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Overview: Affirmation of Nanotechnology between 2000 and 2030

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1.1 Introduction

In the nanoscale domain, nature transitions from the fixed physical behavior of a finite number of atoms to an almost infinite range of physical–chemical–biological behaviors of collections of atoms and molecules. The fundamental properties and functions of all natural and man-made materials are defined and can be modified efficiently at that scale. The unifying definition of nanotechnology, based on specific behavior at the nanoscale and the long-term nanotechnology research and education vision, was formulated in 1997–1999, and its implementation begun with National Nanotechnology Initiative (NNI) in 2000. We have estimated that it would take about three decades to advance from a scientific curiosity in 2000 to a science-based general purpose technology with broad societal benefits toward 2030 [1–3] (see www.wtec.org/nano2/).

A long-term strategic view is needed because nanotechnology is a foundational general purpose field. *Three development stages* of nanotechnology, corresponding to the level of complexity of typical outcomes, have been envisioned: passive and active nanostructures in the first stage of development (*Nano 1*), nanosystems and molecular nanosystems in the second stage (*Nano 2*), and converging technology platforms and distributed interconnected nanosystems in the last stage (*Nano 3*).

We use the *definition of nanotechnology* as set out in *Nanotechnology Research Directions* [2]. Nanotechnology is the ability to control and restructure matter at the atomic and molecular levels in the range of approximately 1–100 nm, and exploiting the distinct properties and phenomena at that scale as compared to those associated with single atoms or bulk behavior. The aim is to create materials, devices, and systems with fundamentally new properties

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and functions for novel applications by engineering their small structure. This is the ultimate frontier to economically change materials and systems properties, and the most efficient length scale for manufacturing and molecular medicine. The same principles and tools are applicable to different areas of relevance and may help establish a unifying platform for science, engineering, and technology at the nanoscale. The transition from the behavior of single atoms or molecules to collective behavior of atomic and molecular assemblies is encountered in nature, and nanotechnology exploits this natural threshold.

This chapter describes the timeline and affirmation of nanotechnology, its three stages, key challenges, and discusses nanotechnology return on investment.

1.2 Nanotechnology – A Foundational Megatrend in Science and Engineering

Nanotechnology is a foundational, general purpose technology for all sectors of the economy dealing with matter and biosystems, as information technology is a general purpose technology for communication and computation. Biotechnology and cognitive technologies are two other foundational technologies growing at the beginning of the twenty-first century (Figure 1.1). Table 1.1

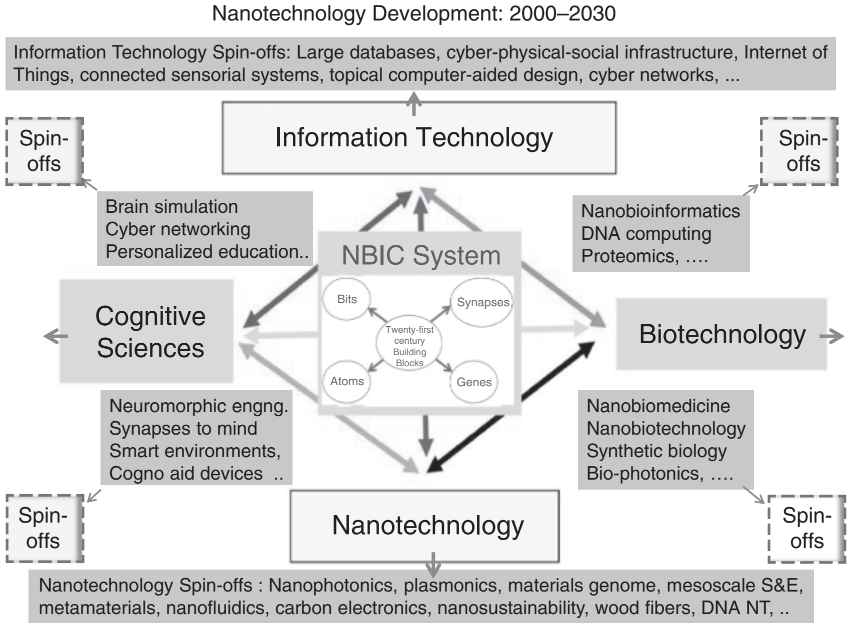


Figure 1.1 Converging foundational technologies, and their interdisciplinary and spin-offs subfields. Modified from Roco and Bainbridge [4].

Table 1.1 Proposed classification of science and technology platforms.

Category	**I. *Foundational* S&T platform (system architecture)**	**II. *Topical* S&T platform (hierarchical system from I)**	**III. *Application field* platform (branched, inter- and recombination)**	**IV. *Product and service* platform (spin-off, inter- and recombination)**
S&T Platforms	• **Nanotechnology**: (atom architecture) • **Information S&T** (bit architecture) • **Modern bio S&T** (gene architecture) • **Cognitive S&T** (synapsis architecture) • **Artificial Intelligence S&T** (system design)	***Essential:*** Photonics Semiconductors Genomics Biomedicine ***Contributing:*** Synthetic biology Neuromorphic eng Proteomics Nanofluidics Metamaterials	Cell phone system Transportation Medicine Energy conversion and storage Agriculture Space exploration	Car components Medical devices Nano coatings LEDs Nano lasers ....
Typical timescales	25–50 years	10–25 years	5–10 years	3–5 years
One-step investment amplification factor	$k_{f\text{(undamental)}}$	$k_{t\text{(opical)}}$	$k_{a\text{(pplication)}}$	$k_{p\text{(product and service)}}$
Cumulative investment amplification factor	$k_f\, k_t\, k_a\, k_p$	$k_t\, k_a\, k_p$	$k_a\, k_p$	k_p
Game changer for:	Knowledge	Technology approach	Application field	User consumption

shows several category levels of science and technology (S&T) platforms according to their level of generality and societal impact: foundational S&T, topical S&T, application domain, and product/service platform. While there are only five foundational S&T platforms most dynamic at this moment (Figure 1.1), the number of topical S&T platforms increases with the number of spin-offs, interplatform and further recombination growth. Each topical S&T platform has several application domains, which at their turn each have a series of products and related services. The importance of foundational platforms – and in particular its most exploratory component part at this moment, nanotechnology – is underlined by the cumulative investment amplification factor by developing the respective S&T platform that is a product of the foundational platform investment amplification factor, with the topical, application area and product amplification factors.

