GAO

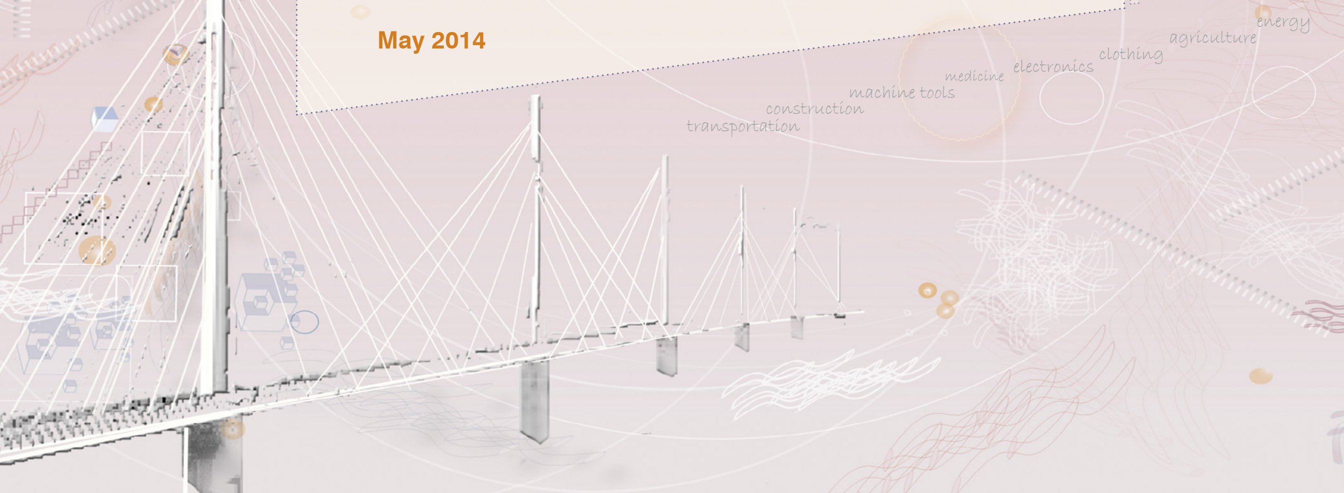
United States Government Accountability Office

A capsule version of

Nanomanufacturing

Emergence and Implications for U.S. Competitiveness, the Environment, and Human Health

May 2014



Forum on nanomanufacturing: Participants

Gene L. Dodaro (Host), Comptroller General of the United States

George Allen, Former U.S. Senator, and former Governor of Virginia

Tina Bahadori, Environmental Protection Agency

Sarbajit Banerjee, University at Buffalo, State University of New York

Lynn L. Bergeson, Bergeson & Campbell PC

Bjorn Birgisson, KTH Royal Institute of Technology

Bill Canis, Congressional Research Service

Vicki L. Colvin, Rice University

Joseph DeSimone, University of North Carolina

Bart Gordon, Former Chairman, Committee on Science and Technology, U.S. House of Representatives, and Partner at K&L Gates LLP

John Ho, QD Vision, Inc.

Hamlin M. Jennings, Massachusetts Institute of Technology

Brian David Johnson, Intel Corporation

Michael Liehr, College of Nanoscale Science & Engineering, State University of New York

Scott E. McNeil, Frederick National Laboratory for Cancer Research, and Science Applications International Corporation

Manish Mehta, National Center for Manufacturing Sciences

Celia Merzbacher, Semiconductor Research Corporation

Michael F. Molnar, Advanced Manufacturing National Program Office, and the National Institute of Standards and Technology

Matthew Nordan, Venrock

Susan E. Offutt, U.S. Government Accountability Office

Timothy M. Persons, U.S. Government Accountability Office

James M. Phillips, NanoMech Corporation

Robert Pohanka, National Nanotechnology Coordination Office

David Rejeski, Woodrow Wilson International Center for Scholars

Mihail C. Roco, National Science Foundation

Sheila R. Ronis, Walsh College

Françoise Roure, Organisation for Economic Co-operation and Development

Paul Schulte, Centers for Disease Control and Prevention

Charles Wessner, The National Academies

This booklet is a capsule version of the report *Nanomanufacturing: Emergence and Implications for U.S. Competitiveness, the Environment, and Human Health.* That report is available as GAO-14-181SP at **www.gao.gov**.

The cover image includes depiction of some of the widely ranging industrial sectors that may be enhanced or transformed by nanomanufacturing. Cover art source: GAO.

Capsule highlights of a forum convened by the Comptroller General of the United States

Why GAO convened this forum

Nanotechnology is the control of matter in the size range of about 1 to 100 nanometers. The U.S. National Nanotechnology Initiative, begun in 2001, focuses primarily on R&D and represents a cumulative investment of almost $20 billion. As other nations increasingly invest in nanotechnology, the U.S. faces rising global competition. Additionally, there are concerns about EHS risks. In July 2013, the Comptroller General of the United States convened a Forum on Nanomanufacturing in response to a congressional request; in January 2014, GAO issued a report to congressional requesters (GAO 2014; also identified as GAO-14-181SP). This booklet presents a capsule version of that report.

View GAO-14-406SP. For more information, contact Timothy Persons, Chief Scientist at (202) 512-6412 or personst@gao.gov

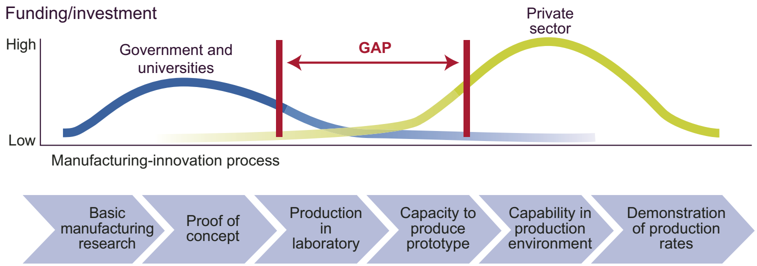
A capsule version of

Nanomanufacturing

Emergence and Implications for U.S. Competitiveness, the Environment, and Human Health

What forum participants said

Participants expressed 10 key views about nanomanufacturing. Notably, participants saw nanomanufacturing as a future megatrend, and they anticipated continuing scientific breakthroughs. Although participants viewed the United States as likely leading in nanotechnology R&D today, they foresaw intense global competition. They also identified emerging challenges to U.S. competitiveness in nanomanufacturing. For example, U.S. funding/investment gaps (one of which is illustrated below) may undermine U.S. innovators' attempts to transition nanotechnology from R&D to full-scale manufacturing—but such gaps do not apply to the same extent in some other countries or are being addressed. Participants also identified ways to enhance U.S. competitiveness in nanomanufacturing—and said that significant new efforts are needed in researching environmental, health, and safety (EHS) implications.



Funding/investment gap in the U.S. manufacturing-innovation process.
Source: GAO, adapted from Executive Office of the President.

Participants suggested two main considerations going forward: specifically, the need to, first, continue a high level of U.S. investment in R&D, and second, address four key issues—(1) challenges to U.S. competitiveness, (2) EHS implications, (3) uncertainty of available data on international investment, and (4) the current (potentially inadequate) level of U.S. participation in developing international standards.

Contents

Preface

At the request of the Chairman of the Committee on Science, Space, and Technology, U.S. House of Representatives, the Comptroller General of the United States convened the Forum on Nanomanufacturing in July 2013, bringing together experts from a wide range of relevant backgrounds. GAO conducted the forum with the assistance of the National Academies. Expert participants discussed

- nanomanufacturing's future;
- U.S. investments and competitiveness in nanotechnology R&D—and challenges to U.S. competitiveness in nanomanufacturing;
- ways to enhance U.S. competitiveness in nanomanufacturing; and
- environmental, health, and safety implications.

