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For nearly ten years, the US National Nanotechnology Initiative (NNI) has set the pace for national and international research and development in nanoscale science and engineering. Without a doubt, increasing our understanding of how matter behaves at the nanometer scale, and using this knowledge to both enhance existing technologies and to create innovative new ones, holds the promise of significant economic and societal benefits. In a world where the needs of a growing population threaten to outstrip increasingly limited resources, and many global challenges – from disease to hunger to renewable energy – remain unresolved, technology innovation is critical to enabling a sustainable future. Yet investing in research and development is just the first step in ensuring responsible, relevant and successful technology solutions. As the NNI enters its second decade, there needs to be an increasing focus on how to translate technology innovations into solutions that work, if the US is to reap the benefits of the considerable investment being made in this area.

By way of background, I have been involved in research on nanoscale materials for over 20 years, and have been intimately involved in nanotechnology research and policy for nearly ten years. Between 1989 and 1992 I studied the application of advanced electron microscopy techniques to the analysis of ambient airborne nanoscale particles. In 1999, while working for the UK Health and Safety Executive, I was co-author on an internal report evaluating health and safety research issues posed by nanoscale materials.[1] From 2000 – 2005, I was a senior researcher with the US National Institute for Occupational Safety and Health (NIOSH), and was instrumental in developing the agency's nanotechnology research program. While at NIOSH, I was involved in some of the first published research into carbon nanotube exposure and toxicity.[2] I also participated in the NNI as the NIOSH representative between 2004 – 2005, and was co-chair of the Nanotechnology Environmental Health Implications (NEHI) interagency working group over this period. Between 2005 – 2010, I was the Chief Science Advisor to the Project on Emerging Technologies at the Woodrow Wilson International Center for Scholars – a non-partisan, non-advocacy initiative dedicated to helping business, government and the public anticipate and manage the possible

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[1] Kenny LC, Maynard AD, Brown RC, Crook B, Curran A, swan DJ. 1999. A scoping study into ultrafine aerosol research and HSL's ability to respond to current and future reasearch needs. IR/A/99/03.health and Safety Laboratory, UK.

[2] Maynard AD, Baron PA, Foley M, Shvedova AA, Kisin ER, Castranova V. 2004. Exposure to Carbon Nanotube Material: Aerosol Release During the Handling of Unrefined Single Walled Carbon Nanotube Material. J Toxicol Environ Health 67(1): 87-107. Shvedova AA, Kisin ER, Murray AR, Gandelsman VZ, Maynard AD, Baron PA, et al. 2003. Exposure to carbon nanotube material: Assessment of the biological effects of nanotube materials using human keratinocyte cells. J Toxicol Environ Health 66(20): 1909-1926.

health and environmental implications of nanotechnology. While in this position, I authored two assessments of research needs for responsible nanotechnologies.[3]

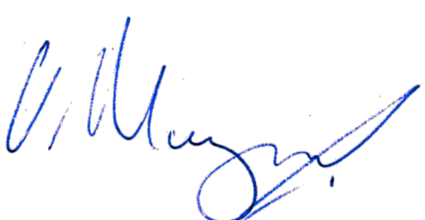
In 2010, I took up the position of Director of the Risk Science Center at the University of Michigan. The Risk Science Center's mission is to support evidence-based decisions on risks to human health though fostering and conducting interdisciplinary research into identifying, assessing and managing existing and emergent risks; exploring innovative new approaches to addressing human health risks; enabling students, academics, field-practitioners, policy makers, citizens and others to make evidence-informed decisions on existing and emergent risks; and engaging stakeholders in effective dialogues on risk, uncertainty and sustainable development. Nanotechnology is one of a number of areas that the Center is focusing on.

Over the past ten years I have published extensively on the social, policy and health and safety issues associated with nanotechnology specifically and emerging technologies more broadly. I have also served on a number of relevant committees and working groups, including groups convened by the National Academies of Science and the Council of Canadian Academies. I was a member of the working group advising the President's Council of Advisors on Science and Technology on their 2010 review of the NNI. I am also currently chair of the World Economic Forum Global Agenda Council on Emerging Technologies.

The current Request For Information poses twenty-two specific questions regarding the future activities of the NNI in addressing four goals. In this submission, I will be addressing a number of these questions, based on my experience and knowledge. However, I would like to preface my comments with some more general observations on nanotechnology, the NNI and the importance of nanoscale science and engineering in underpinning social and economic progress. I add these as, based on many discussions of the importance of emerging technologies and the barriers to their effective development and use, there is a need for an increasingly sophisticated understanding of how nanotechnology fits into a broader innovation, social and economic context. Looking to the future, I am convinced that we will only fully realize the benefits of nanoscale science and engineering if we learn better how to integrate it with other areas of technology innovation, and with a greater understanding of the evolving social, economic and political dynamics that determine the success or failure of emerging technologies.