Nanotechnology continues exponential growth by vertical science-to-technology transition, horizontal expansion to areas as agriculture/textiles/cement, and spin-off areas (~20) as spintronics/metamaterials/…, progressively penetrating in key economic sectors. The number of World of Science publications on nano-extended 20 new terms between 1990 and 2014 that now represent over ¼ of the total publications (Figure 1.2). For this reason, it is increasingly difficult to identify the R&D programs around the word supporting nanotechnology because they are called after an activity that

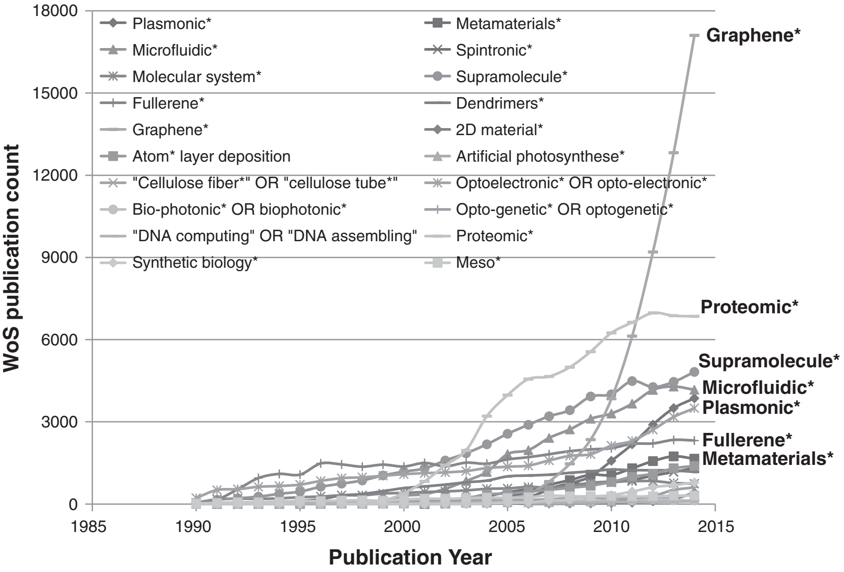


Figure 1.2 The number of World of Science (WoS) publications on nano-extended 20 new terms between 1990 and 2014.

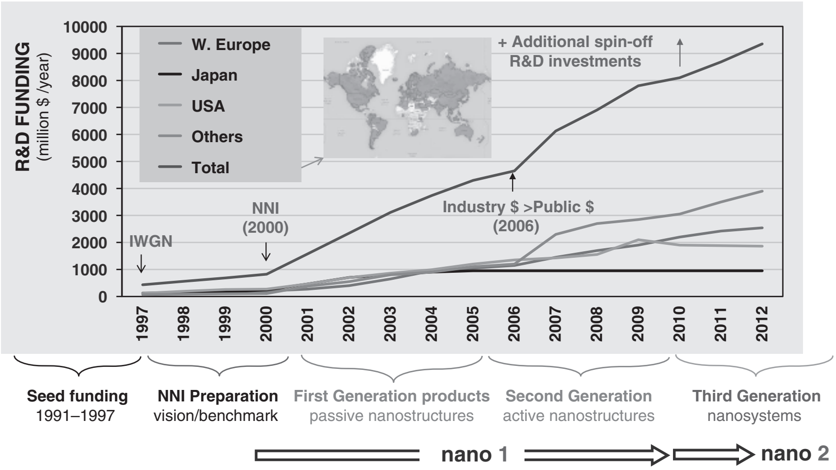


Figure 1.3 International government R&D funding the interval 2000–2012, after 2013 – increase use of new terms and platforms (using NNI definition, 81 countries, MCR direct contacts).

branched out of the foundational field. Figure 1.3 illustrates international government R&D funding the interval 2000–2012 [9].

Most of the larger science and technology initiatives have been justified in the United States and abroad mainly by application-related and societal factors. For example, the Manhattan Project during World War II (with centralized, goal-focused, and simultaneous approaches), the Apollo Space Project (with a centralized, focused goal), and Networking and Information Technology Research and Development (top-down initiated and managed, and established when mass applications justified the return of investment). The initiation of the NNI was motivated primarily by its long-term science and engineering goals and general purpose technology opportunity, and has been managed using a bottom-up approach combined with centralized coordination. A few comments underlying this characteristic are as follows:

> Charles Vest, President National Academy of Engineering (PCAST meeting, White House, 2005): "*NNI is a new way to run an initiative*"
>
> Steve Edwards, "Hall of Fame for Nanoscale Science and Engineering" (Jan. 1, 2006): "*…persuading the U.S. government, not to mention the rest of the world, to support nanotechnology. It was a masterful job of engineering the future*"
>
> Tim [5], President of the European Nanobusiness Association, and Cientifica Co. (2015): "*nanotechnology [is] the first truly global scientific revolution.*"

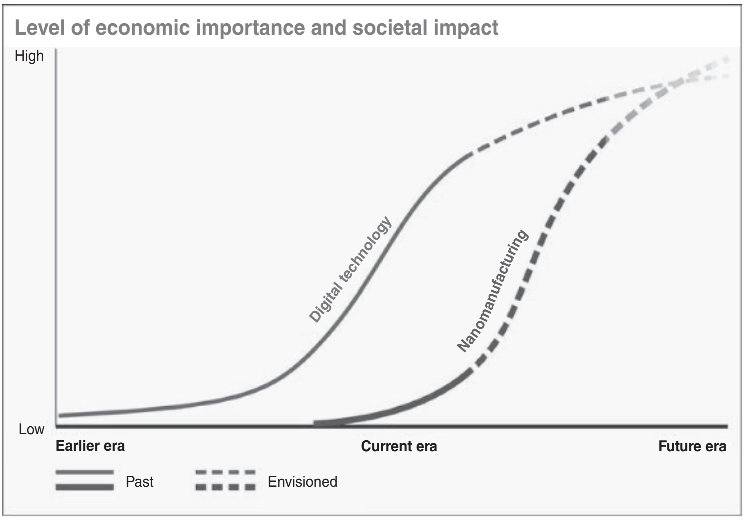


Figure 1.4 S-curves for two science and technology megatrends: past and envisioned conceptualization of "Nanomanufacturing" and "Digital Technology" [6].