Forum discussions in these areas were reported in *Nanomanufacturing: Emergence and Implications for U.S. Competitiveness, the Environment, and Human Health* (GAO 2014). This booklet encapsulates the findings of that earlier report, presenting key views expressed by forum participants, as well as their suggestions for considerations going forward.

Appendix I presents capsules of four forward-looking profiles of nano-industry areas, which were developed as background for the forum. Appendix II summarizes our methodology. Additionally, we note here that many forum participants are active in nanotechnology research or manufacturing—and thus might benefit from increased government funding or other supportive efforts; therefore, we developed the forum with an emphasis on achieving a balance of views, to the extent possible.

T.M. Persons

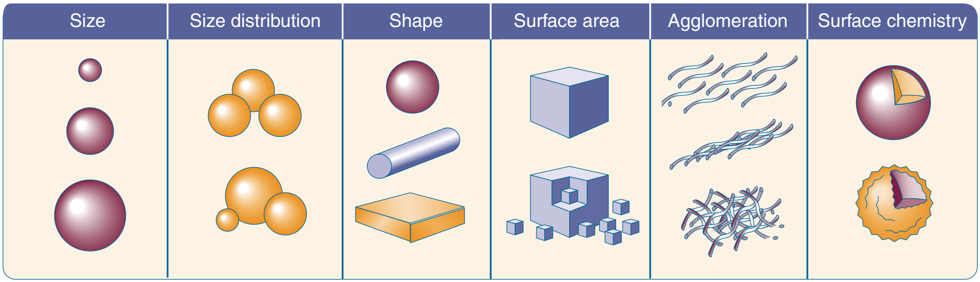
Timothy M. Persons, Chief Scientist

Introduction

Nanotechnology has been defined as the control or restructuring of matter at atomic and molecular levels in the size range of about 1 to 100 nm (Roco et al. 2011, xv). To illustrate relative dimensions, the width of a hair is 75,000 to 100,000 nm. Many scientific fields—such as chemistry, materials science, biology, physics, and engineering—study and apply nanotechnology. The goal is to create materials as well as devices and systems that have fundamentally new properties or functions.

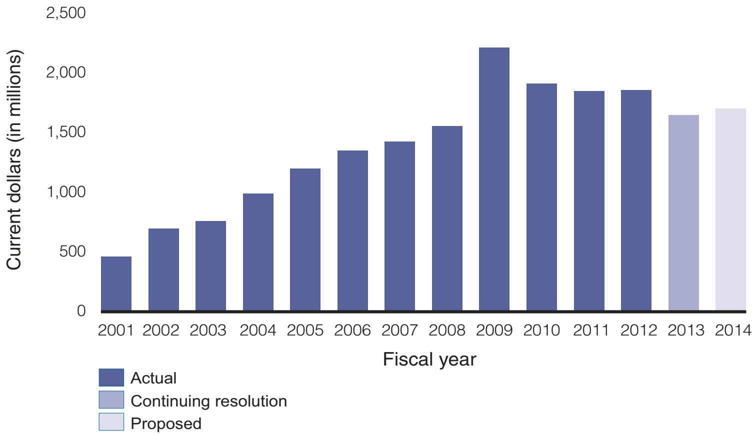
Nano-enhanced materials come in a variety of forms, based on chemical composition and physical structure, as illustrated below. Nanomaterials' varied characteristics can affect environmental, health, and safety (EHS) risks in potentially diverse ways.

U.S. public investment in nanotechnology research and development (R&D) has grown substantially since 2001, as indicated by the funding of the federal interagency National Nanotechnology Initiative (NNI). The amounts budgeted from 2010 to 2014, however, have not shown an increasing trend. (See figure on opposite page.)



Some nanotechnology characteristics. Source: GAO analysis based on GAO (2010b; 2012), Hassellöv and Kaegi (2009), and Mazov et al. (2012).

Note: Characteristics relevant to nanomaterials' properties and potential EHS risks include (1) particle size, (2) distribution of particle sizes in a group of particles, (3) particle shape, (4) surface area, (5) likelihood of forming agglomerates (clumps of particles bound together), and (6) surface chemistry (surface composition, shape, or chemical reactivity).



U.S. National Nanotechnology Initiative funding, fiscal years 2001–2014. Source: GAO, based on data from the U.S. National Science and Technology Council (2003, 2005 through 2013) and other sources.

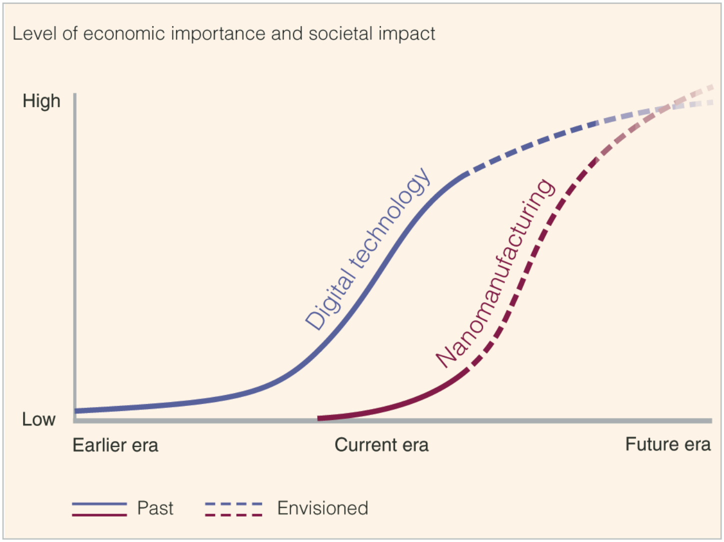
Note: NNI funding is focused primarily on research and development (R&D). Amounts for fiscal years 2009 and 2010 include funding from the American Recovery and Reinvestment Act of 2009. See also GAO (2014, fig.1, 6).

Nanotechnology is increasingly moving beyond research and early-stage development into commercial production. Future developments will likely be affected by global economic dynamics, advances in science and technology, and policy shifts. There are also potential EHS concerns. Within this context, the Comptroller General's Forum on Nanomanufacturing addressed

- the future of nanomanufacturing;
- U.S. investments and competitiveness in nanotechnology R&D—and challenges to U.S. competitiveness in nanomanufacturing;
- ways to enhance U.S. competitiveness in nanomanufacturing; and
- EHS implications.

Forum discussions, reported earlier (GAO 2014), are encapsulated here as 10 key views and two main considerations going forward. Additionally, appendix I presents capsules of profiles of four nanomanufacturing areas; we developed these profiles as background for forum participants.

1 Nanomanufacturing is a future megatrend



Conceptualization of nanomanufacturing and digital technology as megatrends. Source: GAO conceptualization based on participants' statements and the cumulative diffusion of innovation curve suggested by Rogers (1962).

Note: The envisioned "flattening" of the digital technology trend follows the "diffusion of innovation curve" (Rogers 1962). Although not shown here, the two trends may interact; that is, each may influence the other, potentially heightening one or both curves; for example, carbon nanotubes are being explored as a basis for new, smaller, and more powerful transistors (Shulaker et al. 2013).

Forum participants described nanomanufacturing as a future megatrend*—now in its early, formative phases—that will

- likely accelerate because scientists and engineers are beginning to design and control nanoparticles and devices to achieve specific, desired product characteristics (as opposed to previously discovering a nanoparticle and then trying to find a use for the new particle);
- eventually match or outstrip the digital revolution in terms of economic and societal impact (as illustrated);
- bring a diverse array of new societal benefits and new opportunities; and
- potentially create jobs through "disruptive" and "empowering" innovation.**

Forum participants said that future nanomanufacturing developments will likely be propelled by continuing breakthroughs and advancements in the science of nanomaterials, and by new enabling tools and techniques.

