Cross-Industry Issues in Nanomanufacturing

National Institute of Standards and Technology
Gaithersburg, MD
May 20–22, 2008

Keywords: nanomanufacturing, nanomaterials, nanoparticles, surfaces, interfaces, bonding, composites, separations, fractions, instrumentation, characterization, measurement, modeling, simulation, performance properties, consortium

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Workshop Affiliated with and in Support of the National Nanotechnology Initiative

National Science and Technology Council
Committee on Technology
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Acknowledgments

The sponsors wish to thank the principal authors of this report and all the participants at the workshop held on May 20-22, 2008 at the National Institute of Standards and Technology in Gaithersburg, Maryland. A complete list is provided in Appendix A. The presentations and discussions at that workshop provided the foundation for this report.

Special thanks go to the organizing committee, the breakout session leaders (listed below), and to all those who contributed to the writing of this report (noted at the beginning of each section). Thanks to Anne Chaka (NIST), Mike Garner (Intel), Michael Gaitan (NIST), Bob Gelman (Hercules), Ehr Ping Huangfu (DOE), Phil Jones (Imerys), Steve Masia (Sappi), Mike Postek (NIST), Dianne Poster (NIST), Gerard Closset (Agenda 2020 Technology Alliance of AF&PA), and John Cowie (Agenda 2020 Technology Alliance of AF&PA), who played leading roles in organizing the workshop.

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- Gale Holmes (NIST)

Separations and Fractionation:

- Michael Gaitan (NIST)
- Dierk Roessner (Wyatt Technology Corp)

Thanks to NIST conference services staff for organizing the logistics and making sure the workshop went smoothly.

Thanks to Joan Pellegrino and the staff of Energetics Incorporated of Columbia, Maryland, who assisted with the design, coordination, and facilitation of the workshop, and in developing this workshop report.

We thank the members of the Subcomittee on Nanoscale Science, Engineering, and Technology for their helpful input to the development of this workshop topic. We would additionally like to thank the National Nanotechnology Coordination Office staff for valuable guidance in the formulation of the workshop and report. Input and support from Philip Lippel and Liesl Heeter merit out thanks. In this same vein, we thank Geoff Holdridge, who was especially helpful in providing advice and assistance.

The final copy editing of this report and its production was accomplished under considerable pressure by Donna Kimball (NIST), who made it possible for us to meet our publication goal.

Preface

On May 20-22, 2008, numerous thought-leaders from industry, national laboratories, Federal agencies, and universities came to the National Institute of Standards and Technology campus in Gaithersburg, MD, to participate in the NIST *Workshop on Cross Industry Issues in Nanomanufacturing* (See Appendix A for the list of participants).[1] The organizing committee had worked for over a year, holding small workshops and discussions with stakeholders across industrial sectors, to identify the priorities for crosscutting issues in nanomanufacturing. It's been generally understood in the nanomanufacturing community that companies must find the ways and means to determine if nanotechnology-enabled processes and products can lower their costs, add value, or improve performance to provide competitive advantage over current technology. This workshop provided a venue for such discussion. The approach was to find similar problems and potential solutions within widely different industries.

Workshop Objectives: To identify common problems and common solutions specific to nanotechnology, manufacturing processes, and performance of nanomaterials in commercial products within widely different industries, including aerospace, automotive, chemical, food, forest products, medical technology, pharmaceutical, and semiconductor. The technical focus was on the three highest cross-industry priorities identified in previous workshops and meetings as they apply to the design, synthesis, and production of nanotechnology-enabled products:

- **Characterizing nanomaterials and enhancing their separation and fractionation** to address challenges in commercial production of uniform, high quality, stable, and consistent (reproducible) nanomaterials in high volume,
- **Understanding and controlling the surface-dependent properties of nanomaterials,** such as dispersion, aggregation, and adhesion at their interface with a matrix, with an emphasis on non-covalent bonding interactions, to control nanoscale building blocks needed for products,
- **Understanding and controlling multiple properties of nanocomposites** by design to enable the development of more superior and less expensive nanocomposites that simultaneously optimize multiple properties.

Within each of these topics, common issues included, although were not limited to, measurement, characterization, modeling, performance properties, and environment health and safety concerns. Throughout the workshop, emphasis was placed on identifying the needs that were cross-cutting in nature and could impact multiple industries and products.

Workshop Outcomes: Through presentations and breakout sessions, the workshop participants (1) identified several of the discrete and universal technical challenges to meet industrial needs and priorities, and (2) established the agenda and framework to address these challenges by:

- Enabling cross-fertilization and identification of best practices using currently available science and technology to deliver short-term impact,
- Defining collaborative research programs that cross industrial sectors, government agencies, and academic disciplines to address the more difficult challenges and long-term needs,
- Identifying those programs that are appropriate for Federal and/or industrial funding, and
- Setting the groundwork for formation of consortia and multi-organizational R&D projects.

[1] Agenda 2020 Technology Alliance of the American Forestry and Paper Association, BD, The Boeing Company, Cantox Health Sciences International, Corning, DuPont, FMC Biopolymer, GE, General Motors, Hercules Inc., Intel, Imerys Minerals Ltd., International Paper, Luna Innovations, Lux Research, Pall Corporation, Sappi Fine Paper, Specialty Minerals Inc., and Wyatt Technology Europe GmbH. In addition, ten Federal agencies and national laboratories participated (NIST, National Science Foundation, Office of Science and Technology Policy, Oak Ridge National Laboratory, Nanotechnology Characterization Lab, Environmental Protection Agency, National Institute for Occupational Safety and Health, Department of Energy, National Nanotechnology Coordination Office, US Consumer Product Safety Commission), and six universities: the University of Maryland (Department of Materials Science and Engineering and the Sloan Biotechnology Industry Center), University of Massachusetts (Center for Hierarchical Manufacturing, MassNanoTech, and the National Nanomanufacturing Network), Oregon State University, Purdue University, Rensselaer Polytechnic Institute, University of Tennessee, and Washington State University.

This workshop built upon issues identified in recent meetings and workshops including the Joint Chemical & Semiconductor Industry Workshop on Research Needs for Modeling of Nanomaterials (NIST, May 2006), the Interagency Working Group Workshop on Instrumentation, Metrology, and Standards for Nanomanufacturing (NIST, October 2006): http://www.mel.nist.gov/nano.htm; and the Agenda 2020 Technology Alliance of the American Forestry and Paper Association nanotechnology workshop with Federal agencies (February 2007): http://www.afandpa.org/. This workshop was also coordinated with ongoing activities in "Predictive Modeling of Nanomaterial Properties" addressed in the recent National Science Foundation-sponsored workshop (National Science Foundation, October 2007): http://www.ncn.purdue.edu/workshops/predictivemodeling/needs.

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Executive Summary

An increasingly competitive global market is driving industry to identify more effective ways to meet customer needs by adding value and reducing costs. Nanotechnology offers the promise of dramatically increasing competitiveness by removing long-standing performance limitations. In addition, nanotechnology is expected to revolutionize manufacturing processes and products across many high-value industry sectors, such as medical technology, electronics, aerospace, automotive, chemical, food and dietary supplements, forest products, and pharmaceuticals. Global investment in nanotechnology rose to nearly $13.5 billion in 2007, with a global market predicted by Lux Research to grow from $147 billion in 2007 (see Exhibit 1-a) to over several trillion dollars in the next decade. But significant technical barriers inhibit the discovery, high-volume manufacture and widespread commercialization of nanotechnology-enabled products needed to fuel this growth. The United States Government has invested over $10 billion over the last ten years and is a long-standing leader in nanotechnology funding. Other nations are now rapidly increasing their investments and eroding this lead.

Challenges to the discovery, manufacture, and commercialization of nanotechnology arise because nanoscale structures are at or beyond the limits of our current capabilities to characterize, manipulate, model, and control. The requisite scientific, measurement and data infrastructure is still in its infancy. Hence, addressing the barriers to the discovery, manufacture, commercialization of nanotechnology-enabled products is beyond the scope of individual companies. While each industry faces its own set of challenges in harnessing the potential benefits of nanotechnology, there are issues currently hindering widespread industrial applications that are shared by all, and the solutions to these problems will have the greatest effect on establishing U.S. leadership in manufacturing nanotechnology-enabled products. For example, both the medical and the aerospace industries have safety and performance concerns, as well as multimillion dollar testing costs per formulation, that dictate nanomaterials be highly purified, uniform, and consistent in large quantities, which is very difficult to achieve.

Hence, this workshop was organized at the National Institute of Standards and Technology (NIST) with the unique purpose of identifying common problems and common opportunities where focused research and collaboration will deliver high-impact solutions to solve fundamental challenges across many industrial sectors. The organizing committee worked for over a year prior to the workshop, holding small workshops and meetings with stakeholders, to identify the top three priorities for crosscutting issues in nanomanufacturing. These three breakout topics are shown in Exhibit E-1. All the topic areas are strongly dependent on a fundamental understanding of the physics and chemistry of surfaces and interfaces. Within each of these topics, common issues included—although were not limited to—measurement, characterization, modeling, performance properties, and environment, health, and safety concerns.

Exhibit E-1 Description of Cross-Industry Nanomanufacturing Workshop Breakout Topics

Surfaces, Interfaces and Non-Bonded Interactions of Nanomaterials	Nanotechnology-enabled Composites and Matrices	Separations and Fractionation
Identify fundamental science needs and measurement capabilities required to understand and control the surface-dependent properties of nanomaterials such as dispersion, aggregation, and adhesion at their interface with a matrix, with an emphasis on non-covalent bonding interactions, to enable materials by design and overcome challenges in commercial production.	Identify fundamental science needs and measurement capabilities required to understand and control multiple properties of nanocomposites by design to enable superior performance and reduce cost.	Identify fundamental science needs and measurement capabilities required to characterize nanomaterials and enhance their separation and fractionation to address challenges in commercial production of uniform, high quality, stable, and consistent (reproducible) nanomaterials in high volume and at high throughput.

The *Cross-Industry Issues in Nanomanufacturing Workshop* was held on May 20-22, 2008 at NIST, Gaithersburg, MD. Numerous thought leaders from industry, government agencies, and universities came to the workshop with applications in mind that could immediately benefit from investment in common solutions at a fundamental, precompetitive level. The following key questions common to all industrial sectors were posed:

- How can a company determine if nanotechnology offers sufficient competitive advantage to warrant the cost of innovation?
- How can developers predict the value nanotechnology will add to their new product in the face of numerous uncertainties in the manufacturing chain from the properties of the constituent nanomaterials to the performance of the final product?
- How as a nation, can we manage risk to make nanotechnology competitive with other technologies and reap its enormous potential benefit?
- How can we obtain the health and environmental information needed to protect workers and guarantee the safety of end-products?
- What means are available to mitigate the uncertain development cost of breakthrough nanotechnology-enabled solutions?

