by a host of efficiencies facilitated by nanotechnology.
- Nanotechnology will contribute greatly to general economic growth, thereby providing the resources to deal with social problems more effectively, but really solving these problems requires enlightened policy, world peace, and equitable distribution of resources.
- Advanced, high-performance robotics relying on nanoscale components will make possible smart unmanned platforms for deep space exploration and unmaned vehicles.
- Composite materials with a high strength to weight ratio will facilitate very high performance space launchers and aircraft that gracefully adapt to accidents and achieve low life cycle costs.
- Affordable nanoscale miniaturized medical diagnostic and treatment devices will lead to increased longevity at comfortable, active, and productive levels of vitality, easing medical hardships, pain, suffering, and disabilities.
- Persons in hazardous environments, such as soldiers on the battlefield, will benefit from clothing incorporating many nanoscale devices to constantly monitor physiological vital signs, warn of exposure to harmful chemicals, adjust for environmental stresses, provide camouflage that matches changing background and lighting conditions, and even provide first-aid casualty response.

- The revolutionary capabilities of converging technologies at the nanoscale will greatly increase the importance of appropriate measures to ensure we maximize the benefits while minimizing the risks that may be associated with their great power.
- The public will be deeply involved in deliberation and discussion about nanotechnology, through infrastructures that facilitate balanced and inclusive public participation using many different, innovative models.
- Advanced and educationally effective online information resources will be devoted to ethics and social implications of nanotechnology, integrated not only into conventional K-12 and college courses but also into continuing education for companies, scientists, and engineers.
- Interdisciplinary teams developing scientific, engineering or social projects related to nanotechnology will rely upon interactional agents who are experts at communicating across fields, facilitating the formation of trading zones that multidisciplinarity collaboration through such means as developing shared technical terms.
- In response to nanotechnology and its convergence with other technologies, innovations and reforms will take place in many branches of the law, including torts, environmental law, employment and labor law, health and family law, criminal law, constitutional law, international trade law, and antitrust law.
- Advanced biomedical solutions to chronic diseases, and visualization of biological processes within human body.

Research and evaluation methodologies

A large number and variety of research methodologies have been developed by social scientists, economists, and scholars in such fields as philosophy. Many of these can be adapted to understanding the human implications of nanotechnology, but considerable work will be required to do so. For example, everybody understands the rudiments of questionnaire survey research, and yet high-quality work of this kind on public attitudes toward nanotechnology cannot be done until a large and diverse set of effective theory-based or issue-oriented questions is developed and pretested, and until rigorous means for obtaining and calibrating appropriate samples of respondents are established.

Some methodologies are especially well suited for exploring new territory, such as focus groups, case studies, and interviews with decision makers or innovators. A useful tool of theory construction is scenario analysis, in which knowledgeable people try to imagine how various factors might shape the direction nanotechnology takes or the effects it has on markets and institutions. Multi-agent modeling is one way of rendering scenarios more precise and dynamic, through examining interactions among computer representations of individuals, organizations, sectors of the economy, or other social units. Historical studies of earlier innovative technologies, such as biotechnology and information technology, are useful to the extent that it is possible to judge which actually provide appropriate analogies to particular kinds of nanotechnology. Observational field ethnography and content analysis of literature are among the appropriate ways of studying social movement organizations and special interest groups that promote distinctive perspectives on nanotechnology. Once such exploratory methods have identified hypotheses worth testing, more rigorous techniques can be employed to test their validity.

Opinion polls and surveys can determine where the public currently stands on nano-issues, chart the changing meaning of nanotechnology over time, and compare public awareness, understanding and attitudes toward nanotechnology across different societies. The economic impact of nanotechnology can be measured and evaluated through such techniques as econometric analysis, input-output models, and tabulation of data about changing labor markets. Formal experiments can evaluate the educational effectiveness of new curricula, strategies for integrating disciplines, and techniques for distributing information. Comprehensive inventories would be useful in enumerating the institutions that participate in nano-related activities, best practices regarding communication with the public, and new employment opportunities.

Research, education and infrastructure development

There are numerous interesting research topics, potential education programs, and valuable kinds of infrastructure, and it will be necessary to prioritize which should receive the earliest or greatest investment.

