3.1 Introduction

3.1.1 Why Nanotechnology?

The world is formed from a finite number of atoms, each atom having fixed properties. This atomic structure was reached by condensation of matter at a given moment in evolution according to the “big bang” expanding theory. Then, the atoms have had a tendency to assemble in molecules and, progressively, in a variety of larger structures. The first structural level of organization of atoms and molecules is into nanostructures or nanomodules, which typically have dimensions between 1 and 100 molecular diameters. Such nanomodules may have a variety of properties and functions that can be found in all
natural materials, living organisms, and man-made objects. Living organisms exhibit the most complex of such structures. Only in recent decades one has begun to measure and understand the existence of nanostructures and realize their pervasive multidisciplinary nature and determinant role in setting the fundamental properties of materials and systems. Major progress toward scientific understanding and mass use of nanotechnology is expected to be completed between 2000 and 2020. We have a 20 year journey/endeavor that brings our knowledge back in time and inward to our nanoscale roots. As information technology is pervasive because each natural or man-made event contains information, so nanotechnology is pervasive because all natural and man-made objects are made of atoms and nanostructures. This is an opportunity to break the barriers between traditional disciplines such as physics, chemistry, materials, biology, and engineering and learn and design using unifying concepts for the complex systems surrounding us.

3.1.2 Shrinking the Science and Technology Development Timescale

There is evidence that the knowledge is growing on a quasi-exponential path, and science and engineering is converging because more generic concepts are generated and interdisciplinary spaces are filled in. The development is accelerating and is nonuniform per knowledge domains being marked by major science and technology trends in various time intervals. Three megatrends in the last 50 years are computing and communication, modern biology, and nanotechnology. The time interval estimated for development—to advance from societal recognition of basic multidisciplinary concepts to mass application—was about 40 years in information technology (1960 to mass use of internet in 2000), about 30 years for biotechnology (1980–2010), and 20 years for nanotechnology (from 2000 to mass use in 2020). This chapter describes changes in science, economy, society, risk governance, and culture for these 20 years to develop nanotechnology.

3.1.3 Nanotechnology Affirmation in Two Decades

At the end of 2010, after 10 years of focused R&D in nanotechnology worldwide inspired in 2000 by a research oriented multidisciplinary definition (Siegel et al. 1999) and a coherent vision (Roco et al. 1999), we can see major changes in the development of the field, and, on this basis, we can develop scenarios for the next decade (see for illustration the reports by BMBF, 2010; Case, 2011; Lok, 2010; PCAST, 2010; Roco et al., 2010). Ten key indicators summarize the steep growth of nanotechnology field in the interval 2000–2010 (paper and patent applications were searched by keywords in title and abstract using the method described in Chen and Roco, 2009 and 2011):

1. A multidisciplinary nanotechnology community has been established with continuously changing qualifications. The average growth rate has been about 25% per year. The number of workers in nanoscience and nanoengineering has increased from about 60,000 worldwide (of which 25,000 in the United States) in 2000 to about 600,000 in the world (of which 200,000 in the United States) in 2010, and it is estimated to reach 6 million in the world (of which about 2 million in the United States) by 2020.

2. The market including products and services incorporating nanotechnology has increased by an annual rate of about 25% in the world (about 24% in the United States) in the interval 2000–2010, reaching about $300 billion ($110 billion in the United States) in 2010. By considering the delayed impact of basic R&D investment with about 10 years and the expansion of nanotechnology “horizontally” to completely new markets and new sectors or application, one may estimate a continuing average annual rate of 25% in the following decade.

3. The combined public and private R&D funding has increased by an annual rate of about 31% worldwide and about 27% in the United States. The global R&D funding in 2010 was about $18 billion of which about $4.1 billion (about 23% of the world) was in the United States. The U.S. government annual investment per capita for nanotechnology R&D has increased from about $1 in 2000 to about $6.2 in 2010 (about 25% increase per year). The Japan annual investment per capita was $7.3 in 2010.
4. The number of Science Citation Index nanotechnology papers has increased by an average rate of 16% in the world (13% in the United States) in the interval 2000–2010, after a slowdown in 2009. There are about 79,000 papers published in 2010 worldwide of which about 18,000 were in the United States.