Varied participants also anticipated

- added benefits from the convergence of nanotechnology and new developments in fields such as biological science (see Roco and Bainbridge 2013), and
- new national investments—for example, fundamental research on nano-based concrete might yield advances that jump-start major federal investments to renew infrastructure across the United States.

* In this report, we define a megatrend as a long-term, powerful, and evidence-supported process with a formative and transforming impact on the future. The term megatrend may refer to technological, social, economic, demographic, or other developments.

** In the terminology of Christensen (2012; see also Christensen et al. 2000), innovations such as the Model T are both disruptive and empowering. They help create new markets, displace earlier technologies, and may create jobs.

2 Nanomanufacturing has characteristics of a general purpose technology

Stage 1 Evolving nanoscale materials, components, or devices	**Stage 2** Nano-enabled products or intermediates	**Stage 3** Improved or new nano-enhanced products
Nano-transistors	further improved semiconductor chips	ever faster computers,[a] smaller smartphones
Copper nano-wires[b]	lithium-ion batteries	more powerful battery-powered vehicles
Carbon nanotubes	concrete additives that conduct electricity	road pavement with remote sensing
Protein nanoparticles	carriers of chemotherapeutic drugs	chemotherapy targeted to cancer cells (only)

Diverse value chains involving nanoscale materials, components, or devices, as of 2013—looking forward. Source: Forum presentation (Persons 2013).

Note: We define a value chain, for purposes of reporting on the forum, as a series of key steps starting with the processing of raw materials and continuing to the production of a finished consumer product; each step adds value—and may or may not involve a different company or intermediate product. The figure uses three main stages, drawn from a conceptualization by Lux Research (see Bradley 2010 and Holman 2007), to summarize four examples of nanotechnology value chains.

[a] With respect to "ever faster computers," digital development has generally followed "Moore's law" (briefly, a doubling of processing power every 18 months) in part by utilizing chips with nano-features; however, further advances and more innovations in nanotechnology—such as the use of a new generation of nanomaterials in conjunction with 3D chip architecture and optical interconnects—or other novel approaches may be needed for continuous improvement in future decades.

[b] Copper nano-wires represent one example of how nanotechnology might be used to enhance lithium-ion (Li-ion) batteries for vehicles. The figure on p. 15 of this report illustrates a related example.

Nanomanufacturing currently affects diverse industrial sectors. Varied participants said that nanomanufacturing is setting the pace for improvements across a broad range of industrial sectors with an extensive array of important societal benefits. As shown in the figure (opposite page), nanomanufacturing's impacts are already beginning to occur across diverse industrial sectors such as:

- computers and smartphones,
- new batteries to power hybrids and electric vehicles,
- road pavement with sensing capabilities, and
- anti-cancer drugs designed to maximize uptake by cancer cells, while minimizing uptake by other cells.

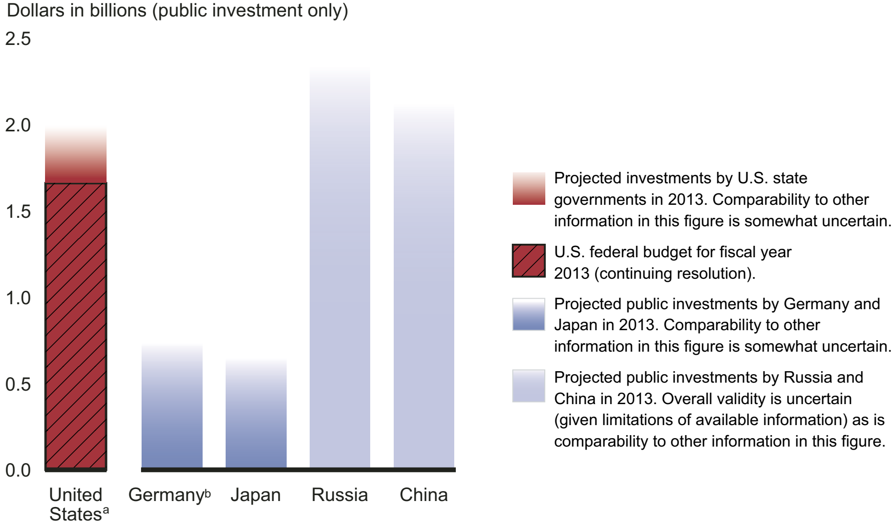
Advances in applied research are continuing; for example, a recent nano-research article described a new bone-enhancing therapy that would be carried directly to the small cracks associated with osteoporosis (Yadav et al. 2013). As one participant said: "Everything will become nano."

Nanomanufacturing may induce "spillover effects." Varied participants said that nanomanufacturing might approach the significance of electricity or computers. Such statements suggest that, like electricity and computers, nanomanufacturing might have not only (1) direct uses in numerous industries but also (2) indirect "spillover effects."*

General purpose technologies. Economists term innovations "general purpose technologies" or GPTs when they have the characteristics discussed above. Appendix III lists several historical examples of GPTs, including, for example, the smelting of ore and the internal combustion engine, as well as electricity, computers, and nanotechnology. (The importance of whether nanomanufacturing is seen as a GPT is indicated in Key View number 8 of this booklet; specifically, see approach 3 in the table on p. 19.)

* To illustrate a spillover effect: "the computer...enabled the development of...precisely controlled robots, which... enabled the restructuring of...highly automated [factories]" (Lipsey et al. 2005, 98).

3 The United States likely leads in nanotechnology R&D but faces global-scale competition



Public investments in nanotechnology R&D in 2013—U.S. compared to selected leading investor nations. Source: GAO based on a forum presentation (Roure 2013), Cientifica Ltd. (2013), and the U.S. National Science and Technology Council (2013).

Note: This bar chart is based on (1) the U.S. Federal Budget; (2) available projections for other government investments; and (3) recognition of the uncertainty associated with these projections. The shading characterizes uncertain levels of available projections for 2013, based on two key participants' opinions. The lighter the color of a bar, the greater the uncertainty. Use of fading on the upper portion of bars is also intended to convey uncertainty. Our intent is to avoid conveying an unwarranted level of precision, which might be associated with a specific data point for each nation; see GAO (2014, 105-106). Importantly, this figure excludes estimates of private-sector R&D investments. Overall—that is, combined public and private—R&D funding/investment is discussed in the text on the opposite page.

[a] Public investments shown for the United States include both state investments (projection) and the federal investment represented by the 2013 budget (continuing resolution) for the NNI, which focuses primarily on R&D.

[b] The projected public investment for Germany does not include its contribution to the European Commission's effort in nanotechnology R&D.

R&D funding/investments. While recognizing the uncertainty associated with cross-nation comparisons, participants viewed the United States as currently appearing to lead in overall funding—that is, combined public and private funding—of nanotechnology R&D, based on publicly available information. However, two participants selected in part for their expertise in this area said that:

- one or more nations' overall R&D investment might be greater than the United States, because some nations' R&D investments might be underreported, and
- the United States is likely surpassed by some nations when public R&D funding alone is considered (as shown opposite).

Additionally, one participant emphasized that (1) the nanotechnology R&D public investment made by Western European governments (combining funding by the European Union with that of individual nations) is larger than any single nation's and (2) U.S. public funding (as represented by NNI's budget) has not increased from 2012 to 2014.

Publications. Turning to publications, the United States dominates in numbers of nanotechnology publications in three highly cited journals, based on an analysis by Roco (2013).* Participants saw this as an indication of U.S. competitiveness in quality research. However, China overtook the United States in 2010 through 2012 (the most recent year reported) in terms of the quantity of nano-science articles published annually (a comparison made without controlling for quality of publication vehicle).