A high priority should clearly be given to physical science research on the possible risks from exposure to nanoparticles and other nanostructures, whether to individual health or the natural environment. At the same time, social scientists should investigate public concerns, perceptions of risk, fears, conceptions and misconceptions. Research on the processes of innovation, diffusion, and adjustment would certainly be useful, as would a better understanding of the complementary influences of private, venture, university, and government investment in nanotechnology development. Other research should examine how social and economic forces affect distribution of benefits and risks, both across social classes and across societies of the world.

An adequately trained scientific workforce is the scarce resource essential for creation and transformation of industries. Because nanoscience and nanotechnology are being developed in all industrialized nations, no country can depend upon foreign students for its scientific human capital, so the United States must produce an increasing number of domestic scientists and engineers. K-16 math and science education must be strengthened, not only through new curricula and educational materials, but through fundamental reorganization of how technical disciplines are taught. Worker transition programs and postdoctoral training in the physical sciences will be important, but also essential will be training that combines specialties in the social sciences and humanities with knowledge of nanoscience and nanoengineering.

These research and education efforts will require development of an infrastructure of nanoscience laboratories, simulated virtual laboratories, and shared social science information systems. A comprehensive information system should be created monitoring the development and applications of nanotechnology, to recognize early signs of negative aspects and risks, permitting a timely response from policy makers. This comprehensive database could be supplemented by an expertise bureau for societal issues related to nano to inform mass media, so they can correctly communicate information about nanotechnology to the public.

The revolutionary applications that may emerge from nanotechnology and the broader suite of converging technologies could have substantial implications for the organizational infrastructure of corporations, government agencies, and academic institutions, requiring them to acquire an increased ability to evolve in an environment of continuous change. Current laws, regulations, policies, the educational preparation of legal professionals, and judicial infrastructures will be challenged, as well. We do not at present know how adequate our institutions, organizations, and laws are to achieve the best balance of innovation, security, equity, health and environmental protection.

Several Report Recommendations

The 10 panels of experts developed a large number of specific recommendations, and the following nine are representative:

- Scientifically reliable and publicly respected organizations should clearly articulate the diversity of methods and principles of nanotechnology, together with the near term and the long term benefits and uncertainties of nanotechnology, to solidify public trust and empower people to make good nanotechnology investment decisions.
- Research should: (1) be broadly funded, primarily based on peer-reviewed investigator-initiated proposals; benefits of nanoscale science and engineering are so broad that funding should not be driven by a few specific top-down priorities; (2) be supported to develop various models of public involvement and interaction, to establish best practices for educating, communicating and engaging diverse publics about nanotechnology; and (3) incorporate ongoing engagement of public in deliberations on nanotechnology to assure two-way interchange between nano-scientists and engineers and the public.
- The government should: (1) significantly increase the funding available to understand the human health and environmental consequences of nanostructured materials; (2) review the adequacy of the current regulatory environment for nanomaterials, given the existence of size-dependent properties; and (3) develop a communication strategy to keep the public informed of representative and fundamental developments of the new technology.
- The government and the private sector should anticipate potential implications and scenarios

to the extent possible and mitigate negative impacts on people, such as workers in obsolete industries, whose lives may be disrupted by the nanotechnology affecting market forces.

- A careful and rigorous analysis of the adequacy of current NNI funding levels and of future investment priorities is necessary to optimize societal benefit.
- Educational initiatives should aim to enhance (1) critical thinking, including structure and support for graduate and postdoctoral students; (2) cross-disciplinary training and experience; (3) models for collaboration of scientists, social scientists, and humanists across disciplines; and (4) the integration of social science and technical research. Nanotechnology education should be provided beginning with K-12 programs.
- To meet current and short-term labor needs, the government should support the implementation of retraining programs to equip underutilized scientists and engineers, in areas with poorer labor market prospects, with nano-related skills.
- Increased capabilities and funding should be developed for conducting science and technology studies in educational contexts, in industrial contexts, and among the public. Workforce development should be undertaken across the full spectrum of job roles (i.e., not just scientists).
- A programmatic approach is needed to increasing synergy in nanotechnology development by creating partnerships earlier in R & D processes between industry, academia, national laboratories, and funding agencies, as well as corresponding international organizations. Multi-functional clusters or partnership coalitions with greater flexibility to adapt should be created that bring together those involved in researching and developing nanotechnology-biotechnology-information technology-cognitive tools, processes, and products.

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