5. The number of patent applications at patent depositories worldwide searched by title and abstract has increased annually by about 33% worldwide (28% at USPTO). There were about 20,000 patent applications published in the world in 2010 of which about 5,000 were in the United States.

6. The number of awarded nanotechnology patents at USPTO searched by title, abstract, and claims have increased annually by 17% for all authors and by 15% for the U.S. first author.

7. The average rate of increase of venture capital was about 20% worldwide and about the same in the United States despite of the 1 year drop of about 40% in 2009 as compared to 2008. The venture funds estimated at $1.3 billion worldwide, of which $1 billion in the United States in 2010 (Lux Research, 2011), are still relatively low as compared to the R&D efforts.

8. The number of consumer products has increased in the last 5 years (after their number has become statistically relevant in 2005) by 30% worldwide and 35% in the United States (WWCS, 2011). Even if the total business for consumer products is relatively small as compared to industrial and medical sectors, the number of products is significant (there were 1317 products manufactured worldwide in 2010, of which 587 were produced in the United States).

9. The number of peer-reviewed publications addressing nano-EHS risk assessment increased from about 50 in 2004 to over 250 in 2009 (the average annual rate of increase is about 38%).

10. The corresponding number of publications addressing nano-ELSI and governance aspects have increased slightly faster than those on nano-EHS in 2004–2009.

One notes that the average annual rate of increase in nanotechnology R&D investment in 2000–2010 of 31% exceeds the average rate for scientific publication of 16%, but it is slightly under the average growth rate of publications of patent applications of 33% per year.

### 3.1.4 Long-Term View after 2010

Several supportive reports and publication have expressed support for continuing the long-term R&D view to 2020 in order to take the benefits of the new technology and investments already made:

- The Presidential Council of Advisors in Science and Technology (PCAST report, 2010) provides a perspective for nanotechnology development for 10 years ahead. Basic research will remain a critical component of the research portfolio, while a new focus will be increasing focus on integration of components and processes and manufacturing that leads to several new R&D grand challenges and commercialization.

- Congress periodically updates the current law for funding nanotechnology R&D in the United States. The European Union (EU 2011), Germany (BMBF, 2010), China, South Korea, and Japan programs plan ahead for 5 to 10 years.

- The NSF/WTEC report “Nanotechnology Research Directions for Societal Needs in 2020” (2010) provides a vision for the next decade. This is followed by a 3 year strategic plan (NNI Strategic Plan [2011] for 2011–2014) and coordinated annual budgets (e.g., Presidential NNI Budget Supplement for fiscal year 2012 [2011]).

- Nanoelectronics Research Initiative in the United States provides a long-term, 10–15 year research plan.

- Nanotechnology Business and Commercialization Alliance (NanBCA) has developed plans for the next 10 years.

- Chemical, electronic, and forest industries have prepared reports to envision 2020. Interaction with other emerging technologies is essential in this context.

- Innovation and nanomanufacturing become two central features in all these reports. The pull of industry is starting to be felt not only for nanocomponents but also for nanosystems and integration of nanotechnology with other emerging technology products. The advancement of nanotechnology platforms based on same tools and similar processes for multiple applications is gaining commercial recognition.
This chapter discusses what is behind the high rates of increase in nanotechnology indicators since 2000 and the momentum to expand the goals of the investments in the next decade. Forward issues are how one best takes advantage of the previous investments and realizes the promised societal benefits by 2020.

### 3.2 Major Achievements in 2000–2010

#### 3.2.1 Outcomes of the Foundational Phase

Development of nanotechnology evolves from a fragmented scientific field at the end of the 1990s to a general-purpose technology by 2020. The progress of nanotechnology in the last 10 years has been significant, and the vision set up in 1999 by *Nano 2010* (Roco et al. 1999) has been realized in most of the components.

The first foundational phase of nanotechnology development “Nano 1” (2000–2010) was dominated by a science-centric ecosystem. The second foundational phase “Nano 2” (2011–2020) will be focused on nanoscale science and engineering integration. It is projected to be driven by socioeconomic considerations.