In addition, the workshop participants emphasized the need for greater investment in fundamental science directed towards industrial problems to enable companies to determine the potential added value of nanotechnology-enabled products and ensure product quality, consistency, and safety. Advances in fundamental science have the advantage of being precompetitive and the most easily leveraged across industrial sectors.

The following (non-prioritized) cross-cutting needs emerged from the workshop:

- The characterization of nanomaterials and their properties in isolation and in matrices, with respect to size, shape, charge, chemistry, uniformity, and distribution. Measurement science needs to be developed that is capable of both nanoscale resolution and statistical significance in high-throughput modes,
- The creation of an accurate database of nanomaterial properties and their nanomanufacturing process conditions to enable materials and processes by design and reduce trial and error,
- The development of validated modeling capability to predict multiple properties of nanomaterials in complex matrices to reduce the time and cost to develop new products and processes,
- The development of nanomaterials with high-value properties that can't be achieved without the novel properties of the nanotechnology components,
- The identification of factors controlling biological interactions of nanoparticles—free and in matrices—to accurately assess and predict environmental, health and safety risks,
- The articulation of reference materials, reference property data, and reference measurement requirements needs,
- The characterization of scale-up challenges for both process control and high-throughput manufacturing and measurement capabilities,
- The challenge to bridge the gap between academic research and commercial needs,
- The development of standards for nanomanufacturing process terminology, nanomaterials specifications, nanomaterial reference standards, and EHS controls.

Workshop participants agreed that the common issues identified in this workshop are only a beginning and that considerable follow-up work is required. These future efforts should be focused on the following:

- Developing validated models and fundamental understanding that can accurately predict the performance and reliability of nanomaterials and nanocomposites,
- Advancing methods for in-line multi-dimensional (size, shape, charge, etc.) high throughput nanocharacterization essential for scaleup, uniformity, and consistency (reproducible quality),
- Advancing methods for increasing manufacturing throughput, yield, and quality.

The prioritized results of the workshop are presented in Exhibit E-2, including major barriers and solutions in each of the topic areas.

Exhibit E-2 Workshop Results: Barriers and Priority Cross-Industry Solutions to Advance Nanomanufacturing

Barriers	Priority Solutions
Surface/Interfaces and Non-Bonded Interactions of Nanomaterials	
· Regulatory/Legal/ Organizational · Characterization and Measurement · Modeling · EH&S · Performance Properties	· Predict and control toxicity of nanoparticles · Develop reference systems relating to market needs · Establish network of labs that test and develop standards for nanomaterial characterization · Research on surface interface properties relevant to performance · Collect list of existing models, measurement tools, and biological interaction assays · Identify or develop surrogate measurement tools for on-line measurements that relate to research tools · Integrate industry needs and academic funding—mechanism and framework to translate commercial needs into fundamental science questions · Correlate fundamental nanoparticle surface understanding to performance priorities · Improved computational models for nanomaterial surface interactions · Measurement techniques and predictive models interaction: identify gaps and devise solution development · Increase collaboration in modeling and experimentation
Nanotechnology-enabled Composites and Matrices	
· Value · Multi-Scale Modeling · Characterization · Measurement · Performance Properties · EH&S	· Nanomaterials informatics and knowledge base to accelerate progress · Develop methodology to control reactions and bonding of nanoscale particles within a matrix and across interfaces · Build value proposition for use of nanomanufacturing to meet customer needs · Develop tool kit enabling measurement at nano- to micro-scale (including dispersion of nanoparticles within a matrix and at interfaces) · Predictably scale up lab-scale processes to manufacturing-scale for production of nanomaterials and products · Optimize manufacturing processes · Coordination of research on nanocomposites and matrices across industry, universities, Government, and Federal laboratories
Separations and Fractionation	
· Measurement Methods · Removal of Non-Nanomaterials · Manufacturability · Purification · Characterization	· Develop parallel microfluidic methods · Build high-throughput production/scalable methods · Enable modeling to predict process and material characteristics · Develop in-line measurements and visualization: transfer laboratory analytical methods to in-line

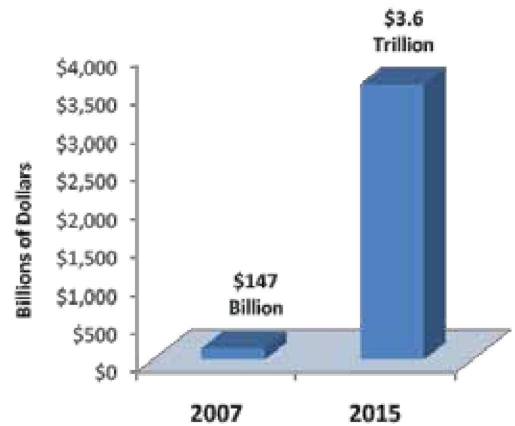
A concerted effort by industry, government and others to address common issues would expedite the resolution of the challenges listed in Table E.2. One important idea that emerged at the workshop was the development of an umbrella alliance which is a multi-industry Nanomanufacturing Consortium, one that would be industry driven (industrial decision makers with long-term commitment, trade associations, and individual companies) and government facilitated and supported. The purpose of this Consortium would be to help consolidate multi-industry research needs, map existing research and capabilities, consortia, and initiatives, and build a nanomanufacturing knowledge base in targeted areas. Moreover, the Consortium would accelerate progress in nanomanufacturing science, engineering, and technology in areas of common need through identification and communication of common needs, and coordinate interactions with funding agencies, Federal laboratories, and academic researchers.

While there is both considerable Federal and private investment in nanotechnology research, the challenges remain in prioritizing what needs to be done and leveraging outcomes (gaining the most benefit for dollars spent). Many government agencies are making a push toward cross-industry programs to expand the reach of research and development. For the U.S. this coordination is critical to attaining and maintaining global leadership in a competitive environment and to achieving the benefits of nanomaterials and nanotechnologies.

1. Introduction

Nanotechnology holds the potential to remove long-standing limitations, solve technical problems, and even revolutionize manufacturing processes and products across many industry sectors, such as medical technology, electronics, aerospace, automotive, chemical, food and dietary supplements, forest products, and pharmaceuticals. Global investment in nanotechnology rose to nearly $13.5 billion in 2007, with a global market predicted by Lux Research to grow from $147 billion in 2007 (see Exhibit 1-a) to several trillion dollars in the next decade. But significant technical barriers inhibit the discovery, high-volume manufacture and widespread commercialization of nanotechnology-enabled products needed to fuel this growth. The United States Government has invested over $10 billion over the last ten years and is a long-standing leader in nanotechnology funding. Other nations are now rapidly increasing their investments and eroding this lead.

Exhibit 1-a Projected Economic Value for Nanotechnology Products



Source: Lux Research

Other parts of the world are emphasizing applied research and development (R&D) to accelerate commercial development of nanotechnologies. The U.S. must do the same to capitalize on its vast investment, ensure cost-effective manufacturing of new nanotechnology-based products, and maintain global leadership in this emerging field.

To achieve the potential of nanotechnology, viable methods are needed to scale up the production of promising nanostructures to a commercial level without losing their unique and valuable properties. Integrating nanotechnology at production scales often entails resolving fundamental issues of physics, chemistry, biology and other core sciences. A cross-industry approach may be the best way to solve these fundamental challenges. While each industry faces its own set of challenges in harnessing the potential benefits of nanotechnology, many issues currently hindering widespread industrial applications are shared by all. A concerted effort by industry, government and others to address common issues could expedite the pace of nanotechnology advancement and benefit all stakeholders.

In the history of industrial innovation, advances that are sufficiently new and disruptive, i.e., that have the potential to change the basis of competition, present challenges to the inventors and early-adopters. Among these challenges is the high up-front investment in R&D before the added-value can be demonstrated, high capital investment for manufacturing, uncertain or non-existent supply chains, and insufficient scientific foundation and measurement capabilities to understand and measure the factors that need to be controlled to ensure quality and performance of the final product. These challenges were seen in the early days of the transistor and integrated circuits, for example, and are now being faced by a wide range of industries considering nanotechnology-enabled technology. In the current global market, companies must find the means to address these barriers to determine if nanotechnology-enabled processes and products can lower their costs, add value, or improve performance to provide competitive advantage over current technology.

1.1 Workshop Overview

The *Cross-Industry Issues in Nanomanufacturing Workshop* was held on May 20-22, 2008 in Gaithersburg, Maryland to explore critical cross-industry issues in nanomanufacturing. The workshop was cosponsored by NIST, the Agenda 2020 Technology Alliance of AF&PA, the University of Maryland Department of Materials Science and Engineering, Imerys, SAPPI Fine Paper, and USFS. The workshop was coordinated with ongoing activities in "Predictive Modeling of Nanomaterial Properties" addressed in a recent workshop sponsored by the National Science Foundation and the Network for Computational

Nanotechnology where it was noted that experimental methods are not always able to probe the length and time scales accessible to electronic structure or simulations at the atomic level.

The objective of the Cross-Industry Issues in Nanomanufacturing Workshop was to identify common problems and solutions specific to nanotechnology, manufacturing processes, and performance of nanomaterials in commercial products. Workshop attendees included experts in the field of nanotechnology manufacturing, as well as generalists in nanotechnology and related fields. A complete list of workshop participants and contributors to this report is provided in Appendix A. The workshop included plenary presentations and focused topical presentations throughout the first two days, interspersed with concurrent breakout sessions. The agenda for the workshop is provided in Appendix B; a list of presentations (many of which are available at the workshop website:
(http://www.ncn.purdue.edu/Content/Workshops/Predictive_Modeling_of_Nanomaterial_Properties_-_Modeling_Needs) is included in Appendix C.