Nanotechnology promises to become a general purpose technology with large-scale applications similar to digital technology. It could eventually match or outstrip the digital revolution in terms of economic importance and societal impact once the methods of investigation and manufacturing are developed and the underlying education and infrastructure are established. During about 2020–2030, nanotechnology could equal and even exceed the digital revolution in terms of technology breakthroughs, investments, and societal importance (Figure 1.4) [6].

The nanotechnology development S-curve shown in Figure 1.4 is supported by the data in Table 1.2 showing an increase of the world annual rate of revenues growth from 25% in 2000–2010 to 44% in 2010–2013.

Examples of S&E generic platforms with areas of high impact

Nanotechnology-enabled products by sectors with the most traded nanoproducts in 2014 according to Lux Research [7] and other industry sources:

- Materials and manufacturing: Fiber-reinforced plastics, nanoparticle catalysts, coatings, insulation, filtration, transportation (cars, trucks, trains, planes, and ships), and robotics (actuators and sensors). For example, Exxon-Mobil has multibillion dollar applications on nanostructured catalysts. TiO_2, MWCNTs, and quantum dots are some of the most frequently encountered nanocomponents. Nanoscale coatings, imprinting, and roll-to-roll are three most common manufacturing processes.

Table 1.2 Global and US revenues from products incorporating nanotechnology.

Revenues all in $ billions	2000	2010	Annual rate 2000–2010	2011	2012	2013	2014	Annual rate 2010–2013	Estimation 2020	Estimation 2030
World	30	335	***25%***	514	852	1190	1620	***48%***	*3000*	*30,000*
United States	13	110	***24%***	170	213	284	370	***38%***	*750*	*7,500*
United States/World	43%	33%	***−1%***	33%	25%	24%	23%	***−10%***	*25%*	*25%*

Source: Data from *Roco et al.* [1] for 2000–2010, est. 2020, and est. 2030; and from Lux Research [7] for 2011–2014.

- Electronics and IT: Semiconductors, mobile electronics and displays, packaging, thermal management, batteries, supercapacitors, paint, and integration with nanophotonics
- Healthcare and life sciences: Diagnostic and monitoring sensors (cancer), cosmetics, food products and packaging, personal care products, sunscreen, packaging, surgical tools, implantable medical devices, filtration, treatments (cancer radiation therapies) and medications formulations, contrast agents, quantum dots in lab supplies such as fluorescent antibodies, and drug delivery systems.
- Energy and environment: Fuel cells, hydrolysis, catalysts, solar cells, insulation, filtration, supercapacitors, grid storage, monitoring equipment (sensors), water treatment, and purification

Nanotechnology development between about 2000 and 2030 is an example of the *convergence–divergence process* for science and technology megatrends. The convergence process has four phases:

a) First is the "*creative phase*" (Figure 1.5). Confluence of knowledge of bottom-up and top-down disciplines, of various sectors from materials to medicine, and of various tools and methods of investigation and synthesis have led to an increasing control of matter at the nanoscale.
b) The convergence enables the creation/integration of successive generations of nanotechnology products and productive methods ("*Integration/fusion phase*").
c) At the beginning of the divergent stage, the spiral of innovation ("*Innovation phase*") leads to new products and applications that are estimated to reach $3 billion in 2020.
d) The spiral of innovation branches out thereafter into new activities, including spin-off disciplines and productive sectors, business models, expertise, and decision-making approaches ("*Spin-off phase*"). An essential element of progress is the emergence of completely new skills in nanotechnology, some of which have resulted from the interface with other fields and others resultant as a spin-off element of nanoscience, such as spintronics, plasmonics, metamaterials, carbon nanoelectronics, DNA nanotechnology, optogenetics, and molecular design to create hierarchical systems. New technology platforms will be created such as in nanosensors systems, components in robotics, nanoelectronics in cars, cyber manufacturing, unmanned vehicles, and light space crafts.

The exponential growth of nanotechnology through discoveries, technological transition, horizontal expansion, and its spin-off areas is expected to continue at high rates through 2030. The economic estimations currently made by

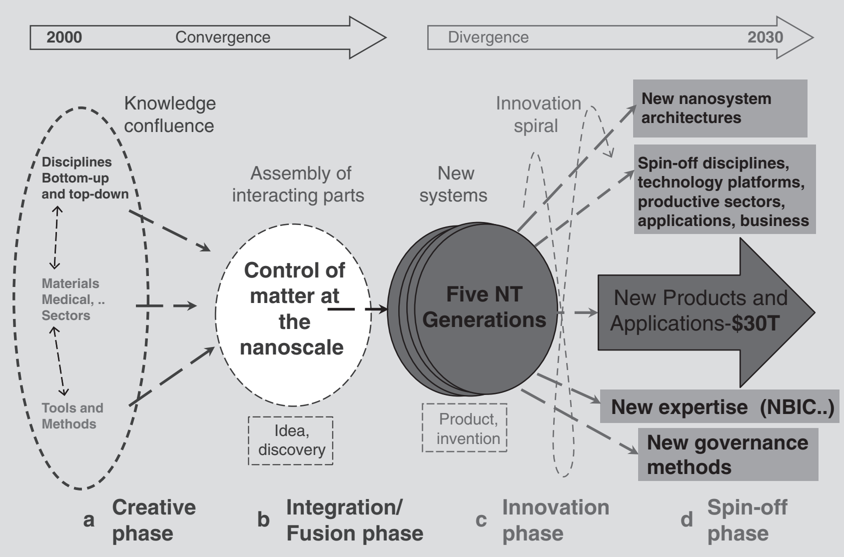


Figure 1.5 2000–2030 convergence–divergence cycle for global nanotechnology development. Modified from Roco and Bainbridge [4].

valuing the commercialization of particular products (e.g., single-wall carbon nanotube of single-sheet graphene) are not the most representative for effective products because the most valuable developments are the know-how and technological capabilities that are changing fast toward composite and modular nanosystems. This is particularly true if the material has mostly a "schooling" role ("model nanotechnology" vs "economic nanotechnology").