In the last decade, an interdisciplinary international community and a complex research and education infrastructure have been established. Nanotechnology has penetrated almost all industrial sectors and medicine, and the production of nanotechnology-enabled products has expanded about 10 times worldwide reaching about $300 billion in 2010.

Scientific curiosity began to transform in 2000 with the help of two key parts of the Nano 2010 report. First, an integrative definition of nanotechnology was formulated based on distinctive behaviors of matter at the nanoscale and the ability to systematically control and engineer those behaviors. Second, a long-term vision and goals were articulated for the transformative potential of nanotechnology R&D to benefit society. Now, nanotechnology is recognized along with information technology and biotechnology as a megatrend in science and engineering.

One main outcome is a library of newly discovered nanoscale phenomena, processes, and nanocomponents, as well as a versatile measurement and manufacturing toolkit. These phenomena have become the foundation for new domains in science and engineering such as plasmonics, negative index of refraction in IR/visible wavelength radiation, spin torque transfer (spintronics), nanostructured and porous materials with very high surface areas, including metal organic frameworks, covalent organic frameworks, and zeolite.
imidazolate frameworks, for improved hydrogen storage and CO$_2$ separations. Nanocomposite membranes, nanosorbents, and redox-active nanoparticles have been developed for water purification, oil spill cleanup, and environmental remediation.

There is greater recognition of the importance of nanotechnology-related environmental, health, and safety (EHS) issues for the first generation of nanotechnology products, and of ethical, legal, and social implications (ELSI) issues.

Nanotechnology has catalyzed overall efforts in and attracted talent to science and engineering in the last decade worldwide. A comprehensive list of outcomes arranged per area of relevance is presented in the 600-page *Nano 2020* report (Springer, 2010, available on www.wtec.org/nano2/ and www.nsf.gov/nano). The forecasts made in the Nano 2010 report generally have been realized, and some have been exceeded.

### 3.2.2 Penetration of Nanotechnology

The penetration of nanotechnology is progressive and significant since 2000 in R&D investments, number of scientific papers, patents, and markets. The proportion of the number of nanotechnology SCI papers published worldwide (searched by keywords in titles and abstracts; Chen and Roco, 2011) has reached about 5% in 2010.

In the United States, the overall NNI government funding relative to the total federal R&D funding has reached about 1.7% in 2010, which is about the same as the percentage for the number of nanotechnology USPTO patents relative to all technology areas (searched by keywords in titles, abstracts, and claims; Chen and Roco, 2011). The percentage of National Science Foundation’s grants with full or partial nanoscale science and engineering content has flattened after reaching 11%–12% in 2005–2010. The nanotechnology papers and patents are estimated to reach and stabilize about the same percentage level by 2020.

While the penetration of nanotechnology market has exceeded 30% in nanoelectronics and nanostructured catalysts in 2010 (see Nano 2020 report, Table 2), the overall contribution of nanotechnology market relative to GDP is still at 0.8% in the United States. This contribution is estimated to increase to 5% in the United States by 2020 following with a time delay the growth trend noted in nanotechnology papers and patents.

### 3.2.3 Returns on Investment

The United States has invested some $12 billion in nanotech through the NNI in 2001–2010. This investment has significant returns. Nanotechnology already has a major and lasting impact that promises to be more relevant for health care, environment, and manufacturing here on Earth than the space program. The cumulative U.S. nanotechnology commitment since 2000 places the NNI second only to the space program in terms of civilian science and technology investment (see Lok, 2010).

We are only at 10 years of discovery and innovation enabled by investments in a field still in rapid formation, and only relatively simple nanostructures are in applications: nanolayers in multibillion dollar semiconductor industry, dispersions in multibillion dollar catalyst industry, molecular recognition and targeting in multibillion dollar medical therapeutics, to name some of the most relevant. Despite that nanotechnology is still in the formative phase of development, if one would consider an average tax of 20% and apply this to about $110 billion U.S. market incorporating nanotechnology in 2010, the result would be $22 billion that exceeds the 10 year R&D investment of NNI by a factor about 2.