The views expressed here are my own, and do not necessarily represent the University of Michigan or other organizations with which I am affiliated. I hope that they are of some use in helping inform the next NNI strategic plan. Please do not hesitate to contact me if I can be of any further help.

Sincerely yours,



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[3] Maynard AD, Aitken RJ, Butz T, Colvin V, Donaldson K, Oberdörster G, et al. 2006. Safe handling of nanotechnology. Nature 444(16): 267-269. Maynard AD. 2006. Nanotechnology: A research strategy for addressing risk. PEN 03. Washington DC:Woodrow Wilson International Center for Scholars, Project on Emerging Nanotechnologies.

General Comments

1. The NNI had had a major impact over the past ten years. Beyond facilitating a substantial increase in nanoscale science and engineering R&D funding, the initiative has led to new and innovative collaborative research, has fostered significant technology innovation, and has stimulated interest in science and technology more broadly. It has also provided test case for how an emerging technology might be developed in an increasingly complex and interconnected world.

2. The roots of the NNI were in supporting new research and development, and in this the initiative has been an unqualified success – over the past ten years, peer review papers and patents associated with nanoscale science and engineering have risen dramatically, and there are now a number of academic journals dedicated to the area that did not exist a few years ago. Yet as the fruits of these efforts have moved into the public and commercial domains, the context within which the NNI operates has changed. There has been a clear shift in recent years from nanotechnology being a driver of research, to it being seen as a significant driver of economic growth and social progress. Expectations have been raised as to what investment in nanotech can do for individuals, for local and national economies, and for solving some of the most pressing challenges faced by global society. With this changing context, it is necessary to consider whether the concepts and expectations embedded within the NNI are still valid, or whether they have become an impediment to progress. This is a tough question to ask of such a well-established and influential initiative. But it is one that needs to be addressed if the efforts of the past ten years are to bear fruit.

3. The indications are that a rethink is needed. As nanotechnology moves from being primarily a research endeavor and into a broader societal, economic and political landscape, the concepts that were so successful at stimulating new research – and new research funding – are now beginning to generate wicked policy problems; where stakeholders are not sure what the problem is, never mind the solutions that are needed to address it. Following debates over the safety of nanotechnology, its regulation, its commercialization and over public understanding, acceptance and engagement, it is increasingly clear that stakeholders are struggling to understand how the concept of "nanotechnology" fits with the issues they are faced with. There is a sense within stakeholder communities that nanotechnology is important and that they should be making decisions about it – in part because of the emphasis placed on it through the NNI. But the concept often fails to translate into something meaningful and tangible within these contexts. The result – communities who feel that they need to do something about nanotechnology, but without a clear sense of what this "something" might be. An example of this is a well-meaning but confused petition recently sent to the Environmental Protection Agency from a group of Non Government Organizations, calling for the agency not to approve an alleged nanotechnology-based dispersant for use in the Gulf of Mexico – simply because of its association with nanotechnology.[4] This petition was as much a product of naïve framing of nanotechnology promulgated in part by the NNI, as it was a result of a disjointed analysis of a possible human health and environmental risk.

4. This is not to say that the nanoscale science, engineering and innovation are not important. On the contrary, I would argue that increasing our understanding and control over matter at the nanoscale is vital. Over the past fifty years, the increasing dexterity with which we can work with matter at the scale of atoms and molecules has enabled tremendous technological advances. And the nanoscale science of today holds the promise of incredible leaps forward in our abilities

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[4] http://2020science.org/2010/05/28/nano-dispersants-and-nano-hysteria-time-to-think-about-the-science-folks/ Accessed 8/15/10

over future decades. But nanotechnology is just one of a number of technology platforms, and technology innovations that lead to new products and processes typically emerge from the intersections between these platforms. And to place undue emphasis on one platform – and to allow this emphasis to spill over from research and development into social, economic and policy arenas – is to run the risk of impeding the process of transforming technology innovations into viable technology solutions.

5. Other emerging technology platforms include synthetic biology, cognitive technology, robotics, computational chemistry, information technology, artificial intelligence and biological/data interfaces. Together with established technology platforms, these are supporting new breakthroughs that have the potential to improve existing products and generate innovative new ones. The resulting products and processes are synergistic amalgams of multiple technologies – not just the product of a single technology. High performance batteries, transparent mineral-based sunscreens, targeted drug delivery systems, high-strength materials, increasingly powerful computers – all depend in some way on working with materials at the nanoscale. But they only do what they do because multiple different technologies are used together. And this in turn means that the broader issues of commercialization, safety, environmental impact, benefits and acceptance *must* be approached from the context of emerging technologies, and *not* from perspective of one technology alone.