A possible "moon race." All things considered, participants see the United States as—currently—likely leading in nanotechnology R&D. At the same time, they foresee intense global-scale competition, which one participant characterized as a "moon race." Participants see it as essential that the U.S. continue a high level of investment in fundamental research.

* The three highly cited journals are *Science, Nature*, and *Proceedings of the National Academy of Sciences.* One participant cautioned that these journals might have favored U.S. authors; see GAO (2014, 21).

4 Nano-innovation means devising (a) new technologies (or products) and (b) new manufacturing processes

According to forum participants, nano-innovation involves devising and developing both

- new technologies (or products), and
- new processes to manufacture those products.

Thus, nano-innovators may face dual challenges: one for technology innovation, the other for manufacturing innovation—although the two efforts may be intertwined.

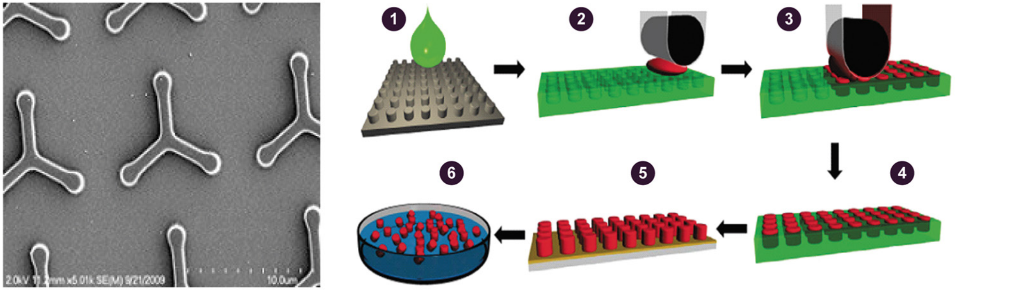
Using the example of nanotherapeutics for drug delivery, innovators at the University of North Carolina (UNC) had to

- advance the maturity of specific nanotherapeutics approaches, and
- create ways to manufacture or produce the new nanotherapeutics—first, in the laboratory and later, in a production environment.

That is, scientists must specially design differently shaped and sized particles to maximize their uptake by different kinds of targeted cells, such as specific types of cancer cells (and minimize uptake by other cells). Then, the particles are manufactured using a process devised by the UNC innovators (the PRINT® production process).* The figure opposite shows (1) an example of a specific particle shape required for a certain type of nanoscale drug delivery and (2) the 6-step method developed to produce particles of this shape and other specifically shaped particles.

According to a forum participant involved with the start-up company that developed PRINT®, this process was launched with three seminal patents in 2004. Many subsequent applications and processes were needed (approximately 80 patents pending thus far) to fully implement the new technology.

* PRINT® is based, in part, on earlier approaches used to produce semiconductors.



Example of specially designed particles and overview of the PRINT® technology process that produced them. Source: University of North Carolina at Chapel Hill (DeSimone Research Group) and Liquidia Technologies.

Note: Each of the specially designed particles, shown magnified above left, is roughly one-tenth the width of a hair, or less. The production process, shown at right, begins with the nanoscale, lithographic patterning of a template, which is illustrated as a grey plate in (1) above. The template defines the size and shape of the particles to be produced. A liquid polymer illustrated as a green drop, see (1) above, is spread across the patterned template, filling the space around all the nanosize features. The polymer is then cured and becomes a solid inverse, which is used as a mold, illustrated as the green plate in (2) above. The mold is filled with a nanoparticle material, as illustrated in red; see (2), (3), and (4) above. A harvesting film, illustrated as a clear strip shown in (5) above, is used to extract the particles from the mold. Each resulting particle, illustrated in (6) above, is of the same size and shape; each also has the same chemical composition.

The distinction between technology (or product) innovation and innovation in manufacturing processes is further discussed in the following section, which concerns participant views about U.S. gaps in funding.

Specifically, a funding gap can occur during the middle stages of both:

- efforts to develop a new nanotechnology product, and
- efforts to develop a new nanomanufacturing process (designed to produce the new product).

5 Gaps in support may undermine U.S. nano-innovation efforts for (a) technologies (or products) and (b) manufacturing processes

Participants said that in the United States, government often funds research or the initial stages of development, whereas industry typically invests in the final stages. As a result, U.S. nano-innovators may find it difficult to obtain either public funding or private investment during the middle stages of innovation. Further, a support gap can characterize the middle stages of

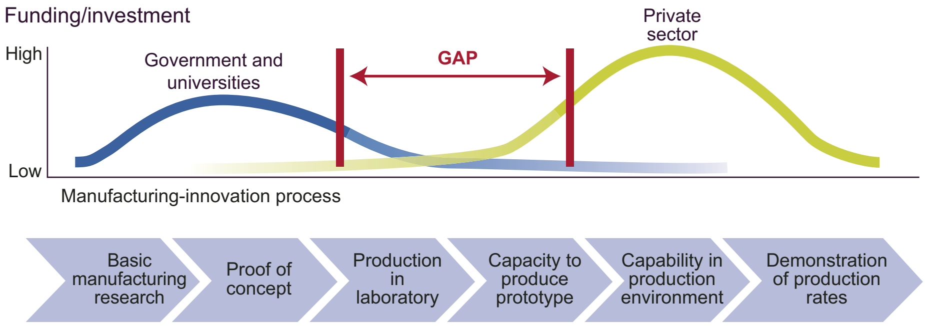
- developing a new technology, and/or
- developing a new manufacturing process.

Thus, U.S. innovators may encounter two support gaps, which participants termed:

- the *Valley of Death* (the lack of funding or investment for the middle stages of developing a technology or product), and
- the *Missing Middle* (a similar lack of adequate support for the middle stages of developing a process or approach to manufacture the new product).

The *Valley of Death* begins once a new technology or product has been validated in a laboratory environment; it continues through prototype demonstration in a non-laboratory environment (before industry acquires it as a commercial technology or product). The *Missing Middle* occurs during analogous stages of the manufacturing-innovation process, as illustrated on the opposite page.

Participants said (1) that substantial amounts of funding/investment are needed to bridge the *Valley of Death* and the *Missing Middle,* (2) that high costs can be a barrier to commercialization, especially for small and medium-sized U.S. businesses, and (3) that there has been a “draining away” of venture capital (VC) funding from physical science areas like nanotechnology to fund new ventures in Internet services that may provide larger and faster returns on investment.



Missing Middle: Funding/investment gap in the U.S. manufacturing-innovation process. Source: GAO adapted from Executive Office of the President (2012, 21).

Additionally, participants noted that in some cases, there is a lack of a supportive regional ecosystem or infrastructure to help overcome challenges in areas such as engineering and establishing efficient supply chains.

Some counterpoints were voiced by forum participants. First, some large corporations (for example, General Motors) provide VC for innovations they see as enhancing their own future business endeavors. Second, the current VC focus on new Internet services may be temporary. Third, some agencies participating in the Small Business Innovation Research (SBIR) program have found ways to indirectly support the pursuit of commercialization (for nanotechnology and other areas)—thus extending SBIR's goal of helping small businesses establish the potential for commercialization; see also GAO (2011a).

Still, participants said that some nations do more than the United States to support commercialization—and that other nations which may have had middle-stage gaps are now addressing them (see Key View number 7 on pages 16-17).

6 Potential barriers to widespread U.S. nanomanufacturing illustrated by prior offshoring and loss of a key industry

Multiple participants gave examples of potential barriers to establishing widespread nanomanufacturing in the United States. Two examples are described below.