Nanotechnology has extensively penetrated several critical industries. Engineered nanostructured catalysts redesigned/designed after 2000 represent about 30%–40% of all catalysts used in 2010 in the U.S. oil and chemical industries (Chapter 10 in the Nano 2020 report); semiconductors with features under 100 nm constitute over 30% of that market worldwide and 60% of the U.S. market (chapter on Long View in Nano 2020 report); and molecular medicine is a growing field, and only in 2010, about 15% of advanced diagnostics and therapeutics were nanoscience based. These and many other examples show nanotechnology is well on its way to reaching the goal set in 2000 for it to become a “general-purpose technology” with considerable economic impact.
Nanoscale science and engineering in the last 10 years is a springboard for future nanotechnology applications and other emerging technologies. We estimate that introduction of nanotechnology in various economic sectors such as electronics and pharmaceutics will lead to at least 1% increase annually in productivity during 2010s in a similar manner as another general-purpose technology—information technology—did in the 1990s.

3.3 New Phase of Nanotechnology Development after 2010

3.3.1 Changes Likely to See in the Next Phase of Nanotechnology

The changes are significant as the field of nanotechnology reaches its “adolescence” in the next 10 years (2010–2020). Since 2010, nanoscale science and engineering has changed focus in both R&D and outputs: We are transitioning from empirical synthesis of nanoscale components for improving existing products and services to science-based creation of new and complex nanosystems by design for fundamentally new products.

The transition from the Nano 1 foundational phase (2000–2010, focused on foundation interdisciplinary research at the nanoscale) to the Nano 2 integration phase (2010–2020, focused on nanoscale science and engineering integration for system applications) includes achieving direct measurements at the nanoscale with time resolution of nanoscale processes and science-based design of nanomaterials and nanosystems. The focus of R&D and applications is expected to shift toward more complex nanosystems and new areas of relevance such as bionanomanufacturing, food and agricultural systems, and cognitive technologies. This phase is expected to be dominated by an R&D ecosystem driven by socioeconomic considerations. Nanotechnology development will be rapid and uneven, with global implications for the economy, balance of forces, environment, sustainability, and public participation. Anticipatory, adaptive governance and risk forecast will be needed to address such changes in the global self-regulating system. Reversing the pyramid in education by earlier learning of general nanotechnology concepts in freshman and sophomore years will become reality in undergraduate education.

3.3.2 Nanotechnology: A Future General-Purpose Technology

Nanotechnology will continue its widespread penetration of specific methods, tools, and materials into the economy as a general-purpose technology, which—as with prior technologies such as electricity or computing—is likely to have mass and far-reaching applications across many sectors. For example, nanoelectronics including nanomagnetics has a pathway to devices (including logic transistors and memory devices) with feature sizes below 10 nm and is opening doors to a whole host of innovations, including replacing electron charge as the sole information carrier and integrating nanoelectronics with specific applications. Many other vital industries will experience evolutionary, incremental nanotechnology-based improvements in combination with revolutionary, breakthrough solutions that drive new product innovations.

By 2020, there is potential to incorporate nanotechnology-enabled products and services into almost all industrial sectors and medical fields. Resulting benefits will include increased productivity and more sustainable development. New applications expected to emerge in the next decade range from low-cost photovoltaic devices (after about 2015), to affordable high-performance batteries enabling electric cars, to novel computing systems, cognitive technologies, and radical new approaches to diagnosis and treatment of diseases like cancer. As nanotechnology grows in a broader context, it will enable creation or advancements in new areas of research such as synthetic biology, cost-effective carbon capture, quantum information systems, neuromorphic engineering, geoenvironmenting using nanoparticles, and other emerging and converging technologies.

Nanotechnology developments in the next decade will allow systematic design and manufacturing of nanotechnology products from basic principles, through a move toward simulation-based design strategies that use an increasing amount of fundamental science in application-driven R&D, as defined in the Pasteur quadrant (Stokes, 1997).
3.4 Nanotechnology Areas with Major Impact by 2020

Emerging and traditional industries will be affected. Medical and sustainable development issues will dominate civilian programs. New topics such as individualized learning, bringing machines closer to humans, and cultural aspects will be addressed. Examples of nanotechnology drivers for 2020 are

- Things not possible now such as materials and nanosystems by design; artificial blood and organs; combined electronics, photonics, and magnetics; energy generation from motion in vivo; and treating chronic diseases based on molecular approaches
- Things that become economic: solar conversion, electric cars, and general manufacturing platforms (carbon-based, DNA-based, coating-based, nanosensor-based, etc.)
- Mass use of products such as nanostructured catalysts, transistors, therapeutics drugs, and diagnostics methods

Three NNI programs starting in 2011 on nanoelectronics, solar energy conversion and storage, and sustainable nanomanufacturing are examples of R&D activities supporting such drivers.