1.3 Three Stages for Establishing the New General Purpose Technology

We have estimated that about 30 years are needed for nanotechnology development from a scientific curiosity to mass use in economy that may be separated into three stages. Each stage is defined by its investigative methods and synthesis/assembling techniques, level of nanoscale integration and complexity of the respective products, typical application areas, education needs, and risk governance. These characteristics are documented in four reports (Figure 1.6). A schematic of the three successive stages and corresponding nanotechnology generation products are shown in Figure 1.7. Each stage differs by the types

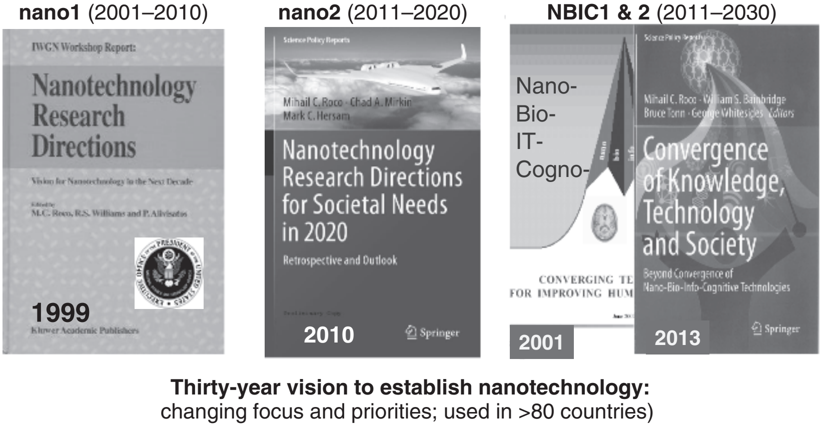


Figure 1.6 Thirty-year vision to establish nanotechnology: changing the research and education focus and priorities in three stages from scientific curiosity to immersion in socioeconomic projects [1–4]. The reports are available on www.wtec.org/nano2/ and www.wtec.org/NBIC2-report/.

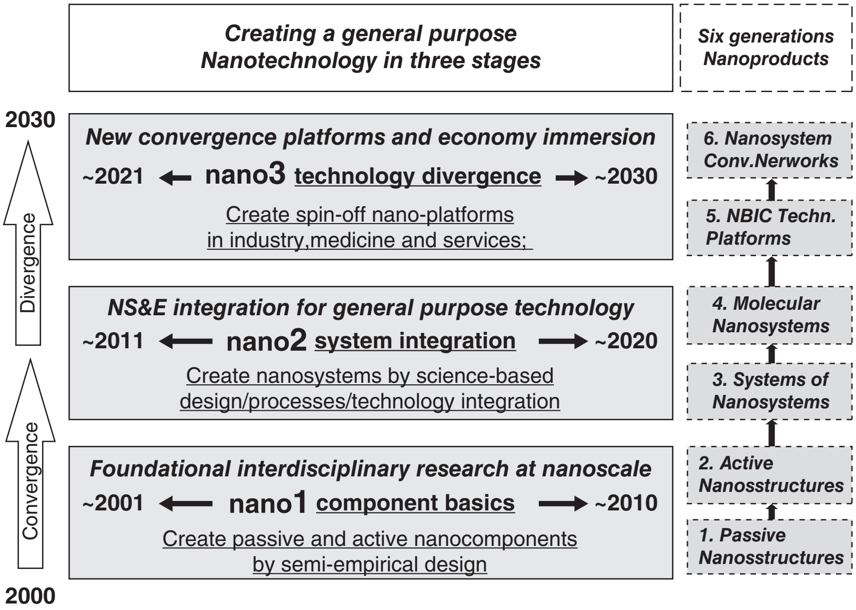


Figure 1.7 Creating a general purpose technology in three stages between 2000 and 2030. Each stage includes two generations of nanotechnology products. Modified from Roco *et al.* [1].

of new measurements and simulation methods, advanced processing/synthesis methods, integration and complexity levels, use and application, as well as risk governance [1].

The R&D focus in nanotechnology is evolving: from synthesizing components by semiempirical processing and creating a library of nanostructures (such as carbon nanotubes, quantum dots, and sheets of graphene) in 2000–2010, to science-based design and manufacturing of nanoscale devices and systems (such as in biomedicine and nanoelectronics) in 2010–2020, and establishing economic nanotechnology applications in various technology platforms and immersion in socioeconomic projects in 2020–2030.

The planning in **the first stage (*Nano 1*)** was focused on discovery of individual phenomena and semiempirical synthesis of nanoscale components. For example, quantum effect repulsion forces between surfaces at small interfaces have been identified, and the first quantum device was built. In another example, quantum dots, nanoparticles, nanotubes, and nanocoatings were created from a majority of elements in the periodic table, and their atom and molecular assembling mechanism explored for generalizations. Typical measurements of the atomic structure with femtosecond changes were indirect, using time and volume averaging. The nanocomponents were used to improve the performance of existing products, such as nanoparticle-reinforced polymers. The main penetration of nanotechnology was in advanced materials, nanostructured chemicals, electronics, and pharmaceutics. For example, Moore's Law for semiconductors has continued because of nanoscale components added in their fabrication. Education transitioned from fixed properties at the microscale to engineered properties based on the nanoscale understanding of nature and technology. Governance was mostly science-centric with a focus on nanotechnology environmental, health and safety aspects. National and international organizations have formulated the basics for nomenclature to be used in scientific publications and for standards classifications. An international, multidisciplinary nanoscale science and technology community has been established.