Example 1: Prior offshoring—the semiconductor industry.
A key U.S. strength is designing semiconductors. Moreover, the actual manufacturing of semiconductors is automated, and engineers are the key employees at a fabrication plant. Some fabrication takes place in the United States, and a fabrication plant in upstate New York employs about 1,000 engineers. Nevertheless, most fabrication of computer chips with nanoscale features takes place abroad. A participant explained that unskilled labor is needed to package semiconductors—and said that it is important for the United States to establish more fabrication plants in this country.*

View of a semiconductor-manufacturing facility.
Source: College of Nanoscale Science & Engineering, State University of New York.

A major problem with offshoring in an innovative area such as nanomanufacturing was described by a participant who said that when "we design here [and] ship [manufacturing] abroad, we lose this shop-floor-innovation kind of mentality." (See app. I of this report, especially profile 1 on p. 26.)

Example 2: Loss of a potentially important industry—lithium-ion batteries. Although the United States developed the underlying technology for lithium-ion (Li-ion) batteries, most such batteries—including

* One company is now developing advanced robotics for semiconductor packaging—a technology that logically would lessen the need for unskilled labor.

nano-enhanced batteries used to power hybrids and electric vehicles (EV)—are manufactured in Asia. According to one participant: (1) smaller lithium-ion batteries for consumer electronics have long been manufactured in Asia because the United States "gave up on [that industry] some time ago," and (2) Asian firms appear to have a competitive advantage in the manufacturing process, which is similar for small lithium-ion batteries and the larger ones manufactured for vehicles.

However, looking to the future, one forum participant said that "the jury is still out" on U.S. competitiveness in this area. Another expert (interviewed prior to the forum) said that some future versions of nano-engineered batteries for vehicles will require different manufacturing processes and thus might represent a new opportunity for U.S. manufacturing. The example shown above right is a new type of battery that requires a different type of manufacturing process; it is now in the research or idea stage for hybrids and EVs. (See also app. I of this report, profile 2, p. 27.)

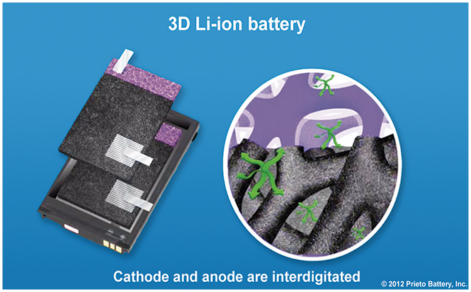


Illustration of a lithium-ion battery requiring a new manufacturing process. Source: Prieto Battery, Colorado, USA.

Note: Briefly, the term interdigitated refers to an interlocked or interwoven design in which the anode is (1) is composed of a copper foam current collector coated with a copper antimonide anode (shown in dark purple); (2) coated with an ultra-thin lithium-ion electrolyte (illustrated in light purple); and then (3) surrounded by a cathode slurry (illustrated in dark gray). The green figures represent the ease of diffusion of ions in the 3D battery design. For a fuller explanation, see Johnson (2013).

See GAO (2014, 32-33; 35) for discussion of other possible barriers to widespread U.S. nanomanufacturing.

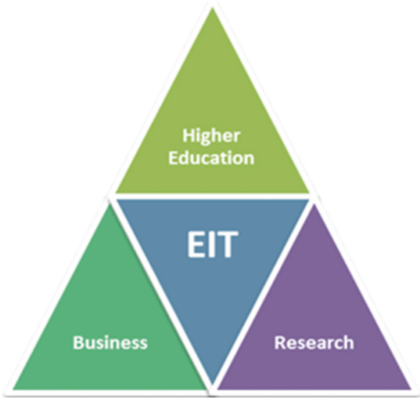
7 The U.S. lacks a vision for nanomanufacturing—while facing global competition and IP threats

Lack of U.S. vision. A forum participant said that the United States lacks a vision for a nanomanufacturing capability. Although four centers, funded by the National Science Foundation (NSF), focus on new concepts and development of methods for nanomanufacturing (that is, these centers conduct research primarily at "early manufacturing readiness levels"), our post-forum communications with an NSF official indicated (1) that funding for three of the centers will end in 2014, and for the fourth, in 2015, and (2) that there is currently no program devoted to supporting nanomanufacturing centers.

A fifth NSF-funded center—the NASCENT center at the University of Texas at Austin—addresses the commercialization of nanotechnology rather than conducting early-stage research on nanomanufacturing. (That center is described in app. IV.)

Global competition. According to participants, the funding and investment gaps that hamper U.S. nano-innovation (the *Valley of Death* and *Missing Middle*) do not apply to the same extent in some other countries—for example, China and Russia—or are being addressed. Varied participants made statements to the effect that other nations do more than the United States in terms of government investment in technology beyond the research stage.

Multiple participants referred to the European Commission's upcoming Horizon 2020 program, specifically mentioning a key program within Horizon 2020 that is termed the European Institute of Innovation and Technology (EIT). As illustrated in the "Knowledge Triangle," EIT emphasizes the nexus of business, research, and higher education. The 2014-2020 budget for the EIT portion of Horizon 2020 is €2.7 billion (or close to $3.7 billion in U.S. dollars as of January 2014).



Knowledge triangle. Source: "Knowledge triangle" illustrating the European Commission's European Institute of Innovation and Technology principles. http://ec.europa.eu/geninfo/legal_notices_en.htm (accessed April 29, 2014).

With respect to foreign competition, multiple participants referred to the previously mentioned example of lithium-ion batteries (in which the underlying R&D was funded by the United States, but other countries dominate mass production). Multiple participants also said that certain other countries are purchasing struggling U.S. nanotechnology companies and making significant offers to U.S. nanoscience researchers and nanotechnology innovators.

Threats to intellectual property. Several participants discussed threats to intellectual property (IP) associated with global competition:

- One participant described an IP challenge to research at U.S. universities: a culture of openness, especially among students, which results in ideas and research "leaking out" before they have been patented or fully pursued by the initial researchers.
- A second participant noted, when interviewed prior to the forum, that one country targeted specific research projects at U.S. universities—and then required its own citizen-students to apply for admission to the targeted universities and seek work on the targeted projects.
- A third participant described persistent attempts by some other countries (or elements in these countries) to breach information systems at his company; this participant summed up the current IP situation as approaching "technological war."

8 Varied approaches might enhance U.S. competitiveness in nanomanufacturing

Challenges to U.S. competitiveness (see Key Views numbered 5, 6, and 7) could threaten realization of U.S. economic benefits commensurate with public and private investments. Participants therefore considered ways to enhance U.S. competitiveness in nanomanufacturing. Three main approaches emerged from these forum discussions (see table below). Logically, the three approaches can be seen either as representing alternatives—or as complementing each other. Each approach is more fully described in GAO (2014, 42-54).

Approach	Proposed actions
1. Strengthen innovation across the U.S. economy	Continue or update federal policies and programs that help strengthen innovation generally (i.e., across all sectors of the economy).
2. Promote innovation in U.S. manufacturing (including nanomanufacturing)	Establish U.S. centers, encourage clusters, or design programs to address the *Valley of Death* or the *Missing Middle*—that is, the gaps in investment or resources discussed earlier. Participants identified two centers that focus specifically on nanomanufacturing and a pilot program that more generally promotes innovation in manufacturing.*
3. Design a grand strategy for U.S. nanomanufacturing	Define a vision for U.S. nanomanufacturing. Design a grand strategy for achieving this vision—using a systems approach and a collaborative process that might be led by the federal government.

Three approaches to enhancing U.S. competitiveness—proposed actions. Source: GAO analysis of statements made by forum participants.