Breakout Session Topics. The organizing committee had worked for over a year, holding small workshops and discussions with stakeholders across industrial sectors, to identify the priorities for crosscutting issues in nanomanufacturing. It's been generally understood in the nanomanufacturing community that companies must find the ways and means to determine if nanotechnology-enabled processes and products can lower their costs, add value, or improve performance to provide competitive advantage over current technology. This workshop provided a venue for such discussion. The approach was to find similar problems and potential solutions within widely different industries. Additional input was taken from the Joint Chemical & Semiconductor Industry Research Needs for Modeling of Nanomaterials, NIST, June 2006; Interagency Working Group Workshop on Nanomanufacturing, NIST, October 2006 - http://sites.energetics.com/nanocrosscutmay08/. These priority topics were selected and adopted as the main focus areas for this workshop. Exhibit 1-b summarizes the scope and context of each of the topics discussed. Within each of these topics, common issues included—although were not limited to—measurement, characterization, modeling, performance properties, and environment health and safety concerns. Throughout the workshop, emphasis was placed on identifying the needs that are cross-cutting in nature and could impact multiple industries and products.

Although not all-inclusive, the common issues shown in Exhibit 1-c served as central themes in all groups. These themes represent some of the known major challenges that must be addressed to ensure that the full potential of nanotechnology can be achieved.

Exhibit 1-b Description of Cross-Industry Nanomanufacturing Workshop Breakout Topics

Surface/Interfaces and Non-Bonded Interactions of Nanomaterials	Nanotechnology-enabled Composites and Matrices	Separations and Fractionation
Identify fundamental science needs and measurement capabilities required to understand and control the surface-dependent properties of nanomaterials such as dispersion, aggregation, and adhesion at their interface with a matrix, with an emphasis on non-covalent bonding interactions, to enable materials by design and overcome challenges in commercial production.	Identify fundamental science needs and measurement capabilities required to understand and control multiple properties of nanocomposites by design to enable superior performance and reduce cost.	Identify fundamental science needs and measurement capabilities required to characterize nanomaterials and enhance their separation and fractionation to address challenges in commercial production of uniform, high quality, stable, and consistent (reproducible) nanomaterials in high volume and at high throughput.

1.2 Organization of the Report

This report is based on the discussions and recommendations resulting from the Cross-Industry Issues in Nanomanufacturing Workshop held on May 20-22, 2008, and the presentations provided by plenary and other speakers.

The industrial needs are presented in Chapter 2 beginning with a summary section, followed by a section contributed by each industrial sector and national nanomanufacturing center in attendance. This chapter also includes a discussion of life cycle needs.

The remainder of the report is organized around the breakout topics shown in Exhibit 1-b, with a section in Chapter 3 devoted to each. For each breakout topic there is an introduction to the topic, a summary of current scientific and technical advances, discussion of the key barriers to success, and—most important—pathways for priority solutions. Mini-roadmaps of the most important factors for priority solutions (including key R&D needs, timelines, goals, existing solutions, barriers, risks, benefits, and partnership roles) were developed for each. The overall path forward is summarized in the concluding chapter, Chapter 4.

At the end of the report, appendices provide a list of participants and contributors (A), workshop agenda (B), list of presentations (C), and acronyms (D).

Exhibit 1-c Common Issues for Nanomanufacturing

Measurement and Characterization: determine the physical, chemical, biological, and technological properties and distribution of nanomaterials in isolation and in matrices with simultaneous high resolution, statistical significance, and high-throughput capacity

Process Control: control the manipulation and interactions of matter at the nanoscale to create nanostructures with unique properties; control their distribution and properties in the final product

Modeling: develop the science to predict the multiple properties of nanomaterials in complex matrices and establish nanomaterials property data infrastructure and an informatics/knowledge base

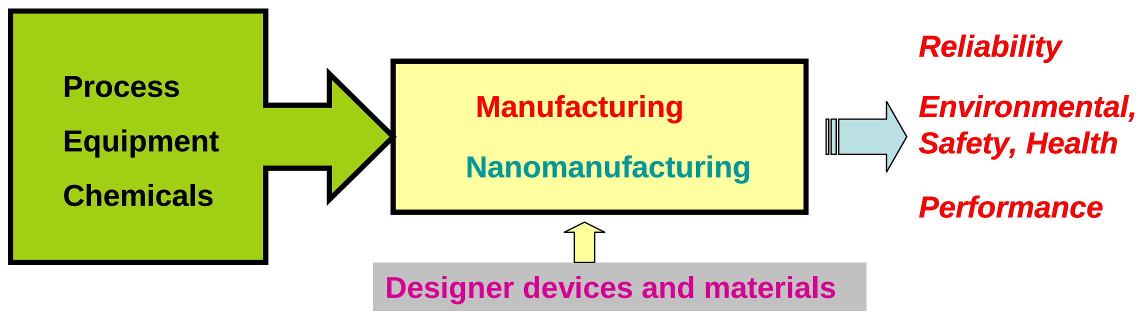
***Performance Properties*:** develop nanomaterials with high value properties that can't be achieved without the novel properties of the nanotechnology components, or lower costs

***Environment, Health and Safety*:** Gain knowledge of factors controlling biological interactions of nanoparticles, free and in matrices. Better enable reliable detection and measurement of the type and amount of engineered and/or preexisting nanoparticles in the workplace and in products across the full product life cycle including end-use environments

2. Industrial Needs in Nanomanufacturing

Generally, nanomanufacturing is defined as manufacturing of products at the nanoscale and targets production of new materials or devices with desired combinations of properties that can't be achieved with conventional methods or materials. The key goals are to use existing manufacturing processing expertise and to combine it with new processes as required. The end product should be new materials that are reliable, safe, and have the desired properties. The figure below illustrates the interdependencies.

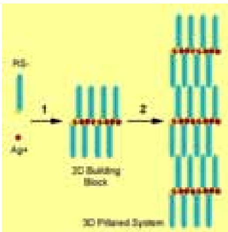
There are several benefits and challenges to nanomanufacturing as outlined in this report. In this chapter selected industries have identified their individual benefits and challenges. Also provided in this chapter are highlights of supporting efforts within the NSF-funded National Nanomanufacturing Network (NNN). Within this network are connections to various university and national lab centers, projects and experts from academic, industrial, and government institutions.

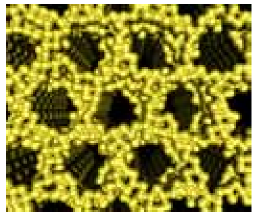


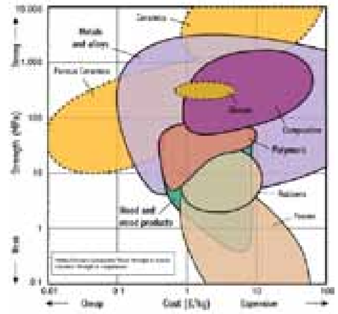
Nanotechnology's impact can be realized only though manufacturing of real products as needed by the different industries. Nanocomposite materials with improved properties can improve the structural integrity of regular materials, expand their operating limits, and provide innovative solutions for many needs throughout practically every industrial segment: electronics, health care, building materials, automotive/transportation, energy technology, and military, to name a few. For example, fundamental needs in the manufacturing and energy sectors for the U.S. include the need to: reduce wear in moving parts; reduce energy consumption; improve the efficiency of alternative energy extraction and utilization from sources such as solar, wind, and bio-fuels; improve catalytic performance of converters or reaction vessels; improve the durability of coatings; and make stronger, lighter composites. These needs can likely only be met through advances in the development of nanocomposite materials. These advances will require the synthesis of new materials and chemicals, the creation of new functional structures, the engineering of new devices, and the application of their use in multiple fields. Moreover, new manufacturing facilities, new technical capabilities, health and environmental studies, regulation for safe use, and adaptation within the educational infrastructure will be required. The synthesis of new materials and chemicals, the creation of new functional structures, the engineering of new devices, and their use in multiple fields will need new manufacturing facilities, new technical capabilities, health and environmental studies, regulation for safe use, and adaptation within the educational infrastructure.

The main challenges that overlap in all the industries represented at the workshop are given in the figure below: bottom-up self-assembly of materials, placement and assembly of materials, predictable and reproducible properties of nanostructured materials. In all the applications, techniques must be developed to (1) integrate nanomaterials into structures where their novel properties are preserved and accessible at the macro-scale, (2) place these structures in predefined locations with sub-nanometer accuracies, and (3) to integrate multiple nanomaterials for achieving desirable system properties. For example, in the semiconductor industry, to be useful in devices, interconnects or package applications, techniques must be developed to integrate these materials into structures where their novel properties are preserved and accessible at the macro-scale, and this is very challenging. For these materials to be useful in devices, the ability to control their nanostructure to enable reproducible semiconductor band-gap must be developed.

For devices and interconnects, the ability to place these structures in predefined locations with sub-nanometer accuracy must be developed. To use these materials in packages in thermal management applications, techniques must be developed to assemble these in high density in predefined directions with a low thermal contact resistance. In the aerospace industry, the additional challenges are two-fold; (1) nanostructured material understanding needs to be communicated and standardized through the entire supply chain, (2) value added compared to current resins needs to be demonstrated.







Self-Assembly **Placement and Integration** **Properties**

[Images courtesy of S. Shankar, INTEL, Corporation]

2.1 Represented Industries

[Photos courtesy of the USDA]

2.1.1 Food Industry

Food-based nanostructures may be envisioned as “structural composites”, where they may provide tailored textural properties and increased shelf stability in foods as well as offering the possibility of food-grade matrices for controlled release applications. Structure formation in all materials, including foods, is a highly complex process. Once molecules self-assemble, they are thermodynamically driven to self-aggregate into larger structures in the ~100 nm range in a process governed by non-covalent molecular interactions (e.g., hydrogen bonding and electrostatic interactions). For proteins, self-assembly drives the formation of secondary, tertiary, and quaternary structures. A similar approach can be envisioned for lipid and carbohydrate self-assembly.

The bioavailability, efficacy, and functionality of food ingredients, additives, and nutraceuticals may be greatly enhanced through nanoscience and nanotechnology. For example, current research involves incorporation of water- and oil-soluble ingredients—all of which are food-grade materials—in microemulsions, solid lipid nanoparticles, and self-assembled dairy peptides. In microemulsion research, the goal is to develop dilutable food-grade systems for controlled delivery of bioactives. One of the biggest challenges is the limited number of food-grade surfactants and co-surfactants available. Most microemulsions are not dilutable, which limits their use in beverages. Solid lipid nanoparticles are oil-soluble compounds in a crystal matrix. They offer increased stability through encapsulation. Potential applications include omega-3 fatty acids and vitamins. In dairy research, the goal is to use nanotechnology to design self-assembled peptide-based nanostructures with dual functions of delivery and bioactivity. Along these lines, emulsion,of plant sterols have been shown to enhance the LDL cholesterol-lowering properties in hamsters, and similar emulsions of gamma tocopherol have been shown to increase bioavailability and anti-inflammatory properties in mice. Self assembly of milk proteins is common in nature, and weak interactions lead to protein folding, micelles, or crystals. Recognizing these phenomena, researchers have been able to create milk protein-based nanotubes through enzyme hydrolysis technology and precise control and manipulation of processing conditions. The presence of calcium may play a role in the initial binding of the proteins. The novel protein structure (i.e., 20 nm diameter nanotube with 12 nm hollow core) provides new functionalities, such as texture, encapsulation, shelf-life stability, viscosity (replaces gelatin), and more.