3.4.1 Projecting a 10-Fold Increase in Nanoenabled Final Product Market over the Next 10 Years

Industries with largest applications will continue to be nanostructured chemicals (and especially catalysts), communication and information equipment, advanced structural nanomaterials, and pharmaceuticals. Other nanoenabled emerging areas of application with large rates of increase include biomedical equipment, energy and water resources, environmental improvement and safety, food and agricultural systems, forestry, hierarchical molecular manufacturing, and cognitive technologies. Current developments presage a burgeoning economic impact: trends suggest that the number of nanotechnology products and workers worldwide will double every 3 years, achieving a $1 trillion market and two million workers by 2015 and $3 trillion market and six million workers by 2020. This would correspond to a continuation of the annual growth rate of 25% corresponding to a 100-fold increase in 20 years (from 2000 to 2020). Nanotechnology R&D has become a socioeconomic target in all developed countries and in many developing countries—an area of intense international collaboration and competition.

3.4.2 Complete Penetration of Nanotechnology in Semiconductor and Electronics Manufacturers by 2020

Currently, all major companies producing semiconductors or memory components are in a race to introduce nanotechnology to remain competitive, reflecting a tendency in all technologies dealing with materials and biosystems. Because nanotechnology components initially entered the semiconductor industry via improving CMOS, and those companies continue their microfabrication product lines, the perception has been divided. Once significantly improved performance of CMOS due to nanocomponents is proved and new paradigms for logic, memory, and transmission of information are introduced using nanosystems—leading to products not available before—the perception that semiconductor and electronics manufacturers are not involved in nanotechnology will change definitively.

Semiconductors had an annual world production of $300 billion in 2010 (of which 30% is the nanoscale range) and expect 8% increase per year. About 50% of semiconductors business is owned by U.S. companies of which 75% produced in the United States. Penetration of nanotechnology in U.S. semiconductors industry is estimated to be 100% by 2020. Among indirect benefits mentioned by the semiconductors industry, one may include reducing inflation about 1% per year and increased societal productivity.
3.4.3 Nanomanufacturing Is Coming of Age

Nanomanufacturing is an opportunity to add high added-value and high-paying jobs to the economy. There are two main drivers that will be reinforced as we advance into nanotechnology’s second decade: creating products and services that were not possible before and more efficiently using materials, energy, environment, and labor. The opportunities in the United States are particularly for the more sophisticated, new generations of nanotechnology products. The investment should focus on areas where there is capacity for assimilation in the U.S. economy, such as highly automated systems, distributed energy conversion and storage, nanobiotechnology, nanomedicine, integration with other emerging fields, and using specific infrastructure.

A condition for the United States achieving prominence in nanomanufacturing is focused R&D and support for continuing processes from discovery to innovation and commercialization at the national level. NSF has supported a funding program in nanomanufacturing since 2002 and the National Nanomanufacturing Network since 2006. Significantly larger efforts by industry, states, and federal government are needed.

Another essential condition is the preparation of the workforce. Since 2001, NSF has supported a series of nanotechnology education activities including individual and group awards, the Nanotechnology Undergraduate Education (NUE) program and the Network for Computational Nanotechnology (NCN), the Nanotechnology Center for Learning and Teaching (NCLT) for multidisciplinary “horizontal” and K-Graduate “vertical” integration of formal education, Nanoscale Informal Science Education (NISE), the National Nanotechnology Infrastructure Network (NNIN) with education components, and Technological/Community College Nanotechnology education in NACK, among other awards.

A main challenge now is to disseminate the results partly via Department of Education and Department of Labor to local school and job training systems. Another main challenge is to institutionalize the programs (like it was done for information technology) to ensure cross-disciplinarity, continuity of educational activities, and long-term impact.