6. This issue is central to the need to rethink nanotechnology and the role of the NNI within a broader social, economic and political context, as nanoscale science and engineering move out of the laboratory and into the marketplace. Looking to the next ten years, there is a need to consolidate within the NNI an emphasis on nanoscale science and engineering – generating new knowledge and developing new capabilities through synergistic and collaborative research. But there is also a need to rethink how broader questions of technology transfer and commercialization, human health and environmental impacts, societal and economic benefits, education, policy, stakeholder engagement and ethics fit into a broader emerging technologies landscape. Rather than placing nanotechnology in a silo as it moves out of the laboratory, it needs to be integrated with other technology platforms that together will lead to the innovations that will help build a sustainable future.

7. This is the only way that the growing wicked problems surrounding how nanotechnology is used and the consequences of its implementation will be resolved in the long run.

Specific Comments

A. Goals and Objectives

A1. What specific and measurable objectives should be established to help achieve the four stated NNI goals?

8. **Goal 1:** Three specific and measurable objectives to achieving this goal include increasing funding for nanotechnology-related research, increasing the number of researchers involved in nanotechnology-relevant research, and increasing the number of peer reviewed papers associated with nanotechnology-based research. Increases in each area have the potential to advance a world-class nanotechnology research and development program. However, it is important to note that increased funding, personnel and publications do not in themselves guarantee a more effective R&D program – they are merely indicators of a program that has the potential to be increasingly effective. It is also important to note that, for these objectives to be useful, they should include a degree of considered specificity. For instance, R&D funding needs to be

strategically awarded to be useful; researchers need to be encouraged and enabled to explore promising new lines of enquiry; and publications should be counted that represent significant progress that will underpin future research and development. Regarding publications, more sophisticated measures of progress should be considered than simply counting number of publications. Assessing the number of times key publications are cited is a useful indicator of impact, but is not always indicative of the importance of a piece of research. Care also needs to be taken to account for publications in specialty journals, where relatively low impact factors and citation rates may under-emphasize the importance of the research.

9. Objectives should reflect this degree of specificity. Their scope should also be clear. In this respect, it might be helpful to clarify what specific aspects of nanoscale science and engineering they cover, thus avoiding questions over the interpretation of "nanotechnology" when measuring progress. In all cases, there is a need to be transparent and honest about how progress is measured towards specific objectives.

10. **Goal 2:** Increases in the number of nanotechnology-related patents granted remains a useful objective here, but is not the only way to ensure useful and effective technology transfer. In assessing patents, it is important to include nanotechnology-related technologies, even though the terms "nano" or "nanotechnology" may not appear in the patent. A second potential objective here would be to increase the number of nanotechnology-enabled businesses in operation and products on the market. The emphasis here is on products that gain value from nanoscale science and engineering – not necessarily products that are classified as "nanotechnology products." This becomes important as nanotechnology is increasingly used synergistically with other technologies to enhance existing products or to lead to new ones. A third objective would be to show measurable progress towards addressing significant challenges where nanotechnology has been identified as a key contributor. These include, amongst others, treating diseases such as cancer; increasing food productivity, availability and security; the provision of clean water; and developing economic sources of renewable energy.

11. **Goal 3:** Measurable objectives here include: Increasing the availability and uptake of complimentary K-12 curricula material on nanoscale science and engineering, and uptake of material. Increasing the number of graduates with training and expertise in nanoscale science and engineering. Increasing the number of graduates equipped to understand the roles of nanoscale science and engineering in a broad social, economic and policy context. Developing relevant and accessible informational and educational material for citizens on the potential benefits and issues surrounding nanoscale science and engineering, and ensuring widespread uptake of the material. Minimizing the differential between supply and demand for employees trained in relevant aspects of nanotechnology. Translating analytical tools between disciplines and areas of expertise, so that they can be used effectively in areas other than those they were developed in.

12. **Goal 4:** Develop accessible and relevant information resources for citizens, corporations, state and federal policy makers on the responsible development and use of nanoscale science and engineering, and ensure uptake of these resources. Develop and implement risk research plans that are strategic and relevant, and that have measurable impacts. Facilitate the translation of safety-related research to informed decisions. Develop and implement an engagement strategy and action plan that addresses who is to be engaged, how they are to be engaged, why they are to be engaged and what impact engaged parties will have on nanotechnology research, development, commercialization and oversight.

A2. Are there other overarching goals that would enable the NNI to better support the vision of a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society?

13. Perhaps the goal that is most noticeable by its absence is the integration of nanoscale science and engineering with other technological developments to provide synergistic technology solutions that have economic and societal value. A goal along these lines becomes increasingly important as commercial uptake leads to the integration of nanoscale science and engineering with other technologies to create innovative products and processes.

B. Research priorities

B1. What are the most important gaps in the NNI R&D portfolio (i.e. specific underfunded areas ripe for success) that should be addressed to achieve the NNI goal(s)?

B2. What nanotechnology R&D areas should NNI member agencies pursue under the Nanotechnology Signature Initiatives model of close and targeted program-level interagency collaboration to help accelerate technology innovation?

B3. What are the most important scientific and technical challenges that would need to be met to realize the NNI goal(s)?