There is 'natural' nanotechnology at work in the creation of food systems and assemblies, such as casein micelles. This strategy, however, is counter to the food industry approach, where a 'top-down' approach (e.g., emulsification via homogenization) produces thermodynamically unstable structures that must be kinetically-stabilized to achieve a suitable shelf life. With nanostructuring, stable entities are created (a 'bottom-up' approach), shifting the focus from microstructures to nanostructures. Nanoscale structuring of foods offers exciting possibilities for enhancing shelf life, functionality, and controlled release of bioactive compounds. Staling, breakdown of gel structures, and phase separation all contribute to textural changes during the storage of foods. With their inherent thermodynamic stability, self-assembled nanostructures may greatly increase shelf life by slowing down, and ideally preventing, such structural changes. This may be equally applicable to the prevention of off-flavors, which are often due to chemical reactions such as oxidation, or changes in color resulting in browning, which is caused by fat and/or moisture migration. The possibility of re-structuring existing food ingredients into nanoscale matrices that increase the viability of processed foods is one of the greatest strengths of this approach.

A specific example of where nanoscale structuring can play an important role is in preventing syneresis, which is the exudation of an aqueous phase from gels that contract over time (in dairy products, gelled desserts, tofu, etc.), and which reduces shelf life. Industry strategies to counter this problem often rely on the presence of added thickeners (e.g., starches) that bind excess moisture. This common strategy does not fundamentally address this problem (and thus the issue of reduced shelf life). Inspired by research in carbon-based nanostructured materials, food-based nanostructures such as self-assembled proteins may be used to generate stable structures capable of resolving this problem.

Lastly, nanoscale controlled release matrices such as microemulsions and solid lipid nanoparticles offer unique possibilities for increased efficiency in drug/bioactive delivery, the ability to cross biological barriers (e.g., cell walls and the blood-brain barrier), passive targeting and local accumulation in tissues, and increased solubility of drugs or bioactive nutraceutical ingredients. However, few if any food-related commercial applications for such nanoscale matrices exist. This field is still in its infancy, though the technological basis exists (e.g., microemulsions, nanoparticles, etc.). It is likely that the food industry will learn from the massive efforts in nanoscale drug delivery currently taking place in the pharmaceutical field.

These few examples show that there are extensive possibilities for the incorporation of nanoscale and nanotechnology derived matrices in foods, such as improvements in texture, shelf life and the development of food-grade controlled release matrices. However, for this revolution or evolution to occur, there are numerous technological hurdles, issues related to consumer acceptability, and safety concerns that must first be addressed.

2.1.2 Semiconductor Industry

The International Technology Roadmap for Semiconductors (ITRS) identifies the challenges that must be overcome for future technologies to continue increasing density and performance for the next fifteen years. The semiconductor industry is currently producing integrated circuits with minimum features less than 50 nm through lithographic pattering and etching and deposition of conventional materials. Continuing improvement requires overcoming challenges in the control of nanostructures and the resulting properties. New materials will be needed to enable technologies with sub-10 nm features in high density, devices with high electrical performance, low resistance electrical interconnects, and package and assembly processes that manage stress in the integrated circuit and effectively remove heat.

The self assembly of nanomaterials in periodic patterns at higher density than possible by conventional lithography has potential applications in extending lithography and in fabrication of high power density capacitors. The directed self assembly of block copolymers into lines and round opening structures with sizes <10 nm could be useful if they could be placed in precise locations with ultra low defect densities. Critical research is needed to enable the controlled placement of structures relative to previously generated structures and eliminating defects. For high power density capacitors, electrical conducting elements need to be assembled in high density with dielectrics placed between them. Self assembly has potential to enable this, but serious challenges must be overcome to achieve high capacitance devices.

Nanostructured materials such as carbon nanotubes or graphene have novel properties including high electrical conductivity, high thermal conductivity and high mechanical strength. To be useful in devices, interconnects, or package applications, techniques must be developed to integrate these materials into structures where their novel properties are preserved and accessible at the macro-scale, and this is very challenging. In devices the ability to control nanostructures to enable reproducible semiconductor bandgaps must be developed. Devices and interconnects require the ability to place these structures in predefined locations with sub-nanometer accuracy, which is not currently possible. To use these materials in packages in thermal management applications, techniques must be developed to assemble these in high density in predefined directions with a low thermal contact resistance.

Future integrated circuit technologies need package polymers with multiple properties optimized for application, processing, and use. Nanostructured materials have unique properties, such as low thermal coefficients of expansion, high mechanical strength, high toughness, and unique electrical properties. The ability to integrate these into polymers could enable simultaneous achievement of multiple desirable properties, but there is no "rule of mixtures" for nanocomposites. Similarly, the ability to integrate multiple nanomaterials into a composite, is needed enhance the potential for multiple properties. Therefore all potential interactions of nanomaterials in the composite structure must be fully understood and controlled.

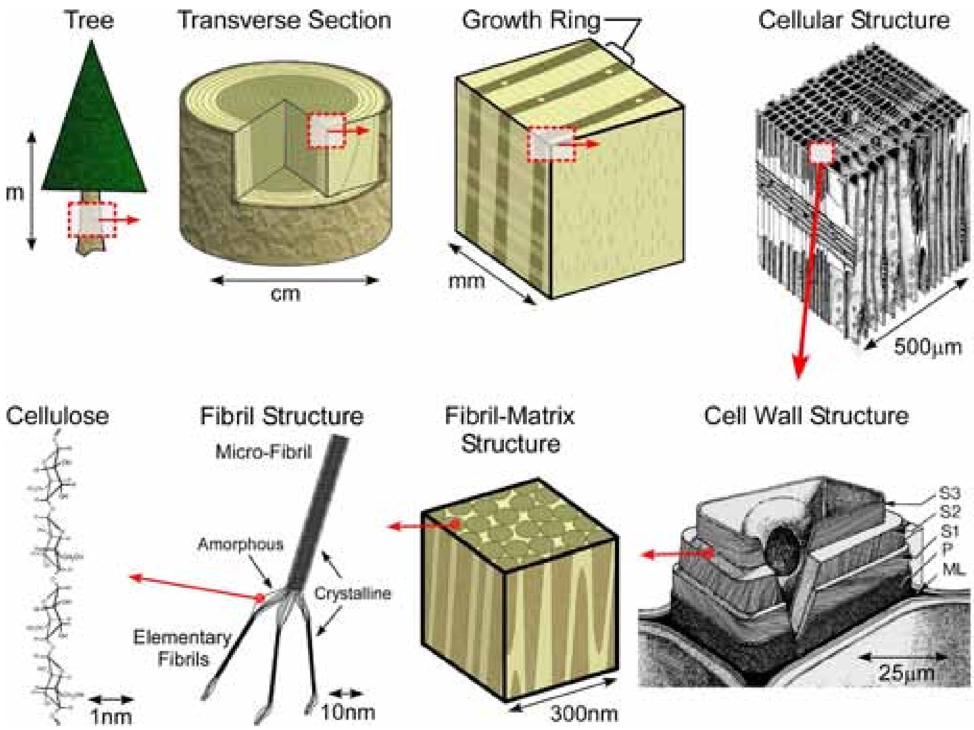
In all applications, the ability to control the nanostructure of materials and their interfaces to other materials is critical to provide solutions to future integrated circuit technology needs.

2.1.3 Forest Products Industry

Nanotechnology is an emerging area that carries enormous promise to revolutionize materials use leading to novel applications and products not feasible with conventional technologies. The forest products industry looks to nanotechnology as a means to tap the enormous undeveloped potential of trees as photochemical "factories" that produce abundant sources of raw materials using sunlight and water. Forest biomass resources provide a key platform for sustainable production of renewable, recyclable, and environmentally-preferable materials to meet the needs of society in the twenty first century. Wood-based lignocellulosic materials (i.e., forest biomass) provide a vast material resource and are geographically dispersed.

The forest products nanotechnology roadmap *(www.nanotechforest.org)* identifies the industry vision as "*sustainably meeting the needs of present and future generations for wood-based materials and products by applying nanotechnology science and engineering to efficiently and effectively capture the entire range of values that wood-based lignocellulosic materials are capable of providing*". In addition, the forest products industry sees its inherent strengths to include stewardship of an abundant, renewable, and sustainable raw material base; a manufacturing infrastructure that can process wood resources into a wide variety of consumer products; and being uniquely positioned to move into new, growth markets centered on bio-based environmentally-preferable products. Nanotechnology will enhance industry's ability to produce new high performance consumer products from lignocellulosic-based materials. The industry vision is well aligned with society's need for establishing a source of sustainable materials and products. The following are priority areas for nanotechnology in the forest product industry.

Improving the Strength to Weight Performance. The strength of lignocellulose-based fiber networks in paper and board are controlled by matrix components, bonding strength, fiber strength, fiber size and shape, effects of any additives or fillers, and uniformity of material distribution. In addition, there are end use product requirements for other key properties such as optical performance, surface smoothness, and stiffness. Large increases in strength-to-weight performance are not attainable with current technology.



Wood Nanodimensional Structure and Composition

This figure depicts how wood is a cellular hierarchical biocomposite made up of cellulose, hemicellulose, lignin, extractives, and trace elements. At the nanoscale level, wood is a cellulosic fibrillar composite. Wood is approximately 30 – 40 percent cellulose by weight with about half of the cellulose in nanocrystalline form and half in amorphous form. Nanocrystalline cellulose is relatively uniform in diameter and length and these dimensions vary with plant species. Cellulose is the most common organic polymer in the world representing about 1.5 x 10^{12} tons of the total annual biomass production. Cellulose is expressed from enzyme rosettes as 3 - 5 nm diameter fibrils that aggregate into larger microfibrils up to 20 nm in diameter. These fibrils self assemble in a manner similar to liquid crystals leading to nanodimensional and larger structures seen in typical plant cell walls. The theoretical modulus of a cellulose molecule is around 250 GPa, but measurements for the stiffness of cellulose in the cell wall are around 130 GPa. This means that cellulose is a high-performance material comparable with the best fibers technology can produce.