During **the second decade (*Nano 2*)** of nanotechnology development, the focus is on integration at the nanoscale and science-based creation of devices and systems for fundamentally new products – including self-powered nanodevices, self-assembling systems on multiple scales from the nanoscale, and nano-bio assemblies. Examples include nanofluidics systems, integrated sensorial systems, and nanoelectronics and display systems. Direct measurements and simulations with atomic and femtosecond resolutions have been undertaken for many-atom systems encountered in biological and engineering applications. There is an increased focus on new performance in new domains of application and on innovation methods. Nanotechnology penetration is faster in nanobiotechnology, energy resources, food and agriculture, forestry, and cognitive technologies, as well as in nanoscale simulation-based design methods. In education, we see more attention to cross-disciplinary "T" or "reverse T" learning including general nanotechnology education in the horizontal component. Societal aspects are increasingly on expanding sustainability, exploiting the potential for increased productivity and addressing socioeconomic issues with a focus on healthcare. Governance is increasingly user-centric and multiple player participatory. Global implications are seen on economy, sustainability, and balance of forces.

After 2010, there is an increased focus on nanoscale science and engineering integration with other knowledge and technology domains and their applications [3] that will continue through the end of **the third decade (*Nano 3*)** of nanotechnology development. After about 2000, convergence of nanotechnology with other key technologies will subsequently lead to bifurcation into emerging and integrated technology platforms. NBIC-based measurements will be needed in these new technology platforms. Integration of foundational and general technologies will branch out to new fields of research and production. Education will need to be more focused on unifying concepts and connecting phenomena, processes, and technologies. The role of bottom-up and horizontal interactions will increase in importance as compared to top-down measures in the S&T governance. The risk analysis will expand to hybrid bio-nano systems and human–technology coevolution. New competencies, socioeconomic platforms, and production capabilities will be taking a significant role in the economy. The international community will be more connected through the scientific and technological developments. It will create opportunities for new models of collaboration and competition.

New generations of nanotechnology products and productive processes are timed with the introduction of new prototypes of nanotechnology products and with the successive increases in the degree of control, integration, complexity, and risk. Table 1.3 defines the estimation for introduction of various generations along the three conceptual stages of nanotechnology development.

A dominant trend in the interval 2020–2030 is envisioned to be immersion of nanotechnology with other emerging and established technologies, in industry, medicine and services, and in education and training for societal progress to become the largest technology driver in most economical sectors together with information technology.

Priorities of the U.S. NNI at the beginning of *Nano 2* [1] were grouped and are funded under several "Nanotechnology Signature Initiatives (NSI)" since 2011: (i) Nanoelectronics for 2020 and Beyond; (ii) Sustainable Nanomanufacturing; (iii) Nanotechnology for Solar Energy; (iv) Nanotechnology Knowledge Infrastructure, and (v) Nanosensors. In 2016, the NSI on "Nanotechnology for Solar Energy" was completed and replaced by the NSI on "*Water Sustainability through Nanotechnology*" (www.nano.gov/node/1577). PCAST [8] has recommended for new set of grand challenges for Nano 2 looking 15 years ahead. The first has been dedicated to "*Nanotechnology-Inspired Grand Challenge*

Table 1.3 Generations of nanotechnology products and productive processes, and the corresponding interval for beginning commercial prototypes.

Stage	Generation	Main characteristics
Nano 1 *Component basics*	**G1:** **Passive nanostructures** (~2000–2005)	The nanostructures have stable behavior during their use. They typically are used to tailor macroscale properties and functions a) Dispersed nanostructures, such as aerosols, colloids, and quantum dots on surfaces b) Contact nanostructures, such as in nanocomposites, metals, polymers, ceramics, and coatings
	G2: **Active nanostructures** (~2005–2010)	The nanostructures change their composition and/or behavior during their use. They typically are integrated into microscale devices and systems and used for their biological, mechanical, electronic, magnetic, photonic, and other effects a) Bioactive with health effects, such as targeted drugs, biodevices, and artificial muscles b) Physico-chemical active, such as amplifiers, actuators, adaptive structures, and 3-D transistors
Nano 2 *System integration*	**G3:** **System of nanosystems** (~2010–2015)	Three-dimensional nanosystems frequently incorporated into other systems and using various syntheses and assembling techniques such as bio-assembling, robotics with emerging behavior, and evolutionary approaches. A key challenge is networking at the nanoscale and hierarchical architectures. Research focus will shift toward heterogeneous nanostructures and supramolecular system engineering. This includes directed multiscale self-assembling, artificial tissues and sensorial systems, quantum interactions within nanoscale systems, processing of information using photons or electron spin, and assemblies of nanoscale electromechanical systems (NEMS)

(Continued)

Table 1.3 (Continued)

Stage	Generation	Main characteristics
	G4: **Molecular nanosystems** (~2015–2020)	Heterogeneous molecular nanosystems, where each molecule in the nanosystem has a specific structure and plays a different role. Molecules will be used as devices and from their engineered structures and architectures will emerge fundamentally new functions. Designing new atomic and molecular assemblies is expected to increase in importance, including macromolecules "by design", nanoscale machines, and directed and multiscale self-assembling, exploiting quantum control, nanosystem biology for healthcare, and human–machine interface at the tissue and nervous system level. Research will include topics such as atomic manipulation for design of molecules and supramolecular systems, controlled interaction between light and matter with relevance to energy conversion among others, exploiting quantum control mechanical–chemical molecular processes, nanosystem biology for healthcare and agricultural systems, and human–machine interface at the tissue and nervous system level
Nano 3 *Technology divergence*	**G5: NBIC integrated technology platforms** (~2020–2025)	Converging technology platforms from the nanoscale based on new nanosystem architectures at confluence with other foundational emerging technologies. This includes converging foundational technologies (nano-bio-info-cogno) platforms integrated from the nanoscale
	G6: **Nanosystem convergence networks** (~2025–2030)	Distributed and interconnected nanosystem networks, across domains and interacting at various levels (foundational, topical, application, products/service), for health, production, infrastructure, and services. This includes networks of foundational technologies (nano-bio-info-cogno) platforms and their spin-offs including for emerging nano-biosystems

for Future Computing" (http://www.nano.gov/grandchallenges). A focus in 2011–2020 is research on the third generation of nanotechnology products including nanosystems, self-powered nanodevices, and nano-bio assemblies. There is an increased focus on nanoscale science and engineering integration with other knowledge and technology domains to create new nanosystem architectures and corresponding technology platforms by 2030 ("Converging knowledge, technology and Society: Beyond Nano-Bio-Info-Cognitive Technologies" [3]).