14. In 2008, I chaired a workshop at the Program on Emerging Technologies at the Woodrow Wilson International Center for Scholars that brought together fifteen leading scientists[5] in the field of nanoscale science and engineering to discuss future research directions for nanotechnology. The results of this workshop were never published. However, ten future high priority research directions were developed by the workshop participants. These ten research priorities are summarized here:[6]

15. **Understanding and controlling quantum behavior within systems.** While properties such as quantum coherence and quantum entanglement become increasingly evident at the nanoscale, they can dominate the macroscopic properties of materials. By understanding and ultimately using quantum properties associated with precisely engineered nanostructures, new classes of advanced materials will become possible that exhibit novel mechanical, thermal, electrical and optical properties.

16. **Designing functional nanomaterials.** While great advances have been made in synthetic chemistry and materials science over the past century, the chemicals and materials currently produces and used represent only a small fraction of those that could be created in principle. Further research into material formation and reactivity at the nanoscale will enable the formation of increasingly complex functional materials, including new classes of synthetic chemicals. In particular, advances in atom-perfect synthesis and thermodynamically optimized assembly will underpin the formation of novel materials from the bottom-up.

[5] Those involved in the Project on Emerging Nanotechnologies workshop were: Andrew D. Maynard (Wilson Center, Chair), Mihail C. Roco (NSF), Harry Atwater (Caltech), Angela Belcher (MIT), Mauro Ferrari (University of Texas), James Heath (Caltech), Mike Heller (UC San Diego), Richard Jones (University of Sheffield), Charles Lieber (University of Harvard), Chad Mirkin (Northwestern University), Virgil Persec (University of Pennsylvania), Mark Ratner (Northwestern University), Fraser Stoddart (Northwestern University), James Tour (Rice University) and Stan Williams (Hewlet Packard).

[6] This summary is provided with the permission of David Rejeski, Director of the Project on Emerging Nanotechnologies. The workshop was funded in part by the National Science Foundation.

17. **Understanding and exploiting interactions between precisely engineered nanomaterials and electromagnetic radiation.** High intensity electromagnetic fields can interact in unique ways with precisely engineered nanomaterials. Understanding and exploiting these interactions will open the door to a range of transformative technologies that range from photon-based computing to meta-materials that transcend conventional optics.

18. **Exploring the nanomaterial-biology interface.** Biology is based on hierarchical systems that are built on nanoscale processes and systems. To fully interact with biological systems—whether communicating with them or altering them—a sophisticated understanding is needed of how artificially constructed materials and devices interact with biology at the molecular and supramolecular scale. Extending understanding in this area is crucial for the development of targeted drugs and regenerative medicine. But it will also have profound implications to how living organisms are interfaced with non-living systems, and how biological entities are used to construct new materials and devices.

19. **Developing turnkey nanoscale imaging and fabrication tools.** The next ten years of nanotechnology will depend on further advances in imaging and fabrication tools, enabling atom-precise construction of new materials and devices. But more critical will be the development of advanced tools that non-experts can use, either for research or for production. The availability of desktop instruments that do not require deep scientific and technical know-how to image materials or fabricate new ones at the nanoscale will accelerate the process of discovery and innovation.

20. **Understanding and constructing hierachical nanoscale-systems.** Increasingly complex nanoscale systems will only become possible through a clearer understanding of how to build functional hierarchies of nanomaterials. The ability to design and construct nanoscale building blocks that can be assembled into functional mesoscale and macroscale materials and devices will lay the foundation for bottom-up, molecular and energy-conservative fabrication.

21. **Developing biology-inspired nanotechnologies.** Over time, evolution has led to the development of intricate and efficient nanscale processes within living systems. A greater understanding of these processes will enable the systematic engineering of biologically-inspired solutions in non-living systems. For instance, learning from biology could lead to a new generation of enzyme-inspired catalysts—"nanozymes"—and artificial ribosome's, capable of transcribing molecular-encoded information into the building bricks of inorganic complex materials. Similarly, functional biological molecules and supramolecular structures could be engineered to perform non-biological functions.

22. **Understanding, stabilizing and using non-equilibrium systems at the nanoscale.** Interesting science and, in consequence, innovative technology, occurs when systems are out of equilibrium and/or exhibit non-linear behavior. Yet stabilizing such systems so that their novel behavior can be harnessed and used to good effect is a complex task, and far harder than establishing and maintaining systems in equilibrium. A better understanding of non-equilibrium phenomena at the nanoscale will underpin radical advances in nanoscale engineering and fabrication.

23. **Process engineering.** Developing intricate nanoscale processes and materials in the laboratory is no guarantee that they will scale up into commercially viable products. Further research is needed into systematically designing and engineering systems that can exploit nanoscale phenomenon on a large scale. Systems approaches need to be developed that lead to material and energy-conservative manufacturing of nanotechnology-based products. A clearer understanding is needed of how small changes in materials and processes can be translated into large impacts, in operating/production efficiency and in product functionality.