Yet another challenge is to use the research results in U.S. industry, and here various national and international governance aspects need to be addressed. A main intellectual driver since 2000 has been the long view of nanotechnology development formulated in the Nano 2010 report that supported the grand challenge on nanomanufacturing since 2002. The recent Nano 2020 report provides a continuation of that vision for nanomanufacturing development (see Chapters 3 and 13). The report encourages support of precompetitive nanoscale science and engineering R&D platforms, system application platforms, private-public consortia, and networks in areas such as health, energy, manufacturing tools, commercialization, sustainability, and nanotechnology EHS and ELSI. The platforms will ensure a “continuing” link between nanoscale fundamental research and applications across disciplines and sectors.

Major industry involvement after 2002–2003 is an assurance for capturing the opportunities. For example, more than 5400 U.S. companies had papers, patents, and/or products in 2008, and Moore’s law has continued for the past 10 years, despite serious doubts raised in 2000 about the trend being able to continue into the nanoscale regime. The establishment of the NanoBusiness Alliance in 2001 was an earlier sign of industry interest.

3.4.4 Qualitative Change in Nanotech due to Direct Measurement Capabilities

Instead of years of indirect measurements and deductive results (measurements based on time and volume averaging approaches mostly on surfaces), one can obtain immediately a realistic picture by a direct measurement. Direct measurements with atomic precision and time resolution of chemical/self-assembling reactions in the biological or engineering domains will open the opportunity to understand and optimize the nanoscale phenomena and processes to help combinatorial methods
and system design. Typical chemical reactions and atomic/molecular assembling processes need femtosecond resolution. The first such measurements for a collection of atoms were performed in 2009.

### 3.4.5 Nanotechnology EHS Evolving in Coming Years

Nanotechnology EHS as we move into the second foundational phase of nanotechnology needs to be addressed on an accelerated path as an integral part of the general physico-chemical-biological research program and as a condition of application of the new technology. Knowledge is needed not only for the first generation but also for the new generation of active nanostructures and nanosystems. As we discussed earlier, in about 2010, nanoscale science and engineering had begun a change of focus in both R&D and outputs. We are transitioning from empirical synthesis of nanoscale components to be incorporated into and improve existing products to science-based creation of new nanosystems for fundamentally new products. We need to emplace new principles and organizations for risk governance of new generations of nanotechnology products and processes with increased complexity, dynamics, biology contents, and uncertainty. There is a need for using nanoinformatics and computational science prediction tools to develop a cross-disciplinary, cross-sector information system for nanotechnology materials, devices, tools, and processes. A focus on nanotechnology EHS hazards and ELSI concerns must be routinely integrated into mainstream nanotechnology research and production activities to support safer and more equitable progress of existing and future nanotechnology generations.

The report *Nano 2020* provides the outcomes in nanotechnology EHS and ELSI after the first 10 years of development and research directions on how to prepare for safe and ethical use of nanotechnology in the next 10 years.

### 3.5 International Perspective

#### 3.5.1 Accelerated and Uneven Growth

The growth rate in investments and of number of publications is higher in several countries abroad, particularly after 2005, and the crisis of 2009 affected the United States more than the average of other countries. The United States maintains the lead in overall quality of papers and in patents, as well as in the number of companies involved and the market. This position will be challenged in the future by the EU, China, South Korea, Russia, as well as other countries for specific subfields of nanotechnology. The United States needs to continue to collaborate, compete, remain in the center of international exchanges, and develop mutually beneficial activities. All countries urgently need to better coordinate standards, nanotechnology EHS and ELSI research, regulations, and sustainable development policies.

International development is rapid and uneven among countries and regions as described in detail in the *Nano 2020* report. The report provides the international government investments per region, as well as for companies and venture funding. The worldwide increases in the number of Science Citation Index papers and patent publication over the past 10 years (2000–2010) have average annual increases of 16% and 33%, respectively.