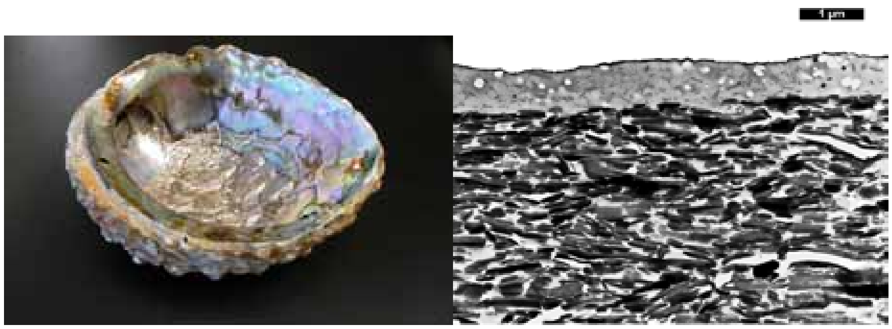
[Sidebar and graphics courtesy of T. Wegner, U.S. Forest Service]

Liberation and use of nanocellulose and nanofibrils. At the nanoscale, wood is composed of elementary nanofibrils (whiskers) which have cross-section dimensions of about 3 – 5 nm and are composed of cellulose polymer chains arranged in ordered (crystalline) and less ordered (amorphous) regions. Nanocrystalline cellulose has strength properties approximately equivalent to Kevlar®, and the forest products industry focus is on liberation and use of both nanofibrils (amorphous and crystalline cellulose) and nanocrystalline cellulose. Success will allow the forest products industry to be a major supplier of nanoparticles for a wide range of other industries. Because of the hundreds of millions of tons of wood available for processing, commercial production would be both sustainable and renewable as well as create an industrially significant supply. High value, renewable nanotechnology-enabled composites can be produced by identifying commercially attractive methods to liberate both nanofibrils and nanocrystalline cellulose and by establishing methods for characterization, stabilization, and blending of these wood-based nanomaterials with a variety of other nanomaterials.

Understanding water-lignocellulosic interactions. The response of wood and wood-based materials to moisture and their durability under high moisture conditions is due almost entirely to the super molecular structure of constituent biopolymers (i.e., cellulose, hemicelluloses and lignin) and nanoscale structures. An understanding of the interactions among moisture and woody material components at the nanoscale will enable development of new, innovative technologies that will improve both the durability and dimensional stability of wood and wood-based materials. In addition, understanding and manipulating the interactions between water and wood/paper should permit huge reductions in energy and water usage in converting wood to consumer products and allow more effective and efficient use of wood raw materials in a broad base of new and existing products. Lastly, development of a substantial knowledge base of lignocellulosic/water interactions is expected to lead to the development of new and improved products through control/modification of surfaces to provide barriers to prevent or control the transfer of moisture. This will enable the substitution of sustainable wood-based products for some products derived from less sustainable materials.

Papermaking: Self-assembly at 60 mph

High-performance nanotechnology-cellulosic enabled composites. Lignocellulose in woody plants is one of nature's most abundant materials, and wood-based lignocellulose at the macroscale level is one of our most used and ubiquitous materials. To date, the intrinsic self-assembling nanoscale structure of lignocellulose, as well as the versatility of its constitutive biopolymers, has not been fully exploited. Cellulose is a material that has unique tensile properties. However, during the processes to extract cellulose from trees or plants while removing lignin, the length and strength of the cellulose fibers are significantly decreased. It is desirable to achieve the next generation of high performance composites in which cellulosic nanomaterials provide maximum tensile strength and to use cellulose and cellulose-derived nanomaterials with varying combinations of other organic and inorganic materials to produce high-performance, multifunctional composites tailored to specific end-use performance needs. Potential composite properties besides strength include formability and geometrical complexity at the nanoscale, resulting in other unique physical properties, surface smoothness, biomedical compatibility, and ability to reinforce polymer foams.



Coating Structure

The structure of clay coating on paper is similar to the structure of an abalone shell (upper left), which achieves its remarkable strength and optical properties from a matrix consisting of 98% $CaCO_3$ nanoplatelets and 2% protein. The top image at right depicts a printed, coated paper. The thin top layer is ink, while the layer under the ink is the clay coating, designed to hold out the ink in a manner that maximizes print quality and performance. The bottom layer is the paper base, consisting largely of treated wood fibers and some pigments.

Nanotechnology-photonics. Many grades of paper require using higher grammage (basis weights) than needed, not because of strength property end-use requirements but because of the need to achieve sufficient opacity. While it is desirable to achieve costs and materials savings by reducing the amount of raw material for a given unit of functionality in both fiber and coating, optical performance of the paper cannot be compromised. More efficient optical performance with minimal weight will benefit all grade levels but especially the ultra-lightweight grades where opacity decreases rapidly with weight. Benefits include significant reduction in materials, processing and distribution costs. In order to be able to make high opacity coated paper in the same weight range of tissue paper, combinations with nanomaterials such as graphene, carbon nanotubes for electronics, optic manipulating nanomaterials, nanomaterials for high strength applications, and nanomaterials to control ink interaction must be explored.

2.1.4 Chemical Industry

The chemical and materials science industries are ideally suited to exploit the benefits of nanotechnology. The synthesis of nanoparticles, and their incorporation into products, is squarely within the scope of the activities of this industrial segment. The chemical engineering know-how in this sector puts the sector in a leading position to bring the potential of these new materials to fruition.

The potential benefits of nanotechnology, to the business enterprise and to society in general, are colossal. The creation of nanocomposite materials with improved properties can improve the structural integrity of materials, enhance their environmental operating limits, and provide innovative solutions for many needs throughout practically every industrial segment: electronics, health care, building materials, automotive/transportation, energy technology, and military, to name a few. Fundamental aspects of the operation of our society, such as: the need to reduce wear in moving parts; improving catalytic performance of converters or reaction vessels; improving the durability of coatings; extending control over drug delivery; making stronger, lighter composites; improving the efficiency of alternative energy sources such as solar, wind, and biofuels; all can be addressed with nanotechnology.

The integrated impact of nanotechnology will fuel economic growth for the next few generations. Nanotechnology may account for millions of jobs in the near future. The synthesis of new materials, the creation of new functional structures, the engineering of new devices, their implementation throughout society—all these activities will necessitate new manufacturing facilities, new technical capabilities, health and environmental studies, regulation for safe use, and adaptation within the educational infrastructure.

Realizing this potential means overcoming the challenges that we presently face. These challenges are as diverse as the resulting benefits. On a basic level, we do not yet have sufficient knowledge about the nanomaterials to be able to predict the wealth of improvement that can be made. Quantifying the magnitude of potential improvements is an ongoing effort in industry and academia at this moment. Nanomaterials push against our metrology limits. Characterizing their physical properties has already created a suite of new experimental approaches, and these have, in turn, begun to spawn new technologies. Manufacturing technology needs to be developed to generate the tons of material that will be necessary. We need to understand how these materials will co-exist with the ecological web of life on the planet. Health risks must be mitigated to be commensurate with potential rewards. There is also a challenge in education—preparing students to participate as workers in this field. Research needs to be incorporated into the current paradigm, and then disseminated to new generations of students, so that nanotechnology will be established at universities ten years from now in the same way molecular biology was established twenty years ago.

Finally, a clear national strategy needs to be enunciated. Currently, nanotechnology is in an embryonic stage. It is important to learn from the lessons of the past—chemical manufacturing, molecular biology, nuclear energy—to create a strategy that will bring lasting benefits to the world. The chemical industry has proposed a plan for a roadmap through 2020 in which the following needs were identified; specifically on manufacturing and processing. Several unit operations have been identified by the chemical industry as critical areas of focus; synthesis, separation, purification, stabilization, and assembly. In addition, surface engineering needs to address catalysts, ceramics, coatings, sorbents and membranes. Few programs are dedicated to issues of nanomanufacturing, and in the existing programs scale-up issues are not fully addressed. A research center or virtual center dedicated to process development is needed to provide sufficient impetus for progress in this area.

2.1.5 Aerospace Industry

In the aerospace industry, nanotechnology is seen as one possible route to the material systems and components of tomorrow's aircraft. The tremendous promise of nanotechnology to provide breakthrough material solutions has generated wide interest in nanotechnology-enabled materials among aerospace industry researchers. Material needs are as varied as their applications, and nanotechnology-enhanced materials provide opportunities to fill many of these needs. Aerospace structural material applications require materials that are large in scale, often meters in one or more dimension, such that the nanotechnology-constituents provide improvements to macroscopic materials properties. Aircraft electrical components, on the other hand, benefit more directly from nanotechnology for miniaturization, resulting in decreased power demand, lighter weight, and in some cases increased sensitivity. Such components are developed by the semiconductor industry; section 2.1.2 contains a detailed discussion of the electronics industry's needs in nanomanufacturing. The remainder of this assessment focuses on structural material systems.

The impacts of nanotechnology on the aerospace industry are broken into two categories: those technologies that allow the aerospace industry to improve its current designs, and those technologies that open new regions of design space. A nanomaterial that offers an incremental cost or weight savings over a current material, a nanotechnology-enabled electronics box that weighs less and uses less power, or a nanoscale surface modification to improve environmental protection, allow improvements in future designs. Weight savings are particularly precious to aircraft design; any material weight savings is realized several times over once the reduced propulsion, lift, and fuel needs are considered.

Other technologies may offer disruptive changes to the industry. Nanotechnology-enabled distributed sensor systems are being researched for structural health management, which may extend the usable lifetime of a vehicle. Lighter and stronger structural materials, especially with improved ablative properties, could extend the range, speed, and maneuverability limits of fighter aircraft. Structural materials that incorporate microwave absorption would provide increased defense against electronic attacks. Nanotechnology has the potential to enable multiple functions in a single material, which will be a great boon to aerospace design.

The aerospace industry has stringent certification requirements for materials to be used in planes and spacecraft. The high level of quality and process control applied to materials for the aerospace industry has caused certain materials to be classified as "aerospace grade," where materials without that qualification are considered "commercial grade." The methods used for certification drive an intense need for repeatability in material performance, which in turn drives a need for repeatability in the synthesis of materials. Manufacturing and processing technologies have been developed to produce consistent aerospace grade materials; moving to nanotechnology-enhanced materials will require the development of new manufacturing technologies and new processing technologies. In-process monitoring and control of dispersions and non-destructive proof of proper dispersion are nanotechnology needs that will enable the certification and use of nanomaterials. Other technologies are required to produce certifiable nanomaterials besides dispersions, such as surface roughness measurements over square meters in ambient conditions to certify surface treatments.