24. **Education.** The success of emerging nanotechnologies will depend on scientists and engineers with new skill-sets. While exploratory research will still demand deep knowledge of basic science, progress will be made increasingly at the interface between areas of expertise. This will require scientists who can either interface effectively across disciplines, or work comfortably between disciplines. New educational approaches and concepts will need to be developed to train a new generation of researchers who are not constrained by traditional boundaries, but have the skills to transcend them.

C. Investment

C1. What types of research and development investments (e.g. support for individual investigators, small teams, centers, research infrastructure, etc.) should the NNI agencies create, sustain and/or expand to achieve the NNI goal(s)?

25. **Goal 1:** To sustain the nanotechnology innovation pipeline, the Federal government needs to maintain a diverse portfolio of R&D investment mechanisms. Research Centers have proven to be powerful engines of research and innovation over past ten years, and should continue to be supported. Similarly, large-scale investment in infrastructure such as the National Nanotechnology Infrastructure Network should continue to be supported, to provide much needed access to large scale and distributed resources. But there also need substantial funding for individuals and small groups, to allow the innovation that is often associated with inspired individuals to flourish. In considering R&D investment mechanisms, care should be taken to ensure sufficient sized awards are available for research addressing strategically important areas. This is particularly important where small grants run the risk of prohibiting innovative research. In the past, risk research for example has been limited in some cases by awards that are not sufficient to support research that is strategically important.[7] In such cases, there will always be proposals that fit within the limitations of the call for applications, but there will not always be proposals that provide the new knowledge necessary for progress to be made.
26. **Goal 2:** Although the NNI has contributed to technology transfer over the past 10 years, further effort is needed to develop mechanisms for working with industry, and for building greater support for technology transfer if government investment in nanotechnology is to bear fruit. New and innovative support mechanisms are needed for overcoming development barriers, including the so-called "valley of death." While there are no easy solutions here, the NNI strategy should include provisions for developing new approaches to fostering socially and economically sustainable commercial products that benefit from nanoscale science and engineering.
27. **Goal 3:** There remains a need for significant additional funding of collaborative initiatives in informing, educating and engaging with citizens, businesses, media, educators, decision-influencers and policy makers. These should build on initiatives such as the Centers for Nanotechnology in Society at Arizona State University and UC Santa Barbara, and the Nanoscale Informal Science Education Network (NISE Net). And they should move toward implementing plans and ideas that engage and empower stakeholders and lead to demonstrable impacts. Within the social science, education and engagement communities there is a wealth of knowledge and experience that the NNI should consider tapping into, as the results of nanoscale science and engineering are likely to have an ever-greater impact on people's lives.

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[7] In vivo research and epidemiology in particular are expensive. Limiting grants to levels below which effective research in these areas can be conducted either excludes important research from being funded, or substantially reduces the quality and relevance of the research funded. In these and other areas, reducing the magnitude of individual awards often has a disproportionately large impact on output and outcomes.

28. **Goal 4:** The federal government needs to invest in initiatives that are primarily focused on areas of responsible development, including human health and environmental impact, societal implications, stakeholder engagement, decision-making and ethics. In order to build capacity, engage experts and lend credibility to research in these areas, these initiatives should not simply be add-ons to research programs focused primarily on exploiting the benefits of nanoscale science and engineering. However, they should be developed in close collaboration with research that underpins the use of nanotechnology in commercial applications. Centers addressing specific aspects of responsible innovation and development are essential. But there should also be investment in individuals and small groups. As the commercial use of nanoscale science and engineering escalates, it will be increasingly important to develop and maintain areas of expertise relevant to responsible development, while fostering cross-disciplinary collaboration.

C2. What relative distribution of research and development investment among the PCAs is needed to achieve the NNI goals(s)?

29. Relative investment is only possible to assess once the strategic plan has been developed, and a clear set of strategic objectives established. At this point, it should be possible to estimate the level of research and development investment necessary to achieve the measures of success identified for specific objectives in a timely and effective manner.

D. Coordination and partnerships

D1. How could the NNI strengthen interagency coordination and collaboration towards specific NNI goal(s) and objectives?

30. **All goals:** The most important step toward strengthening interagency coordination and collaboration is to develop a clear, compelling, integrated and actionable strategic plan for the NNI. In implementing this plan, participating agencies should be engaged at a senior level. The implementation process should aim to foster a culture of common good amongst participating agencies, and work against the tendency within interagency collaborations for unenlightened self-interest. To this end, the implementation plan should clarify the benefits to specific agencies of coordinating with other partners, and the national benefits of agencies working toward a common set of goals. The action plan should ideally include rewards and consequences for participating agencies, thus strengthening ownership and accountability. It should also include specific interagency goals and timelines that are agreed with the participating agencies. To help implement the action plan, the National Nanotechnology Coordination Office should be provided with increased funding, increased staff resources and increased authority to engage with agencies at a senior level.