* One center is described in appendix IV. For the other center and the pilot program, see GAO (2014, 46-48).

We note that strong proponents of certain approaches objected to the others—saying, for example, that approach 1 would be insufficient by itself; that the effectiveness of approach 2 had not been firmly established; and that approach 3 would not necessarily create significant numbers of well-paying jobs in the United States. However, each approach has a specific rationale (see table below).

Approach	Rationale
1. Strengthen innovation across the U.S. economy	The U.S. government acts to supply goods and services critical to innovation when private markets fail to do so, often because firms cannot capture the full benefits of providing them. Beyond these measures, which include providing education and building infrastructure, firms are in a better position than government to make decisions about how to allocate resources to the most promising innovations.
2. Promote innovation in U.S. manufacturing (including nanomanufacturing)	The United States needs a strong manufacturing base because it is essential to the economy and to innovation itself. Assuring this base means "leveling the playing field" in the global economy—by directly addressing the *Valley of Death* and the *Missing Middle*, especially as these apply to innovative manufactured products or innovative manufacturing processes. Moreover, structures separating manufacturing from design (e.g., too much offshoring) can have significant adverse results.
3. Design a grand strategy for U.S. nanomanufacturing	Nanomanufacturing is a megatrend that will significantly affect future U.S. competitiveness in global markets and provide societal benefits. Nanomanufacturing may be a future general purpose technology (GPT) akin to digital technology or electricity, and thus classifiable as a public good with anticipated benefits for the entire economy—potentially justifying targeted federal support. Moreover, nanomanufacturing may become an engine of job creation in the U.S. economy.

Rationale for each approach to enhancing U.S. competitiveness in nanomanufacturing. Source: GAO analysis of statements made by forum participants.

9 An integrated framework could help assess and address EHS implications

Forum participants offered a range of perspectives on the environmental, health, and safety (EHS) implications of nanotechnology, nanomanufacturing, and nanomaterials.

The participants presented information on what is currently known about these implications and expressed frustration about the lack of progress in understanding the risks from potential exposure to nanomaterials. Some also noted a current dilemma related to identifying or determining EHS risks: because few nanomaterials have been studied and no long-term or chronic data are available, the risks of new nanomaterials are difficult to predict or manage.

Forum participants identified significant research needs to discern EHS implications and discussed the need to fully communicate the benefits and risks of nanotechnology to the members of the public, to help them distinguish between perceived and real risks. See GAO (2014, 55-63).

Multiple participants suggested developing an integrated EHS framework for thinking about nanotechnology, nanomanufacturing, and nanomaterials. One participant explained that the framework would be based on incorporating assessments of EHS implications into the design phase of the product—not at the end of life, not at disposal, and not after problems or health impacts to consumers or workers have already occurred. Participants characterized this concept as "safer by design." One participant explained the idea as capturing the functionality of the product while addressing safety concerns.

Participants also discussed the importance of considering the life cycle and conducting life-cycle material assessments. Such an assessment would consider not only the use of the material, but all stages of the product's life cycle from production and development through disposal and recycling. The following figure illustrates an example of a life-cycle assessment.

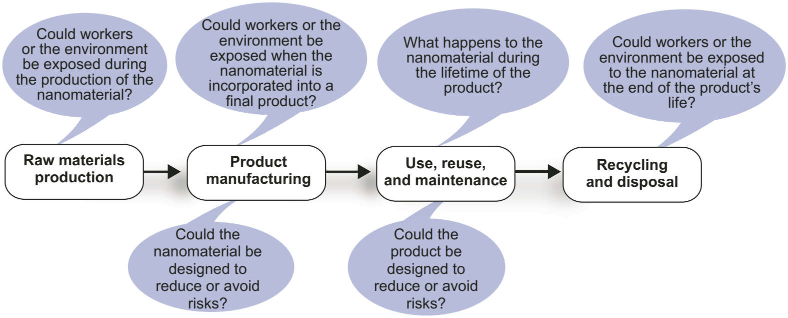


Illustration of product life cycle and issues posed. Source: GAO.

Varied participants made three points. They said (1) that the United States lacks a coherent governance and oversight system for nanomaterials and nanotechnology, a lack they saw as potentially problematic for U.S. industry and innovation; (2) that the first nations to complete standards and risk-management systems will have an advantage in supporting development of new nanotechnology products and companies; and (3) that the European Union's precautionary approach and required labeling reduces uncertainty in how such products are regulated in that market.

One participant noted personal experience in international or global cooperative efforts over the past 8 years. These efforts included participation in about 10 different efforts for nanotechnology. Another participant discussed one international effort at the 34-nation Organisation for Economic Co-operation and Development's (OECD) Working Party on Nanotechnology: developing approaches for the responsible development of nano-science and nanotechnology. We previously reported (GAO 2013) that early and ongoing coordination with foreign governments in emerging areas before regulations are in place might facilitate international regulatory cooperation.

10 Standards-development efforts are important

Lack of a unified system. Varied forum participants said that the current lack of a unified system to describe nanomaterials—including naming conventions, definitions, and standards—is a possible limitation on innovation efforts. Participants noted that a unified system

- is needed to create a database of nanomaterials, and if developed,
- might enhance "capacity to scale up innovation . . . [creation of] revenue downstream . . . [and] conditions for international trade [and] security—which are important [for] investors, citizens, and consumer groups."

Need for basic international standards. Additionally, participants said that basic standards can greatly facilitate the accumulation of a knowledge base that is necessary for greater transparency in markets—and can also facilitate progress in addressing EHS aspects of nanomanufacturing. One participant said that nanotechnology standards have been issued by American standard-setting organizations for nomenclature and measurement, but that international standards-development efforts have been more challenging. This participant was referring to developing International Organization for Standardization (ISO) standards (see also inset on opposite page).*

Some pointed to the risk that U.S. nano-innovators might have to contend with other countries' taking the lead in developing international nanotechnology standards, leaving the U.S. behind. Negative outcomes could include (1) the development of international standards with relatively little input from the U.S. nanotechology community or (2) the development of a patchwork quilt of diverse national standards. Such outcomes could make it harder for U.S. producers to compete in foreign markets.

Lack of funding—and a need to increase U.S. participation in international standards development. Participants stressed a lack of

* As noted in Key View number 9, one forum participant mentioned having participated in about 10 different international or global standardization efforts for nanotechnology during the past 8 years.

U.S. funding and time needed to participate in standards-development efforts—in particular, international travel.

Governments as well as the scientific community and the private sector have important roles to play in this regard because international standards can facilitate expanding international trade in nanotechnology-enhanced products. While the U.S. model of developing and setting standards reserves a larger role for leadership from non-government stakeholders, U.S. government support for the scientific and business communities' efforts can help avert negative outcomes. Importantly, multiple forum participants said that there is now a need to increase U.S. participation.

Examples of international standards-developing organizations:

- The International Organization for Standardization (ISO) describes itself as an independent network consisting of the national standards bodies of 162 countries—and as the world's largest developer of voluntary international standards.
- The International Electrotechnical Commission (IEC) provides a platform to companies, industries, and governments for developing international standards for electrical, electronic, and related technologies; each country has one vote.
- The International Telecommunication Union (ITU) is the United Nations specialized agency for information and communication technologies. Its Telecommunication Standardization Sector produces ITU-T Recommendations (ITU-T Recs), which are standards defining how telecommunication networks operate and interwork.
- The IEEE* Standards Association (IEEE-SA) brings together a wide range of individuals and organizations from over 160 countries to facilitate standards development and collaboration.

* IEEE refers to the Institute of Electrical and Electronics Engineers.