1.4 Several Challenges for Nanotechnology Development

Several key challenges for nanotechnology development in the next 15 years are identifying and realizing:

- *Path to new technological platforms.* Identifying and supporting technology platforms exploiting the main features at the nanoscale such as self-assembling, quantum materials and devices, nanofluidics fluid-based manufacturing, new logic and memory paradigms, nanophotonics, and plasmonics.
- *Path to economicity*. Increasing productivity and economical production are the main reasons for advancing the tools of nanoscale science and engineering. In the first stage, the challenge was to prove the ability to create and change nanostructures by control no matter the cost or sustainability. Now, we increasingly aim at minimizing the cost and resources. For example, a general approach is nanomodular materials and systems by design that would allow efficient assembling of nanomodules that individually maintain their nano-specific properties [9]. The purpose is to build economical and versatile products at relatively low temperatures and pressures, as well as to create things that are not possible otherwise such as nanosensors systems and synthetic organs.
- *Path to sustainability.* An initial goal of nanotechnology has been manufacturing using less materials, energy, and water while reducing the waste. An approach was leaving the molecules to do what "they like," such as self-assembling at low temperature and pressures using noncovalent molecular interactions. This may be associated with the term green nanomanufacturing. Another goal was to develop new methods for efficient energy conversion and storage, economic filtration, and computing, to name several important pathways to sustainable society.
- *Path to creativity, inventions, and innovations in nanotechnology applications.* Because nanoscale science and engineering is at the confluence of multiple disciplines and methods and there are multiple application areas including by convergence with other technologies, there is a good potential for

innovation. For example, the technology and business branching out in the nanotechnology convergence–divergence cycle created multiple opportunities for value add, such as nano-biomedical devices and synthetic biology, nanosensors for medical and industrial use, and nanotechnology for robotics and autonomous vehicles.

- *Path to wellness.* Nanotechnology enables replacing clinical medicine with individual treatment based on conditioning the cell at the subcellular level, and treating chronic diseases with molecular medicine. Physical and mental wellness is at the core of quality of life.
- *Path to almost zero-power internet of things.* The connectivity between efficient logic and memory devices, sensors, robotics, and distributed energy harvesting enabled by nanotechnology
- *Path to a comprehensive, flexible, and connected infrastructure* responding to the requirements of the three nanotechnology stages (Figure 1.7). Examples of the connected R&D infrastructure in the United States in 2015 are shown in Table 1.4.
- *Path to responsible governance and public acceptance.* There is an increased role of ethical, legal, and other social issue (ELSI) and of emergent nano-biosystems, nano-neurotechnology, and overall converging technologies effects.
- *Nanotechnology growth potential in the future.* It depends on setting the proper vision and goals, planning R&D to reach the vision, and assuring R&D funding under public scrutiny, and competition with other sectors and other economies.

1.5 About the Return on Investment

Foundational science and technology fields have a larger impact as compared to topical technologies they generate, but need longer time to be developed and implemented. *Nanotechnology is a foundational technology with implications on knowledge, productivity, health, sustainability, security, and overall wellness that is establishing its methods, transformative approach, and infrastructure between about 2000 and 2030.*

Still in its infancy in creating novel nanosystems, nanotechnology in 2015 has already shown its promise to society. The United States invested about $20 billion in nanotechnology R&D through the NNI in the fiscal years 2001–2015. The cumulative US nanotechnology commitment since 2000 places the NNI second only to the space program in terms of civilian science and technology investment [10]. Overall, it has been estimated that NNI spent about one fourth of the global government funding since 2001.

Table 1.4 Examples of main NNI R&D centers, user facilities, and networks sponsored by NSF.

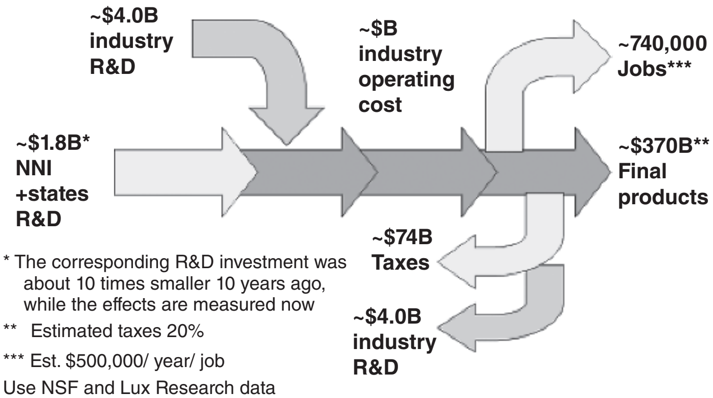
Name	Institution(s)
NSF – 10 Networks	
National Nanofabrication Infrastructure Network (NNIN) – 15 nodes (user facilities) (www.nnin.org)	Cornell University – main node (NNIN recompetition in 2015)
National Nanotechnology Coordinated Infrastructure (NNCI) after September 2015 – 16 nodes	
National Nanofabrication Infrastructure Network (NNIN) – 15 nodes (user facilities) (www.nnin.org)	Cornell University – main node (under recompetition in 2013–2014)
Network for Computational Nanotechnology (NCN) (nanoHUB.org)	Purdue University – main node
National Nanomanufacturing Network (NNN) (www.internano.org)	University of Massachusetts, Amherst – main node
Centers for Nanotechnology in Society (CNS) (cns.asu.edu)	Arizona State University and University of California, San Diego
Nanoscale Informal Science Education (NISE) Network (www.nisenet.org)	Museum of Science, Boston – main node
Nanoscale Science and Engineering Centers (NSEC)	Distributed centers
Materials Science and Engineering Centers (MRSECs)	Distributed centers
Nanosystems Engineering Research Centers (NERC)	Distributed centers
Centers for the Environmental Implications of Nanotechnology (CEIN) (www.cein.ucla.edu)	University of California, Los Angeles, and Duke University
Center for National Nanotechnology Applications and Career Knowledge (NACK) (nano4me.org)	Pennsylvania State University
NSF – Three Science and Technology Centers	
Center for Energy Efficient Electronics Science (nanoelectronics) (www.e3s-center.org)	University of California, Berkeley
Emergent Behaviors of Integrated Cellular Systems (nanobiotechnology) (hhttp://ebics.net/about)	Massachusetts Institute of Technology
Center for Integrated Quantum Materials (ciqm.harvard.edu)	Harvard University

One successful case study at the beginning of the NNI about 2000 was for giant magnetic resonance (GMR) that brought a significant performance improvement in computer hard disks and had an annual economic impact of few billions dollars.