D3. What are the most effective roles of the government, industry, academia, and other stakeholders in achieving this NNI goal?

31. **Goal 1:** The NNI research strategy should be informed by experts and stakeholders from outside government. Input into the R&D strategy should be considered from stakeholders who will benefit from its outputs, including citizens. Mechanisms are needed to ensure that this form of stakeholder engagement is effective and has demonstrable value, and is not just a box-ticking exercise (Placing notices in the Federal Register of public comment opportunities does not in itself constitute effective stakeholder engagement). In addition, expert input from industry,

academia and the NGO community should be sought when planning and reviewing R&D supported by the NNI. Development and implementation of expert review and input mechanisms will add considerable value to R&D associated with the NNI, while avoiding embarrassing missteps. As an example, the harsh critique of the 2008 NNI nanotechnology environment, health and safety research strategy by a National Research Councils panel[8] might have been avoided if expert review and input were solicited and acted on as the strategy was being developed.

32. **Goal 2:** The federal government can play a significant role in fostering effective technology transfer, and in encouraging developments that address critical national and international challenges. As the boundaries between exploratory research and applied research become increasingly diffuse, all research agencies have a role in facilitating the commercial use of new knowledge that is generated under their support. But this role is perhaps most significant within mission focused agencies such as the Department of Energy. At the same time, agencies that modulate commercial activity – regulatory agencies in particular – have a responsibility to ensure their actions support safe products and processes without unnecessarily impeding commercialization. Here, there is a need for greater communication between oversight agencies and industry to ensure products and processes that exploit nanoscale science and engineering are developed responsibly. In an increasingly technologically complex world, there is a need to rethink the relationship between regulators, manufacturers and users in order to protect people and the environment, while ensuring that the potential societal benefits of emerging technologies are not lost.

33. **Goal 3:** If responsible, beneficial and sustainable applications of nanotechnology are to be developed, government agencies have an important role to play in helping develop educated, informed and engaged communities. This should include ensuring adequate integration of nanoscale-related science and engineering into K-12 curricula and into graduate and postgraduate courses, to provide an educated workforce. It should also include providing resources and opportunities for informal education, through museums, TV, the internet and other media. As well as being an integral part of larger research initiatives, a specific nanotechnology education strategy should be developed and implemented across government agencies. This should include plans for partnering with non-government organizations, including businesses, professional societies and science museums. In many cases, stakeholders are already developing informational and educational materials – the recently launched series of nanotechnology podcasts developed by the American Society of Mechanical Engineers is an excellent example.[9] However, the impact of these resources would be increased substantially through strategic partnerships with government agencies.

34. **Goal 4:** If responsible uses of nanotechnology are to be developed, all stakeholders need to be at the table. A forum is needed – convened by an independent body – that ensures effective stakeholder engagement in the process of developing products that exploit nanoscale science and engineering. This could be convened by government, although there would need to be a firewall between agencies that predominantly have a vested interest in commercial development, and those that are primarily focused on preventing harm. Alternatively, this is a role that an independent organization could be charged with leading, with government having a seat at the table. The forum should allow for substantive input from government agencies, businesses, academia, non-government organizations and other citizen representatives. Mechanisms should be developed that facilitate the adoption and implementation of recommendations arising from the forum.

[8] National Academies. 2009. Review of the federal strategy for nanotechnology-related environmental, health, and safety research. Washington DC: The National Academies Press.
[9] http://nano.asme.org/Nano_Educational_Series.cfm, accessed 8/15/10

35. In addition, government agencies have a coordinated responsibility to support pre-commercial and trans-commercial research, development and other activities that facilitate the responsible development of products and processes that rely on nanotechnology. Pre-commercial activities are essential for providing manufacturers with the tools and framework within which responsible innovation and development can be conducted effectively. Trans-commercial activities address barriers to responsible development that are too big, broad or diffuse for individual corporations to address. Both activities include the strategic development of knowledge on potential adverse impacts of materials, products and processes arising from nanoscale science and engineering, and the use of this knowledge in supporting effective oversight, safe products and informed decisions.

D4. What new forms of collaboration between stakeholders should be explored to facilitate nanotechnology-based innovation into applications?

36. **All goals:** More effective collaborations are needed between the generators and users of information and professional communicators, to inform, educate and empower stakeholders. These should use formal and informal education routes, and should be tailored to suit the needs and capabilities of specific stakeholders, including citizens, businesses, academics, journalists, decision-makers and decision-influencers.

37. New mechanisms are urgently needed to engage with stakeholders – citizens in particular. These should enable stakeholders to become partners in the process of developing technologies and technology-based solutions that rely on nanoscale science and engineering. *A NNI strategy for stakeholder engagement should be developed and implemented that includes specific details of who will be engaged, why, what impact the engagement will have, how the effectiveness of the engagement will be measured and over what timescale it will be implemented.* This should include upstream engagement with citizens who stand to be impacted by the use of nanotechnology – for good or bad – and who will increasingly be placed in a position of having to make decisions on the use of products that are based on nanotechnology. In particular, opportunities for meaningful engagement should be developed that are primarily at the convenience of the participants rather than the organizers. Innovative new approaches to engaging with stakeholders in formal and informal forums should be explored, including the use of new media. Where other economies have developed effective approaches to stakeholder engagement, the applicability of the mechanisms they have developed to the US should be investigated. In this respect, the experiences of the UK and EU in engaging with citizens and experts in particular are worth evaluating.