Forum participants suggested two main considerations going forward

1 Continue U.S. investment in nanotechnology research, possibly targeting nanomanufacturing research

Continuing U.S. investment in fundamental nanotechnology research. Forum participants said that it is essential for the United States to maintain a high level of investment in fundamental nanotechnology research. This is because, as explained earlier

- while participants view the United States as the likely overall leader in nanotechnology R&D, certain other countries are now making significant investments in R&D–and one is publishing large numbers of research papers; and
- ongoing research breakthroughs will drive the future of nanomanufacturing.

Targeting some funding to early-stage research on nanomanufacturing processes. One participant emphasized that as nanotechnology increasingly moves into manufacturing, it may be important to consider both (1) continuing funding for fundamental nanotechnology research and (2) targeting some funding to early-stage research on nanomanufacturing.

As explained earlier, nano-innovators may need to both (1) develop a new technology or product—an effort that typically begins with fundamental research (or "early technology readiness levels"),* and (2) devise a new and potentially innovative process to manufacture (and mass-produce) that product—an effort that may begin with basic engineering research (or "early manufacturing readiness levels").**

These two research efforts may often be intertwined. Early-stage research on nanomanufacturing processes would include conceptualizing innovative processes for eventually testing and mass-producing new nanomaterials and nano-enabled products—as well as developing these processes in a laboratory environment.

* Early technology readiness levels describe the transition from scientific research to applied research and proof-of-concept validation; see GAO (2011b, 36).

** Early manufacturing readiness levels range from identifying basic manufacturing implications through developing a manufacturing proof of concept; see GAO (2010a, app. II).

2 Address challenges to U.S. competitiveness and other key issues

Challenges to U.S. competitiveness. As described earlier, participants identified challenges to U.S. competitiveness in nanomanufacturing—for example, gaps in U.S. support for innovation and lack of a U.S. vision for a nanomanufacturing capability. Participants suggested that pursuing one or more of the following approaches might enhance U.S. competitiveness: (1) strengthen innovation across the economy, (2) promote innovation in U.S. manufacturing, and (3) design a grand strategy to achieve a U.S. vision for nanomanufacturing.

EHS issues. Participants noted (1) limited EHS research, which makes predicting and managing risks difficult; (2) an underlying tension between advancing innovation and adopting regulation; and (3) the need for a revitalized, integrative, and collaborative approach.

Uncertainty of data on R&D investment. Although forum participants viewed the United States as likely the current lead R&D-investor nation, two participants cited concerns about the reliability of international investment information. According to one of them, a pathway forward might include convening international conferences on public investment and other related data.

International standards development. Forum participants said there is insufficient effort by the United States to participate in international standards development. They noted restricted budgets and an apparent low priority on international travel—and said that it is important to remedy this situation for conferences on international nanotechnology standards.

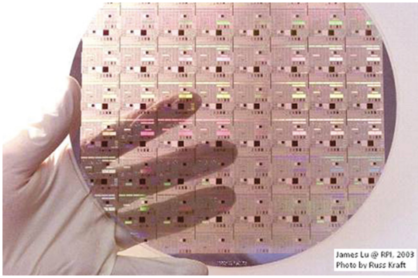
Finally, the areas recapped here—and future efforts to address them, if made—may overlap; for example, achieving basic international standards could help in achieving more comparable international R&D-investment data. Such overlap could serve as the basis for developing a coordinated framework for nanomanufacturing-related issues.

Appendix I: Capsules of four forward-looking profiles developed as background

We created four profiles, presented here in capsule form, as background reading for forum participants. Full profiles are presented in GAO (2014, 79-98; see also 75-78, 101-102).

Capsule of profile 1: Nanotechnology and the future of the semiconductor industry

Semiconductors represent "the foundation of the electronics industry," and semiconductor chips with nanoscale features (see figure below) are now pervasive. This technology is continuing to evolve. Global sales, totaling $292 billion in 2012, may rise to $333 billion in 2016.



Glass wafer with multiple semiconductor chips. Source: Rensselaer Polytechnic Institute, Troy, New York.

Semiconductor-industry tools are expensive; some cost, for example, $100 million each.

As a result, some companies (U.S. as well as other nations' companies) partner with the College of Nanoscale Science and Engineering (CNSE) of the State University of New York. CNSE is a unique research, development, prototyping, and educational cluster for nanotechnology. Varied experts said that

- the United States is dominant in the design of new advances in semiconductors;
- U.S. manufacturing in this area has declined (although some plants are located here);
- U.S. policy changes to counter the trend might be initiated in areas such as tax policy and environmental regulation; and
- the United States does not have a strategy to assure U.S. leadership in the semiconductor industry.

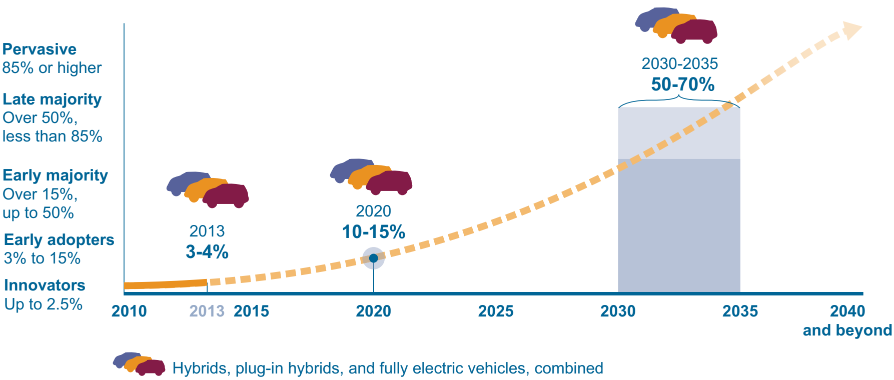
Some experts also expressed concerns about worker safety and the need to carefully manage waste products.

Capsule of profile 2: Nanotechnology and the future of battery-powered vehicles

Nanotechnology is improving the advanced batteries that power hybrids, plug-in hybrids, and fully electric vehicles (EV). Such vehicles now represent about 3 to 4 percent of U.S. and worldwide auto markets, but some experts anticipate (1) a fast increasing market share (see figure below), and (2) intense international competition.

Although U.S. research developed the underlying technology, almost all such batteries are manufactured in Asia. Experts said that new U.S. policies could improve future U.S. competitiveness in this area—perhaps especially for new types of nano-batteries requiring new manufacturing processes.

Experts also said little research has been conducted on potential EHS concerns associated with nano-enhanced batteries designed to power hybrids, plug-in hybrids, and EVs.



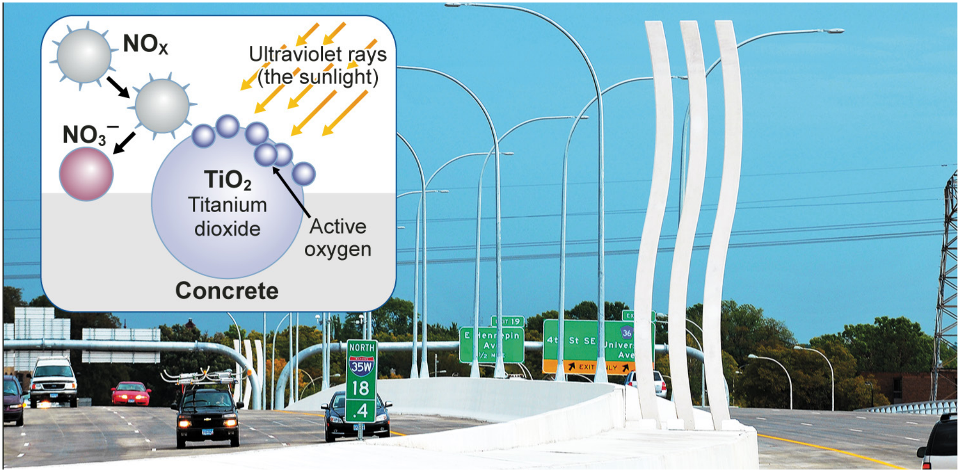
One view: Future market expansion for battery-powered vehicles. Source: GAO analysis based on (a) varied estimates and predictions from expert interviews and literature (Hirsh 2013; Price Waterhouse Coopers 2013), and (b) the cumulative diffusion of innovation curve suggested by Rogers (1962).