The ability to determine bulk properties of nanomaterials based on their constituents, or even better the ability to design a nanomaterial based on the required bulk properties, lies at the end of a very long road of future research. The understanding required to predict bulk properties and produce consistent nanomaterials is being gained through research via experiments and computational modeling. Establishing research and reporting standards and applying informatics will hasten the realization of these goals.

The aerospace industry has a wide variety of needs to which nanotechnology is beginning to be applied. Discovery of new solutions can be accelerated by understanding how to surpass or enhance existing materials in highly repeatable nanotechnology-enhanced material syntheses.

2.1.6 Filtration and Separation Industry

Nanoscale needs manifest themselves in multiple areas for the filtration and separation industry. There are specific products that need to be either purified or separated for the end user in both the industrial and life sciences market areas, and which can only be processed using filtration. The materials that are used to enable the filtration and separation require finer and finer elements down to the nanoscale in order to meet these stringent demands.

The life sciences market encompasses biopharmaceutical, biotechnology, and medical requirements. Manufacturers in the pharmaceutical and biotechnology areas require certain products to have viruses removed, contaminant particulate removed, and final product selected down to a set level in the nanotechnology region. Filtration and separation materials for such applications must have the correct selection capabilities and low extractables, meet government requirements in regards to use, and have high throughput and flow/flux capabilities. The challenge is being able to do this at an affordable cost. To accomplish this, quite often a series of separation steps are used in conjunction, for example, pre-filtration, chromatography and final filtration.

The life sciences market also covers diagnostics and detection where concentration, selection, and detection of molecules in the nanogram, or below, concentration range are to be found for various disease states and wellness programs. Obviously as the amount of material is low to start with, the amount of sample lost on route to the final detection point should be minimized throughout the process.

Medical requirements can be fairly stringent as nanoparticulates can be used for targeting tumors and drug delivery applications. All materials must meet regulatory as well as the application's needs.

The filtration and separation industry markets encompass food and beverages, semiconductors, power, water, chemical, transportation, aerospace, and military. Quite often the filtration and separation employed here is required to remove unwanted side products or contaminants from a production process making materials that will be used in a consumer product. Many of the filtration products deployed in these markets, combine polymeric and inorganic porous materials that have structures on the nanometer scale.

Nanoscale organic polymers and inorganic materials need to be essentially pure, because unwanted larger particles within a nanotechnology product can have undesired effects in any composite material made from them—such as mechanical failure, non-uniformity defects, or adverse pharmacological effects.

Filters are used to remove a wide range of submicron, and nanoscale particulate matter and micro-organisms, which would otherwise have an adverse effect on the product quality. In some cases, the end product is entirely enabled by the filtration process. Further still, filtration technologies can be deployed to remove soluble species to purify a fluid, for example, contaminants such as metals, or salts. This application is truly "sub-nano" in scale and requires filtration and separation structures with very fine pores.

With the drive in nanoscale processes for faster, more efficient ways to achieve the required end product purity level whilst maintaining affordability, the combination of multiple filtration and separation steps with on line nanoscale detection could help to achieve these lofty goals.

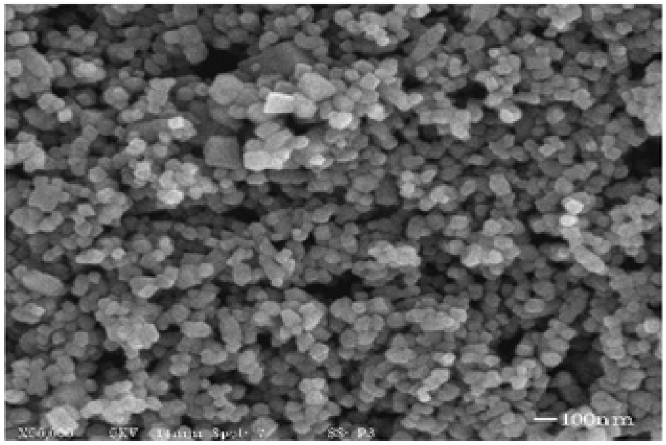
2.1.7 Industrial Minerals Industry

Industrial minerals are widely used in diverse applications and are the fabric of society. Many applications, such as cement/concrete, ceramics, filtration materials, bricks, plastics, paint/coatings, and paper coatings and fillers, have been in use for centuries where mankind has empirically developed formulations and methods of manufacture. Largely, these have been seen as traditional industries with no new scientific challenges. In fact these materials and applications are so complex that until recently people have largely stayed away from studying them at a fundamental level. Developments in analytical techniques are now allowing us to begin to understand the nature of these materials and realize that many of the key performance features are the result of interactions taking place at the nanoscale. In particular, studies of materials such as abalone shells, bone, dental enamel, and sea sponges are pointing the way to manage the interfaces and develop high strength materials through these biomimetic pathways.

Mining abundant nanoparticles (Image courtesy of P. Jones, Imerys)

For many years bentonites or montmorillonites have been intercalated and surface modified to provide nanocomposites of remarkable mechanical performance. These represent “nano-minerals” that exist relatively abundantly in nature and require modest processing to refine them to usable performance specifications. Other minerals such as calcium carbonate, alumina, and diatomaceous earth can be ground to nano-dimensions that expand their applicability. Many of these natural mineral forms can also be synthesized at large scale. Precipitated calcium carbonate (PCC) is just one example of this 'bottom up' approach to nano-minerals and is currently manufactured with primary particle size in the 20-70 nm range.

The challenge for synthesis is control of primary size, shape, surface chemistry, and dispersion. It is also possible to find minerals existing in the ground with at least one dimension less than 100 nm and showing performance properties different from the same minerals that have all dimensions greater than 100 nm. These “nano-minerals” such as thin crystal kaolin and halloysite have, for the most part, been overlooked because they have shown such radically different properties from commonly used clays and often have been difficult to disperse and stabilize. It is expected that there are many more nanodimensional minerals available for mining. We need the necessary protocols to be established to allow their discovery.



70 nm PCC for high impact, low temperature ductility PVC

Properties by Design: Synthetic mineral nanoparticles tailored to improve composite properties

"Synthetic minerals" refers to synthetic approaches to inorganic materials that allow control of product morphology while retaining the relatively low cost basis of common mineral compositions. These synthetic approaches are 'bottom-up' (growth from molecular scale) rather than 'top-down' (size reduction). Precipitated calcium carbonate (PCC) is made this way from lime and carbon dioxide. In nanoscopic form, it is used in plastic reinforcement, in rheological improvement of inks and sealants, and in high quality coated ink jet papers. The advantage of synthetic minerals often lies in their characteristic narrowness of distribution in dimension and shape. This allows for tuning of their morphology to the needs of a specific application. A typical application for many years is in highly impact-resistant PVC fittings such as the pipes and joints shown in the figure above.

The opportunity exists to increase exploration work to identify other nano-dimensional minerals that will be cheaper to recover and beneficiate so that we can expand their use into commodity applications. The existing minerals industry process in the United States has substantial capacity in place not only to mine but also refine minerals by "cracking" (grinding) and "distilling" (by a variety of centrifuge types) nano-dimensioned minerals. Similarly it is possible to capitalize on the installed capacities to synthesize minerals. Often these nano-dimensioned minerals have unusual properties compared with conventional mineral forms and have been passed over because of this. The opportunity exists to focus efforts and tools of nanotechnology to enable the manufacture of large volumes of well characterized nano-minerals at price points of less than $1 per pound.

As with other materials discussed in this report, the use of industrial minerals is challenged by the same lack of understanding of means to separate and stabilize nanotechnology mineral components, the ability to disperse and handle these building blocks, and to assemble them into useful composite structures. Findings emerging from biomimetic studies are beginning to point the way towards ways of assembling minerals into tougher pragmatic composite materials[1]. Combining natural and synthetic approaches to develop hierarchical composite nanostructures may be the ultimate way to bring the advantages of the nanoscale into practical, large-volume applications.

A number of formidable scientific and technical challenges remain with respect to advancing nanotechnology involving the production and use of nano-dimensional minerals. These challenges include characterization, separation and refining, dispersion, surface chemistry and interface interactions, and self-assembly. Nanoscale minerals need to be able to be quickly and accurately characterized with respect to their particle shape, particle size distribution, and bulk and surface chemistry. Commercially viable processes are need for separation and refining based upon mineral type, mineral particle size, and mineral three-dimensional shape. New and improved dispersant technologies are needed to effectively and efficiently disperse nano-dimensional minerals in order to keep the particles separate. In addition, it is also desirable for dispersants to be functional so that they can participate in subsequent reactions. Additionally it is critically important to be able to understand the surface chemistries of nano-dimensional minerals and to be able to quickly characterize them with respect to bonding site types, location, and bonding site density. It is also important to be able to identify the range of chemistries useful for a particular mineral species. Lastly, it is important to identify and develop self-assembly strategies that will allow production of high-strength and high-toughness composites made up of varying combinations of minerals and other organic and inorganic constitutive materials and that enable development of smart surfaces and structures.

"Synthetic minerals" refers to synthetic approaches to production of inorganic materials that allow control of product morphology while retaining the relatively low cost basis of common mineral compositions. These synthetic approaches are "bottom-up" (growth from molecular scale) rather than "top-down" (size reduction). PCC is made this way from lime and carbon dioxide. In nanoscopic form, it is used in plastic reinforcement, in rheological improvement of inks and sealants, and in high quality coated ink jet papers. The advantage of synthetic minerals often lies in their characteristic narrowness of distribution in dimension and shape. This allows for tuning of their morphology to the needs of a specific application. A typical application for many years has been in highly impact-resistant PVC fittings such as the pipes and joints shown in the sidebar above.

2.1.8 Pharmaceutical and Medical Device Industries

The pharmaceutical and medical device industries are aggressively pursuing "nanomedicine" applications of nanotechnology and nanoparticles.[2,3] Pharmaceutical applications of nanotechnology include drug discovery & development, drug and gene delivery, nanoparticle drugs, and *in vivo* imaging and cell labeling. Medical device applications of nanotechnology include *in vitro* diagnostics, biomaterial composites for dental, orthopedic, and tissue engineering scaffolds, and active biomedical implants and artificial organs.