D6. What partners of types of partners would need to collaborate (i.e., government, specific foundations and industry groups, new ideas for consortia) to accomplish the NNI goal(s)?

38. **Goal 1:** Increased collaboration between government and industry would be helpful in guiding and stimulating relevant research and development. More effective collaboration between government researchers and academics would support a better focused and more effectively implemented research program.

39. **Goal 2:** Partnerships and collaborations between government, advocacy groups, business and NGOs in particular will foster the effective transfer of new technologies into sustainable and beneficial products. Collaborations with NGOs are no always easy, as some groups consider their role as one of watchdog rather than collaborator. Nevertheless, lines of communication should remain open where possible to ensure that potentially important concerns and opportunities are not overlooked. New and more effective mechanisms are needed to engage with citizens, and to

give citizens a voice in addressing how nanoscale science and engineering might lead to safe and effective products. One option worth exploring is to consider building constituencies around specific challenges that engage all relevant stakeholders.

40. **Goal 3:** More effective engagement is needed between the NNI and organizations that support the development of an educated workforce and an informed and engaged populace. Partnerships should be further developed between teacher organizations, professional organizations, universities and media. A NNI strategy is needed for how such partnerships can help facilitate informed, educated and engaged stakeholders.

41. **Goal 4:** Increasingly strong partnerships should be fostered between government agencies, international organizations such as the World Health Organization, The International Standards Organization, the Organization for Economic Cooperation and Development and the World Economic Forum,[10] and other organizations that support the development of responsible technologies. In recent years, agencies participating in the NNI have begun to develop strong ties with some organizations – OECD and ISO in particular. As the commercialization of nanoscale science and engineering continues, it is important that these ties are extended, and that the federal government engages with groups that will have influence over the possible future trajectory of nanotechnology. Ultimately, the emergence of safe and successful nanotechnology-enabled applications will depend on all stakeholders having a voice in the technology's responsible development.

D7. What are effective mechanisms to leverage and/or coordinate US-funded research and development with international efforts?

42. To support international coordination and to leverage research and development being supported elsewhere, greater funding needs to be made available for agency representatives to participate fully and authoritatively in international initiatives. In addition, lines of communication need to be kept open between international efforts to ensure opportunities arising are taken full advantage of. The possibility of joint funding for research between different economies should continue to be explored. However, there is still a need for more effective collaboration mechanisms that lead to joint funding opportunities enhancing research rather than placing additional hurdles before researchers.

D8. What mechanisms could NNI use to regularly engage experts in academia and industry and other organizations for input on its approach to addressing specific NNI goals?

43. *Establishing a federal advisory committee of experts for the NNI is strongly recommended*. This would help keep the NNI informed of activities and developments outside the federal government, would provide independent assessment and insight into federal nanotechnology activities, and would help identify potential issues before they became significant. In effect, an advisory committee would provide a much-needed formal link stakeholders

44. The continued use of public and expert workshops to address specific issues is also recommended, with the proviso that they are conducted effectively and efficiently, and that the

[10] Through the Global Agenda Councils, the World Economic Forum is emerging as a significant high-level forum for exploring and addressing opportunities and challenges associated with developing technology-based solutions to global challenges. See for example: World Economic Forum. 2010. Everybody's Business: Strengthening International Cooperation in a More Interdependent World. Report of the Global Redesign Initiative. Geneva: World Economic Forum.

results are published in a timely manner – within months rather than years. In addition, forming *ad hoc* small groups of experts as needed is recommended to address specific goals and objectives. However, these should be run in a transparent manner.

D9. What is the role of public engagement in achieving specific NNI goals? In what ways can the federal government best engage with citizens to ensure the sustainable development of nanotechnology-based products with the broadest economic and societal benefits?