Capsule of profile 3: The future of nano-enhanced concrete

Nano-enhanced concrete can potentially build longer lasting, better functioning roads, bridges, and buildings—and may also be designed to convert polluting gases into less harmful substances by converting nitrogen oxides to nitrate ions, as illustrated below. Research is being conducted on the use of nano-materials to produce concrete with self-sensing, self-healing properties that would, for example, allow engineers to monitor bridges and roads remotely.

Looking to the future, experts anticipated an expanding global construction market, but expressed differing views on U.S. global competitiveness in nano-enhanced concrete. Positive signs for U.S. competitiveness include (1) a well-established U.S. research capacity and (2) the competitiveness of the U.S. chemical industry, which can produce nano-admixtures designed to strengthen concrete or otherwise enhance its properties.

EHS issues are of concern for nano-enhanced concrete, in part because construction is labor intensive and performed outdoors.



Nano-enhanced concrete in sculpture removes harmful pollutants. Sources: GAO analysis (inset). Minnesota Department of Transportation (photo).

Capsule of profile 4: The future of nanotherapeutics in medicine

Nanotherapeutics target drug delivery to specific cells, thereby reducing negative side effects. Few such drugs are currently on the market, but experts anticipate an increasing trend over the next 7 to 10 years—with more drugs for cancer and the introduction of drugs for infectious diseases, vascular disorders, and degenerative diseases. According to a recent research report (BCC 2012), the anticancer segment of the global nanomedicine market is expected to reach $12.7 billion in 2016.

Experts said that the United States is currently dominant in nanotherapeutic research, commercialization, and manufacturing, but added a caution about the future. Specifically, experts said that in the United States, R&D for nanotherapeutics is generally carried out by small companies without the resources needed to support the drug development process of discovery, pre-clinical testing, clinical trials, and regulatory review—which can average 15 years (see figure below). Thus, future U.S. competitiveness in this area will be affected by whether the nanotherapeutic industry, including small firms, (1) can secure sufficient funding, particularly for commercialization and manufacturing, and (2) will have clear regulatory guidelines.

Turning to EHS issues, experts expressed somewhat differing views:

- On one hand, nanotherapeutics experts did not see nanotechnology products as warranting more concern than other new technologies.
- On the other hand, EHS experts emphasized the need to assess risks across the life cycle of nanotherapeutics.

Drug development process. Source: GAO based on industry estimates.

Appendix II: A note on forum methodology

Our earlier report on the July forum (GAO 2014) was produced through a multiphase process. Three main phases included:

1. selecting and inviting forum participants, who had a wide range of expertise and views, with the assistance of the National Academies;

2. developing a pre-forum reading package that included four nanomanufacturing industry profiles (based primarily on expert interviews), and sending this to participants in advance of the forum; and

3. holding the forum, preparing an initial post-forum summary of the forum's discussions and submitting that summary to participants for review—then considering and, as appropriate, incorporating the participants' responses and comments.

Regarding (2), above, we recognized that the profiles reflect the views of interviewees in positions to benefit from increased government funding (as well as government interviewees). We therefore encouraged forum participants to be aware of the interviewees' perspectives when considering these profiles, and our pre-forum communications to forum participants included a disclaimer to this effect.

The Preface to this capsule report similarly highlights this issue with respect to forum participants' interests. Additionally, we took steps to exercise due diligence and to understand forum participants' potential conflicts of interest.

With respect to our presentation of international public investments in nanotechnology R&D (see the figure on p. 8), available information did not meet our usual criteria for a conventional bar chart—partly because different countries use different definitions and partly because not all countries report such data publicly. However, consulting firms projected relevant figures, and notwithstanding quality issues, we felt it was important to convey the relative magnitude of public investments by some countries. We therefore used shading techniques to convey the lack of precision in the projections.

We conducted our work in accordance with relevant sections of GAO's quality assurance framework. Additional information on our methodology is presented in GAO (2014, app.V).

Appendix III: Transforming general purpose technologies: Examples

Era	Event
9000–8000 BC	Domesticated plants
8500–7500 BC	Domesticated animals
8000–7000 BC	Smelting of ore
4000–3000 BC	Wheel
3400–3200 BC	Writing
2800 BC	Bronze
1200 BC	Iron
Early Medieval	Waterwheel
1400s	Three-masted sailing ship
1500s	Printing
Late 1700s– early 1800s	Steam engine Factory system
1800s	Railway Iron steamship Internal combustion engine Electricity
1900s	Motor vehicle Airplane Mass-production, continuous-process factory Computer Lean production Internet Biotechnology
Early 2000s	Nanotechnology*

Source: Lipsey et al. (2005, 132).

Note: Lipsey et al. (2005, 98) define a general purpose technology as "a single generic technology, recognizable as such over its whole lifetime, that initially has much scope for improvement and eventually comes to be widely used, to have many uses, and to have many spillover effects."

* "Nanotechnology has yet to make its presence felt as a general purpose technology, but its potential is so obvious and developing so quickly that we [Lipsey et al.] are willing to accept that it is on its way to being one of the most pervasive general purpose technologies of the 21st century" (Lipsey et al. 2005, 132).

Appendix IV: The NASCENT center

The Center for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies (NASCENT) was founded at the University of Texas at Austin in 2012, with funding from NSF. Two key objectives are:

- to create processes and tools for manufacturing nano-enabled components for mobile computing, energy, healthcare, and security—as well as simulations for testing potential nanomanufacturing approaches; and
- to provide an ecosystem with computational and manufacturing facilities—for example, large-area wafer-scale and roll-to-roll nanomanufacturing (see Morse 2011), as well as the university's resources, including faculty, staff, and students.

The overall goal is to facilitate the rapid creation and deployment of new products and to mitigate the risks associated with the *Valley of Death* and the *Missing Middle.*

A co-director of NASCENT told us that another goal is to use "10 years of NSF funding to develop the center infrastructure so it will . . . [become] self-supported from industrial partnerships and other [non-NSF] funding sources."

Center partners include

1. industrial partners—such as toolmakers, materials suppliers, and device makers—that will provide both technical and financial support;
2. companies ranging from start-ups to well-established firms that will implement or adopt technology created by the center; and
3. "translational research partners" such as technology incubators and technology funds.

Appendix V: Abbreviations

CNSE	College of Nanoscale Science and Engineering (State University of New York, Albany)
EHS	environmental, health, and safety (issues or implications)
EIT	European Institute of Innovation and Technology (of the European Commission)
EV	electric vehicle
GPT	general purpose technology
IP	intellectual property
Li-ion	lithium-ion (batteries)
NASCENT	Center for Nanomanufacturing Systems for Mobile Computing and Mobile Energy Technologies (The University of Texas at Austin)
NIST	National Institute of Standards and Technology
nm	nanometer (one billionth of a meter or 10^{-9} m)
NNI	National Nanotechnology Initiative
NNMI	National Network for Manufacturing Innovation
NNN	National Nanomanufacturing Network
NSF	National Science Foundation
OECD	Organisation for Economic Co-operation and Development
R&D	research and development
SBIR	Small Business Innovation Research
UNC	University of North Carolina
VC	venture capital

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