Drug discovery. Nanotechnology is currently being investigated to speed up the drug discovery and development process. Applications include, but are not limited to: (1) nanoparticles for detection, quantification, synthesis and analysis of drug targets; (2) rapid target screening; (3) rapid target validation and assay development with reduced sample and reagent volumes and cost; (4) nanofluidics; and (5) personalized medicine approaches that encompass imaging studies, rapid screening, rapid optimal formulation development, toxicity studies using remote sensing, and the identification and measurement of compounds that are indicative of disease.

Drug delivery. Nanoparticle drug delivery mechanisms and formulations can improve therapeutic efficacy and bioavailability. Issues such as poor solubility, tissue damage, rapid breakdown of drugs *in vivo*, unfavorable kinetics, poor biodistribution, and lack of selectivity are being solved with applications of complex nanoparticle surface and layered structures.[4,5] The development of controlled release nanoparticles appears to be a rich field for drug delivery improvements. Nanoparticle properties that may impact drug delivery include size, shape, charge, hydrophobicity, and surface targeting (labeling).

Drugs. Nanoparticles themselves may be used as therapy in the treatment of disease. Applications include dendrimers and fullerenes.

***In vivo* imaging.** Nanoparticle MRI and ultrasound contrast agents have been developed, and much current work is being done to develop extra- and intra-cellular optical and infrared reporters taken up by specific cell types and sensitive to individual molecules within the cells.

Diagnostics. Nanoparticle-based diagnostics promise to dramatically improve the sensitivity and specificity of detection of biological molecules, enabling measurement of compounds that are rare (i.e., outside the range of compounds measured in currently available medical diagnostic tests) or that are present at only minute levels in the body. Current approaches make use of *in vitro* samples for testing, but nanoparticle-based diagnostic approaches are predicted to enable *in vivo* monitoring within the body. In fact, new methods of nanoparticle-based diagnostics are frequently reported in today's literature base. Some examples include carbon nanotube-based sensors,[6] multiplex protein assays using magnetic nanotags with giant magnetoresistance sensing,[7] quantum dots for fluorescent sensing, and gold nanoparticles for SERS (Surface-Enhanced Raman Sensing).

Biomaterials and Implants. Nanotechnology research promises to improve the design and control of material bulk and surface properties. The research is enabling development of better nanocomposite materials for dental and bone replacements, porous materials for tissue and bone regeneration and replacements, surface modification and control, including non-fouling and biofilm-suppressing nanomaterial coatings to improve infection control in medical devices, non-thrombogenic surfaces for cardiovascular implants, nanoporous materials for nanofiltration separations, and nanocoatings for biomolecule adsorption and immobilization, to name but a few examples.

These applications of nanotechnology to the pharmaceutical and medical device space will require robust manufacturing processes and measurement systems to meet quality system validation requirements and bring these nanotechnologies to the market.

2.2 Manufacturing and Life Cycle Challenges

The research conducted to date indicates that engineered nanomaterials can undergo rapid alterations in composition, surface property, morphology and physical state. This is especially evident when these compounds interact with other engineered nanomaterials, with other compounds, or as they move through the environment (air, water, soil). Current research also indicates that the toxicity of these materials changes as their properties are changed. For example, a nanomaterial that has a certain coating that becomes degraded may express toxicity although the original form may not. Consequently, there is a need to understand where in the life cycle of the product the nanomaterial exposure could occur, what form the nanomaterial is in at that point (detection and characterization), and how stable the resulting nanomaterial is. Research to improve our scientific understanding of how and when these materials enter the environment, how and where they are transported, and what transformations they have undergone, is a critical need for the appropriate and accurate assessment and management of potential risks. An appropriate risk assessment and management strategy is necessary to enable the industry to develop products and materials that will not pose major risks to human health or the environment.

2.3 Manufacturing Centers

The potential economic and societal benefits of nanotechnology cannot be realized without manufacturing. For the U.S. to excel in manufacturing at the nanoscale, various branches of science, engineering, business, and government must work together. Nanomanufacturing research and development requires the collaboration of interdisciplinary partners, information exchange, and the integration of diverse manufacturing techniques. The *National Nanomanufacturing Network* (NNN) works to provide connections to nanomanufacturing centers, projects, and experts from academic, industrial, and government institutions through cooperative "real-space" activities and cyberinfrastructure.

2.3.1 National Nanomanufacturing Network and InterNano

In 2007 the National Science Foundation, the NSF Center for Hierarchical Manufacturing (CHM) at the University of Massachusetts, and partner centers announced the launch of the ***National Nanomanufacturing Network***—a community-driven open-access network that facilitates cooperative activities and disseminates information among the nanomanufacturing research, education, and development community. This network serves as an important catalyst for the advancement of new approaches in nanomanufacturing in the U.S. The NNN is funded by the National Science Foundation, as part of the National Nanotechnology Initiative. Further information regarding objectives, partners, and working with the NNN can be found at www.nanomanufacturing.org.

The NNN offers a network of expertise and technologies, thematic workshops on emergent nanomanufacturing methods, educational opportunities in nanomanufacturing and a web-based nanomanufacturing information clearinghouse. The NNN nanomanufacturing information clearinghouse, entitled InterNano (www.internano.org), is a community knowledgebase that is designed to provide information on nanomanufacturing centers, experts and resources, nanomanufacturing processes, nanostructured materials, best practices, events, and a database of nanomanufacturing research information. The NNN links the four NSF nanomanufacturing NSECs: The *Center for Hierarchical Manufacturing at the University* of Massachusetts Amherst, the *Center for High-Rate Nanomanufacturing* at Northeastern/UMass Lowell/UNH, the *Center for Scalable and Integrated Nanomanufacturing* at Berkeley/UCLA, and the *Center for Nanoscale Chemical-Electrical-Mechanical Manufacturing Systems* at the University of Illinois. The NNN also highlights the activities of other affiliated research centers with a nanomanufacturing emphasis, including the *Center for Integrated Nanotechnologies* at Sandia National Labs, other Government labs at NIST, DOD, DOE, NIH, NIOSH, and other academic centers. Perhaps most importantly, the NNN engages industry to help identify and communicate manufacturing needs and challenges to academic and government research centers to develop effective strategies to build a robust platform of U.S. nanomanufacturing. The NNN collaborates with industrial consortia, professional societies, and individual companies on focused issues and roadmapping to aid the advance of nanomanufacturing.

InterNano (www.internano.org) is designed to serve as the premier information service for the nanomanufacturing community and the informatics portal of the National Nanomanufacturing Network. InterNano provides its users with searchable collections on the state of practice in nanomanufacturing that are both current and comprehensive, as well as industry news, networking opportunities, best practices, and research support. InterNano has a long-term strategy to employ the most appropriate and up-to-date web technologies to enable its users to both extract and contribute information to the InterNano knowledgebase. InterNano incorporates informatics technologies to satisfy the data sharing and analysis needs of NM practitioners. InterNano works cooperatively with complementary informatics initiatives in the U.S. to facilitate data sharing with other groups engaged with aspects of nanomanufacturing and nanotechnology.

Key Needs. Nanomanufacturing process technologies are currently at various levels of maturity, with most at a state of infancy. To effectively evaluate the value proposition for a particular nanomanufacturing process technology a range of issues must be considered. First of all, the process must be built upon robust science and technology so that the impact on product performance is significant. This involves an accurate determination of mean value and statistical distribution of each physical property associated with the target nanomaterials, as well as the reproducibility and reliability to produce those values. Without this information it is difficult to design products and a manufacturing process to produce them. Huge uncertainty in design margins presents too great of a risk to a manufacturer. Guaranteed reproducible physical properties requires reliable process metrology, calibration standards, materials or component certification, documentary standards, and ideally, a deep knowledge of manufacturing process-property relationships. For the last, the more that can be understood and modeled in terms of fundamental science, the better, although in manufacturing practice this is not always achieved.

Currently nanomanufacturing is involved in perhaps only one or two steps in the value chain of a product's production, perhaps as a nanomaterial feedstock or as a value-added nanostructuring process. In integrated process situations, a nanomanufacturing process needs to be compatible with the surrounding process technologies, used prior to or subsequent to the nanomanufacturing process step. This means that the physical or chemical conditions of one process step should not deteriorate or hinder the properties achieved by another—or to detrimentally contaminate the process equipment. In the future, it can be envisioned that many more nanomanufacturing processes may involved, either as sequential processing steps, or in simultaneous guided self-assembly schemes, resulting in a heterogeneously integrated nanosystem.

Availability of the requisite nanomanufacturing process tools is another important consideration. Although some companies are vigorously developing process tools for nanomanufacturing, there are plenty of opportunities to develop commercial-scale equipment for processes that have demonstrated proof of principle, but currently only exist at the laboratory level. The decision to purchase nanomanufacturing equipment, at some cost, is weighted by its extensibility to future manufacturing opportunities. That is, the equipment is of the greatest value if it can be effectively deployed in one mode of manufacturing or another for an extended foreseeable future. If it is to become obsolete quickly, it has little competitive advantage. The decision between performing a manufacturing process step in-house versus outsourcing is, as always, another factor.

New process technologies require skilled operators and engineers. Workforce training is an important issue. As new nanomanufacturing processes develop and mature, education and training is needed through university, technical community college, and professional certification programs, in which the NNN partner institutions play a critical role. Responsible manufacturing also includes well-planned environmental, health and safety controls throughout the product life cycle. NIOSH, FDA, EPA, and other organizations provide important guidance for worker, consumer, and environmental protection.

The NNN and Nanoinformatics. The nanomanufacturing community requires data, information, and knowledge. Nanoinformatics involves the development of effective mechanisms for collecting, sharing, visualizing, and analyzing information relevant to the nanotechnology. It also involves the utilization of the latest information and communication technologies to support efficient communities of practice. Various organizations in the U.S. are currently working together is to identify and prioritize nanoinformatics needs, discuss ongoing activities, and draw up strategies for the future. InterNano is the informatics arm of the NNN, working to identify, aggregate, analyze, and apply information in the nanomanufacturing domain. In addition to the functions described above, InterNano includes a dynamic taxonomy of nanomanufacturing process terms, to aid the organization of information pertinent to the nanomanufacturing community. The NNN and other organizations focused on complementary nanotechnology subject domains (health, safety, simulation, and others) have identified the need to create a system of federated nanotechnology databases. This is leading to the creation of a pilot project that includes the development of a minimal set of metadata standards that will lead to very effective database federation.