While most countries generally follow the nanotechnology and converging technologies concepts initially advanced in the *Nano 1* report, there are several differences. The U.S. NNI, for illustration, was focused more on creating a public scientific and engineering foundation for a general-purpose technology. Other countries have dedicated more funds for applications, and information exchange has been more limited in those areas. Balanced exchange of information and collaborations based on mutual interest is essential for rapid nanotechnology development. In another example, several regulatory agencies in the EU and United States have proposed in 2010, after 10 years of community use of multidisciplinary nanotechnology definition based on distinct physico-chemical-biological behavior at the nanoscale, to extend the definition of nanoparticles for their own use to 1–999 nm beyond the initially defined nanoscale domain of about 1–100 nm.
3.6 Concluding Remarks

3.6.1 Main Challenges for Nanotech and the Nanotech Community over the Next Decade

A lot of progress has been made in the last 10 years. And yet, nanoscale science, engineering, and technology are still in a formative stage, with most of their growth potential ahead and in still-emerging directions. We cannot yet do direct measurement at the nanoscale, build by computational design for a given function, or even understand the spatial–temporal complexity of a general nanosystem.

There is a need for continued, focused investment in theory, direct measurement, and simulation at the nanoscale. We need to promote focused R&D and education programs, such as “signature initiatives,” “grand challenges,” nanotechnology platforms with multiple application areas, education and training regional “hubs,” and other kinds of dedicated funding programs, to support the development of measuring and production tools, manufacturing capabilities in critical R&D areas, and a nanotechnology-adapted innovation ecosystem.

Ambitious scientific and technical goals remain over the next decade, including

a. Integration of knowledge at the nanoscale and of nanocomponents in nanosystems with deterministic and complex behavior, aiming toward creating fundamentally new products

b. Better control of molecular self-assembly, quantum behavior, creation of new molecules, and interaction of nanostructures with external fields in order to build materials, devices, and systems by modeling and computational design

c. Understanding of biological processes and of nano–bio interfaces with abiotic materials, their biomedical and health/safety applications, and nanotechnology solutions for sustainable natural resources and nanomanufacturing

Anticipatory and adaptive governance is needed for increasing innovation and public–private partnerships; oversight of nanotechnology safety and equity building on nascent models for addressing EHS, ELSI, multistakeholder, and public participation; and international collaborations in the process of transitioning to new generations of nanotechnology products. Sustained support for education, workforce preparation, and infrastructure all remain pressing needs. A potential risk is the pressure on funding nanoscale R&D for long-term societal benefits in a period of budget deficits. Another risk is not generalizing program and organizational changes by preserving topical stoves in research and education.

3.6.2 Looking Forward

Nanotechnology is recognized today along with information technology and biotechnology as a mega-trend in science and engineering. In the coming decade, one expects nanotechnology commercialization to become a powerful driver of innovation and job and wealth creation in the global economy. Already, the R&D pull of industry has grown significantly around 2010, especially for nanodevices and nanosystems in addition to nanomaterials.

Partnerships between industry, academia, NGOs, multiple research and regulatory agencies, and international organizations need increased attention. Priority should be given to support R&D platforms and creation of additional regional “nano-hubs” for R&D, system-oriented academic centers, earlier nanotechnology education, nanomanufacturing, and nanotechnology EHS and ELSI. We need to promote global coordination to develop and maintain viable international standards, cross-sector nomenclatures and databases, and patents and other intellectual property protections. We should seek international coordination for nanotechnology EHS activities.
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(such as safety testing and risk assessment and mitigation) and nanotechnology ELSI activities (such as broadening public participation and addressing the gaps between developing and developed countries). An international cofunding mechanism is envisioned for maintaining databases, nomenclature, standards, and patents. Another priority is the development of experimental and predictive methods for exposure and toxicity to multiple nanostructured compounds analogous as they are encountered in the environment. A further challenge is support for horizontal, vertical, and system integration in nanotechnology education, to create or expand regional centers for learning and research, and to institutionalize nanoscience and nanoengineering educational concepts for K-16 students. Furthermore, we need to explore new strategies for mass dissemination, public awareness, and participation related to nanotechnology R&D, breaking through gender, income, and ethnicity barriers. This is a great challenge in the next 10 years.

As nanotechnology applications are expected to satisfy essential societal needs in production, medicine, education, defense, and overall economy, an overarching challenge is to institutionalize the nanotechnology in R&D, education, manufacturing, medicine, EHS, and ELSI programs. Experts from 35 countries document this need in the comprehensive Nano 2 report.

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