An estimation about the long-term impact of nanotechnology was presented in September 2000 during the review of NNI and published in 2001 [4]. The estimation was based on consultation with experts and technical executives in industry in 10 sectors. The level of penetration of nanotechnology was estimated in each sector per group of products and then multiplied by the total production levels. The findings lead to the overall conclusion that nanotechnology will bring revenues of about $1 trillion by 2015 increasing with an annual rate of about 25%. In 2004, Lux Research adopted a similar approach of evaluation using direct surveys in industrial units. The respective survey data on past intervals have a good international database and were used for comparison. Other topical studies on market size based on the collection of information from a single sector and partial databases have been less useful for comparison.

In 2014, the US annual public R&D investment (from federal, state, and local sources) has been estimated to about $1.8 billion while the private investment was about $4.0 billion [7]. In 2013, in the United States alone, according to the same industry surveys, there are more than about $370 billion in revenues from products incorporating nanotechnology as a key functional and competitive component. In several areas, nanotechnology has become a large part of the market. For example, around 60% of semiconductors and over 40% of manufactured catalysts have some form of nanotechnology involved. The technology has also shown a footprint in emerging research, with approximately 70% of energy-related proposals submitted to National Science Foundation having a basis in nanotechnology. The numbers are significant considering the variety of proposals and ideas. If we consider that for each $0.5 million annual production is needed a nanotechnology worker, then this would require about 740,000 nanotechnology jobs (Figure 1.8). The revenues from products incorporating nanotechnology are about 150 (~318/2.1) times larger than public R&D funding in 2013 that have catalyzed such output. The *investment amplification factors* from foundational nanotechnology to the topical technologies and then to application technology platforms leading to final product and service delivery (Table 1.1) support such a large return.

Nanotechnology is rapidly growing in a field still in formation, at the beginning of the S curve of development (Figure 1.4). Only relatively simple nanostructures are found in applications, such as nanolayers in semiconductor industry and coatings, dispersions in catalyst industry and paints, and nanomodules with surface molecular recognition for targeted medical therapeutics, to name a few. Despite the fact that nanotechnology is still in the formative phase of development, if one would consider an average tax of 20% and apply this to about $318 billion US market incorporating nanotechnology in 2013, the result would be



* The corresponding R&D investment was about 10 times smaller 10 years ago, while the effects are measured now

** Estimated taxes 20%

*** Est. $500,000/ year/ job

Use NSF and Lux Research data

Figure 1.8 The flow of nanotechnology R&D investments and outcomes in the United States in 2014. Roco 2016; updated data and Figure 1.4 from Roco *et al.* [1].

$64 billion in tax revenue in 1 year (2013) that exceeds the total 13 year R&D investment of NNI by a factor of almost four.

The revenues from products incorporating nanotechnology in the world based on direct survey in industry [7] have reached $1014 billion in 2013, with 31.8% of this amount in Europe, 31.3% in the United States, 30.5% in Asia, and 6.4% in the rest of the world. The main sectors identified in the survey are materials and manufacturing with 59%, electronics and information technology with 29%, healthcare and life sciences with 10%, and energy and environment with 2%.

Key long-term qualitative and quantitative targets set up in 2000 for this interval have been realized and even some exceeded such as in memory devices, nanoelectronics, molecular detection of cancer, and market impact. Several illustrations are as follows:

- In his presentation made on January 21, 2000, at Caltech, President Clinton stated in his announcement of NNI [11]: “Just imagine materials with 10 times the strength of steel and only a fraction of the weight; shrinking all the information at the Library of Congress into a device the size of a sugar cube; detecting cancerous tumors that are only a few cells in size. Some of these research goals will take 20 or more years to achieve. But that is why – precisely why – ….there is such a critical role for the federal government.” All these targets are currently more advanced than initially envisioned with significant progress on structural metals, foams and composites, creating addressable nanostructures for memory devices that go to 12 atoms and even one atom, and methods for targeted detection and treatment of cancer [1].

- The original report with a 10-year vision [2] recommended progress from fundamental concepts to applications in 10 sectors, and establishing a flexible infrastructure and education community. The progress reported after 10 years shows that a multidisciplinary community has been established using a suitable specialized infrastructure and the progress in various sectors generally has reached the core objectives [1]. The exploratory concepts outlined in the 1999 report are still valid. Nanotechnology as a foundational S&T field promised to branch out in various technology platforms. Large impact illustrations of the potential of nanotechnology with multibillion dollar revenues have been the applications GMR at the beginning of NNI 1998–000 (about $2 billion in direct production in 2000, R&D lead by IBM), targeted drug delivery (PHARMA), semiconductors (SRC), and nanostructured catalysts (Exxon-Mobil) [1]. The promise that nanotechnology will penetrate several key industries has been realized. Catalysis by engineered nanostructured materials impacts 30–40% of the US 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 US market (Chapter on Long View in Nano 2020 report); molecular medicine is a growing field, and only in 2010 about 15% of advanced diagnostics and therapeutics are 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.
- We have estimated that nanotechnology funding and production will grow by about 25% in the first 10 years after 2000. Global nanotechnology development has shown significant and consistent increases by high annual rates from 2000 to 2013 of about 25% for primary workforce (about 600,000 in 2010) and market value of final products incorporating nanotechnology (about $300 billion in 2010). The nanotechnology labor and markets are estimated to continue to double every 3 years, reaching about $1 trillion market with 2 million jobs around 2015, and $3 trillion market encompassing 6 million jobs by about 2020. The rate of increase for venture capital investment is about 30% reaching about $1.3 billion in 2010. As shown earlier, in 2000, it was estimated that the products incorporating nanotechnology will bring world revenues of $1 trillion by 2015 [4]. The industry survey of Lux Research [7] has reported that this target has been realized in 2013.