45. **Goal 1:** Two-way engagement should be facilitated between researchers and citizens. This will help raise awareness amongst researchers of areas of public interest and potential issues, while helping citizens connect with researchers and the research being conducted. At the same time, opportunities should ne provide for researchers to learn how to engage with stakeholders effectively. Mechanisms to inform broad research directions through including citizen engagement should be explored, where the end goals have social significance. This is an area where the UK Research Councils have had some success.[11][12] However, it should be stressed that while citizen engagement can help inform research directions, it is not proposed as a means of exploring research solutions.
46. **Goal 2:** If facilitated appropriately, citizen engagement can support the development of sustainable technologies by providing insight into technology solutions that more effectively address their wants and needs while addressing their concerns. Engagement also helps to bring citizens into the development process as partners, rather than as passive receptors. As the world becomes increasingly interconnected, established hierarchical decision-making structures are being replaced by new dynamics that provide citizens with increasing power to determine the fate of new technologies and products. A failure to engage with them effectively runs the risk of creating significant barriers to technology transfer – a lesson that was hard-learnt with the introduction of genetically modified foods in Europe.
47. **Goal 3:** Extensive investment is needed in informal and formal education, to help develop a skilled workforce and to enable citizens to get the maximum benefit from emerging technologies – either by helping people make informed decisions, helping them to understanding decisions they are forced into making, or by enabling them to appreciate better emerging science and technologies.
48. **Goal 4:** As citizens will be affected by decisions made over the development of products based on nanoscale science and engineering, they need to be an integral part of the conversation. Mechanisms are needed where there is effective engagement; where citizens are given a voice. This also means providing citizens with the tools and information the need – on their terms – to play an effective and active role in the responsible development of nanotechnology.

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[11] See for example Professor Richard Jones' account of the UK experience of public engagement: http://www.softmachines.org/wordpress/?p=443 (accessed 8/15/10). Professor Jones is the former nanotechnology advisor to the Research Councils UK

[12] Earlier this year, the Research Councils UK published three documents on Britain's approach to public engagement on science, covering their strategy for public engagement with research, providing a guide to researchers and teachers on engaging young people with cutting edge research, and outlining the benefits of public engagement for researchers. Further details at: http://2020science.org/2010/03/10/engaging-the-public-on-science-surely-youre-joking/

E. Evaluation.

E1. What specific criteria (e.g., nanotechnology publications and citations, nanotechnology patent activity, nanotechnology-related job creation, relative international nanotechnology investments) should the NNI use to evaluate its progress towards the NNI goal(s), and in what priority order?

49. If appropriate objectives are established in response to question A1, these criteria should become clear. That said, care should be taken not to limit the impact of the NNI by ignoring or dropping criteria that are not easily measured – in some cases impacts will intangible and yet still be important (an example might be the extent to which the NNI has stimulated new interdisciplinary research collaborations that have led to innovations only marginally related to nanoscale science and engineering). In these cases, qualitative indicators of impact might be helpful. However, there also needs to be accountability, to ensure resources and efforts are being used effectively. It is also important to consider nanotechnology in the context of emerging technologies more generally: Nanotechnology doesn't exist in a vacuum, and to set criteria of success that do not reflect this could well be detrimental. One possibility is to consider how advances in nanotechnology have contributed to progress toward specific challenges – renewable energy, managing climate change, alleviating hunger, etc. These could be specific, such as the development of new biofuels, flexible solar cells, food productivity, or clean water provision.

E2. Which organizations (e.g., government committees, independent organizations, international bodies) should perform the evaluation of progress towards the NNI goal(s)?

50. Evaluation of progress towards NNI goals should be conducted by an independent organization. Currently, responsibility lies with the President's Council of Advisors on Science and Technology (PCAST). While this group has only limited expertise in nanoscale science and engineering, its most recent review of the NNI[13] drew on the expertise of a specially convened working group. This process appeared to be reasonably successful (I served on the working group), but it was hurried, and somewhat disjointed. In the future, either a specialty subgroup of PCAST or a standing working group might be considered. Alternatively, responsibility of evaluating the NNI could be given to a new federal advisory committee.

E3. How can NNI best balance fundamental and applied research and development towards the NNI goal(s)?

51. While this is a deceptively complex question, it can only be approached I suspect by recognizing the reality that the boundaries between fundamental and applied research are extremely blurred, and that often the most innovative research occurs through a synergistic combination of fundamental and applied research.[14] In this case, the more appropriate question is perhaps how can a diverse and flexible research portfolio be developed that maximizes the opportunities for innovation?

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[13] PCAST. 2010. Report to the President and Congress on the Third Assessment of the National nanotechnology Initiative. Washington DC: President's Council of Advisors on Science and Technology.

[14] e.g. see Donald E. Stokes, Pasteur's Quadrant - Basic Science and Technological Innovation, Brookings Institution Press, 1997.

F. Policy.

F1. What new, or existing, policies should the NNI agencies develop or adjust to support the NNI goal(s) and to realize the broader economic and societal benefit associated with advances in nanotechnology?

52. Perhaps the most useful new policy stance that NNI agencies could adopt is to decouple the science of the nanoscale from policies governing its application in products and processes. This applies specifically to regulation, where too narrow a focus on nanotechnology can lead to ill-formed policy problems. But it also applies in other areas. The reality is that commercial products and processes depend on multiple technologies, of which technologies arising from nanoscale science and engineering may be just one component. Policies are needed that maximize the economic and societal benefits of the end products while minimizing adverse impacts. These need to be responsive to how nanoscale science and engineering can add value, and they should support this. But to be successful they should not be overly nano-centric.