The nanotechnology R&D investment has significant returns despite the relatively short term for fundamental discoveries of a foundational field in science and engineering to find the way to applications. Nanotechnology already has a major and lasting impact that promises to be more relevant for healthcare, environment, and manufacturing here on Earth than the Space program. The R&D

challenges for the future in establishing nanotechnology in the economy are the creation of science-based nanosystems, new nanosystem architectures for new technology platforms, emergence of nano-bio hybrid systems, and convergence with other foundational technologies for societal benefit. The nanotechnology revenues are estimated to reach about 5% of the Gross Domestic Product (GDP) in developed economies by 2020 and, respectively, over 10% of GDP by 2030.

Nanoscale science and engineering in the past 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 the 2020s in a similar manner as another general purpose technology – information technology – did in the 1990s.

R&D investments for various topical S&T platforms have been recognized to have significant returns in long term (with an average investment amplification factor for topical platforms of $k_t \sim 3$–5 times; Table 1.1) as they support creation and use of new products, services, and tools with higher efficiency. Nanoscale science and engineering, like information and communication technology, is a foundational, general purpose technology that supports the topical S&T platforms. By assuming a similar fractal effect in improving basic methods and tools in foundation and topical platforms ($k_f \sim k_t$), then the cumulative return on investment may be roughly estimated as being ($k_f \times k_t$) ~ 10–20 times.

Nanotechnology would reach economic, large-scale application including convergence with other foundational technologies and their spin-offs domains by 2030, at a similar level of development of infrastructure, tools, and design methods that information technology and the Internet achieved by about 2000.

1.6 Closing Remarks

Nanotechnology development has become an international scientific and technological endeavor with focused R&D programs in over 80 countries after the announcement of the NNI in the United States in 2000. The long-term vision and collaboration among the national and international programs are essential factors in this global development. Across the major developments in science and technology at present, nanotechnology positions itself as the most exploratory of them. With much of the research in many sectors, such as in information technology for example, focused on applications, in nanoscale science and engineering there are less established methodologies – giving it perhaps the greatest scope for discovery, manipulation, and diversification in coming years.

Nanotechnology is still in the formation phase of creating nanosystems by design for fundamentally new products. As we are at the beginning of the S-curve of nanotechnology development [6], a main challenge is to prepare the knowledge base, manufacturing, people, physical infrastructure, and anticipatory governance for nanotechnology of tomorrow. In this phase of development of nanotechnology, there is a need to invest in dedicated R&D programs on new nanotechnology methods and system architectures suitable for various economy sectors, adapt education programs and physical infrastructure to its unifying and integrative concepts, and institutionalize nanotechnology in the respective societal institutions. The global nanotechnology-based labor and markets are estimated to double about every 3 years, reaching over $3 trillion market encompassing 6 million jobs by 2020, and about one order of magnitude more by 2030 when nanotechnology will become a key competency and a significant component of GDP in developed countries.

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This chapter is based on the author's experience in the nanotechnology field, as founding chair of the NSET subcommittee coordinating the NNI and as a result of interactions in international nanotechnology policy arenas. The opinions expressed here are those of the author and do not necessarily reflect the position of U.S. National Science and Technology Council (NSTC)'s Subcommittee on Nanoscale Science, Engineering and Technology (NSET) or National Science Foundation (NSF).

References

1 Roco, M.C., Mirkin, C., and Hersam, M.C. (2011) Nanotechnology research directions for societal needs in 2020. *Journal of Nanoparticle Research*, **13** (**3**), 897–919, (Full report with the same title was published by Springer, Dordrecht, 2011, 670p). Available on www.wtec.org/NBIC2-Report/.

2 Roco, M.C., Williams, R.S., and Alivisatos, P. (1999) *Nanotechnology Research Directions: Vision for the Next Decade*, Springer (formerly Kluwer Academic Publishers) IWGN Workshop Report 1999, Washington, DC: National Science and Technology Council. Also published in 2000 by Springer, Dordrecht. Available on http://www/wtec.org/loyola/nano/IWGN.Research.Directions/.

3 Roco, M.C., Bainbridge, W.S., Tonn, B., and Whitesides, G. (2013) *Converging Knowledge, Technology and Society: Beyond Nano-Bio-Info-Cognitive Technologies*, Springer, available on www.wtec.org/NBIC2-Report/.

4 Roco, M.C. and Bainbridge, S.M. (2003) *Converging Technologies for Improving Human Performance: Nanotechnology, Biotechnology, Information Technology and Cognitive Sciences*, Springer.

5 Harper, T. (2015) AzoNano Reviews.

6 GAO (Government Accountability Office) (2014) Forum on Nanomanufacturing. Report to Congress, GAO-14-181SP.

7 Lux Research (2016) Revenue from nanotechnology (Figure 11), in *Nanotechnology Update: U.S. Leads in Government Spending Amidst Increased Spending Across Asia* (eds I. Kendrick, A. Bos, and S. Chen), Lux Research, Inc. report to NNCO and NSF, New York, p. 17.

8 PCAST (2014) *Report to the President and Congress on the Fifth Assessment of NNI*, White House, Washington, DC, http://www.whitehouse.gov/sites/default/files/microsites/ostp/PCAST/pcast_fifth_nni_review_oct2014_final.pdf.

9 Roco, M.C. (2014) *Nanotechnology Tomorrow: to System Integration and Societal Immersion*, Nano Monterrey, November 10, Keynote presentation.

10 Lok, C. (2010) Nanotechnology: small wonders. *Nature*, **467**, 18–21.

11 Clinton (2000) Caltech, “Presidential archives”. http://www.gpo.gov/fdsys/pkg/WCPD-2000-01-24/html/WCPD-2000-01-24-Pg122-3.htm