The NNN and International Standards. Nanomanufacturing is a global enterprise. As such there is the strong need for useful international standards. The American National Standards Institute (ANSI) has submitted a proposal to the International Standards Organization (ISO) TC 229 to develop documentary standards on nanomanufacturing process terms and definitions. The standards proposal was modeled after the NNN InterNano taxonomy combined with a British Standards Institute document on nanofabrication terms. This project, slated to begin in 2009 and co-led by the U.S. and the UK, will be an opportunity for a wide range of international companies and organizations to weigh in and reach consensus on an initial list of nanomanufacturing terms and definitions. Other ISO standards with nanomanufacturing relevance are in process or under development. It is vital that U.S. industry have strong representation in these standards development activities, either as direct members of ANSI or indirectly through cooperation with current ANSI members.

2.3.2 National Nanotechnology Manufacturing Center

The National Nanotechnology Manufacturing Center in Georgia (http://nationalnano.info/aboutus.aspx) is a non-profit corporation dedicated to the development of a robust, sustainable, domestic nanomanufacturing infrastructure by leveraging existing manufacturing capabilities and supporting the creation of new capabilities when necessary. To address technological barriers in manufacturing, for example, NNMC would identify small-to-medium sized existing manufacturers as a resource for pilot and initial production runs. Small-to-medium sized manufacturers offer several important advantages over any comparable research facility. These are:

- Knowing how to make small volumes profitably so even the earliest production can generate revenue or at least break-even. This transition from strictly investment to cash generating is a vital milestone in any project.
- Making use of existing manufacturers to employ established process control schemes to the material/device and to provide a robust basis for identifying needed improvements. As process control improvements are defined, they can be implemented in a system that allows assessment of impact.
- Generating product within an established manufacturing paradigm. This supports validation and accelerated commercialization by prospective customers. There is frequently a reluctance to qualify product for an application if it has been manufactured in a research facility because product from a different facility may have significant variation.

Finally, engaging the innovative spirit as well as the physical capabilities of America's small manufacturers may be the surest way to catalyze an economic revolution along with the technical revolution.

2.3.3 Forest Products Center – University of Tennessee

The University of Tennessee's Forest Products Center conducts multi-disciplinary research and outreach directed at the effective and efficient utilization of renewable resources (http://wood.Tennessee.edu and https://www.utbioenergy.org). The program is structured into two broad science and technology areas. The bio-based materials program, including engineered composites and nanotechnology-reinforced polymer systems, is a longstanding emphasis area for the center. The program encompasses fundamental studies on interfacial structure and properties of composites, as well as development of novel process technologies to yield performance improvements in materials. Recently, the center has expanded to investigate opportunities for biorefining of lignocellulosic biomass. Research in this area focuses on defining fundamental transformation pathways to create value-added chemicals and products from the carbohydrate stream of the biorefinery. Additionally, methods of cell wall deconstruction that enhance carbohydrate release are under development. The Forest Products Center has acquired considerable expertise in rapid assessment methods for the determination of relevant properties, a capability that cuts across the two program areas, and builds on the center's process monitoring strengths. The individual program areas are tightly integrated, leading to extensive collaboration between faculty and a unique capacity to address a range of information needs.

3. Workshop Breakout Session Topics

The workshop was structured to identify common problems and common solutions specific to nanotechnology, manufacturing processes, and performance of nanomaterials in commercial products within widely different industries, including the aerospace, automotive, chemical, food, forest products, medical technology, pharmaceutical, and semiconductor sectors. Breakout sessions provided a venue for participants to focus on the three highest cross-industry priorities identified in previous workshops and meetings as they apply to the design, synthesis, and production of nanotechnology-enabled products. The three breakout session topics were:

- Surface/interfaces and non-bonded interactions of nanomaterials.
- Nanotechnology-enabled composites and matrices.
- Separation and fractionation.

Within each of these topics, common issues included, although were not limited to, measurement, characterization, modeling, performance properties, and environment, health, and safety concerns. Throughout the workshop, emphasis was placed on identifying the needs that were cross-cutting in nature and could impact multiple industries and products.

3.1 Surfaces/Interfaces and Non-Bonded Interactions of Nanomaterials

> **Session Scope**
>
> - Identify what surface and interface issues are critical to nanoscale building blocks
> - Identify what kinds of measurements, chemistry and metrology are useful to control the nanotechnology building blocks needed for products
> - Provide possible solutions to overcome the challenges and barriers for furthering efforts

Material surfaces and interfaces play a crucial role in a variety of chemical, electrical, mechanical, and biological phenomena and applications, cutting across a wide swath of industries, government programs, and university research. Chemical, physical, and biological interactions take place on the surface of a particle. The increased surface-area-to-volume provided by nanoparticles and nanostructured materials leads to a dominant role of surfaces/interfaces in the development and performance of nanomaterials.

Material properties that nanomaterial-enabled surfaces and coatings can impact include: lubrication, adhesion, agglomeration, dispersion, wetting, surface tension, surface chemistry, solubility, permeability, cleanliness, biofilm formation, bioactivity, biocompatibility and toxicity, charge, protein binding, and others. Active research continues to explore the range of surface properties that can be expanded through the use of nanoparticles and nanostructured surfaces.

While the past 25 years have seen tremendous growth in the development of tools and techniques to characterize the composition and structure of bulk surfaces, the corresponding tools and techniques to control and predict the performance at nanoparticle and nanostructured surfaces is just beginning. This performance control and prediction of nanomaterial surface properties is required to enable broad, robust manufacturing of products leveraging nanosurfaces.

A large number of nano-dimensional materials have been developed for diverse applications, demonstrating the effectiveness of understanding materials at this scale. However, substantial difficulties in dispersing and stabilizing nanoparticles have emerged. At this scale—where surface area and number of particles are very large—the building block interactions become significant, causing systems to agglomerate. In addition, when incorporated into systems for applications, interactions are further compounded by this added complexity. The non-covalent forces such as Van der Waals and hydrogen bonding can become very large due to the very high surface area and large number of particles. In many natural materials such as wood and bone, the summation of these forces can result in materials with useful strength properties.

High priority areas include the discovery of ways to measure and quantify the many types of forces between the particles in a wide range of modifying systems. For example, characterization of the nature and complexity of surfaces, both idealized and pragmatic, in concert with the interactions and effects of defects, is a challenge in manufacturing of nanotechnology-enabled products. Effective treatment of nanoscale building blocks and systems needs to be identified and developed to allow their practical use in applications.

Even small variations in processing of nanoparticles can result in variations of surface chemistry, which may have a significant effect on performance as well as safety. This sensitivity has led to widely variable and conflicting results because it is difficult to make precise measurements of surface chemistry of nanoparticles that have both chemical resolution as well as statistical significance.

3.1.1 Current Advances

Current advances in surfaces, interfaces, and non-bonded interactions of nanomaterials are enabling the use of nanomaterials in medical applications as well as other fields. Exhibit 3.1.1-a illustrates many exciting possibilities and opportunities being explored. For example, optical imaging techniques are used extensively in clinical diagnosis. However, the organic fluorophores in common use are not photostable and have low intensity. The use of fluorescence proteins or bioluminescence systems is also limited because these cannot be optimized in multicolor assays. Nanoparticles are being used today to overcome these problems.[8]

Exhibit 3.1.1-a Examples of Commercial Applications of Nanoparticles*

Nanoparticle component	Application	Indication	Company
Liposomes	Drug delivery	Cancer	Liplasome Pharma (Lyngby, Denmark) Schering-Plough Corp (Kenilworth, NJ)
	Drug delivery	Vaccines: influenza, hepatitis A	Berna Biotech AG (Basel, Switzerland)
	Drug delivery	Fungal infection	Enzon (Bridgewater, NJ), Gilead Science (Foster City, CA)
	Nutrient and bioactive food compounds	Improved bioavailability in the body, improved functionality in food system	AquaNova (Germany)
Dendrimers	Therapeutics	HIV, cancer, ophthalmology, inflammation	Starpharma (Melbourne, Austalia)
Carbon nanotubes	*In vitro* diagnostics	Respiratory function monitoring	Nanomix (Emeryville, CA)
	Imaging	Atomic-force microscopy probe tip	Carbon Nanoprobes Inc (Seattle, WA)
Quantum dots	*In vitro* diagnostics, imaging	Labeling reagents: Western blotting, flow cytometry, biodetection	Evident Technologies (New York, NY), Quantum Dot Corp (Hayward, CA), Nanoco Technologies Ltd (Manchester, UK)
Magnetic nanoparticles	*In vitro* diagnostics	Cancer	Immunicon (Huntingdon Valley, PA)
	Imaging, therapeutics	Liver tumors, cardiovascular disease, anemia	Advanced Magnetics (Cambridge, MA)
	Therapeutics	Cancer	Nanospectra Biosciences Inc (Houston, TX)
Gold nanoparticles	*In vitro* diagnostics	HIV	Amersham/GE (Little Chalfont, UK)
	In vitro diagnostics, imaging	Labeling reagents (PCR, RNA, Western blotting), angiography and kidney function testing	Nanoprobes Inc (Yaphank, NY)

* "Multifunctional nanoparticles – properties and prospects for their use in human medicine," Trends in Biotechnology Vol.26 No.8, 425-433, (2008)

As shown in Exhibit 3.1.1-a, there are already several nanoparticle-based systems in use for medical diagnostics, and future possibilities for nanoparticle applications in this field are almost unlimited. The unique properties of nanoparticles enable their use as selective tags or markers for a range of medical targets such as bacteria and individual molecules (e.g., proteins, DNA). Drug delivery is another area where nanoparticles provide many advantages, such as enhancing drug-therapeutic efficiency and pharmacological characteristics. Nanoparticles can improve the solubility of poorly water-soluble drugs, increase drug half-life, enable a more controllable release, and allow the delivery of two or more drugs simultaneously for combination therapy.

3.1.2 Characterization Instruments

Electron microscopies—scanning electron microscopy (SEM) and transmission electron microscopy (TEM), proximal probe microscopies such as scanning tunneling microscopy (STM), atomic force microscopy (AFM), scanning probe microscopes (SPMs), and to a lesser extent near-field scanning optical microscopy (NSOM)—are currently used in nanoscience and nanotechnology research. Line-width measurements are performed by chromatic dispersion (CD), SEMs, CD atomic force microscopes, and optical scatterometry tools. Special tools also exist for measuring pattern distortion and overlay. These tools provide the ability to image the samples and view sample surfaces on the atomic scale as well as with the ability to *manipulate* the particles (atoms, molecules, clusters, etc.) that make up the system. [9]

Over the last two decades, research efforts have sought to provide tools capable of performing measurements on complex, heterogeneous, nanometer-scale systems that are similar to those provided by conventional spectroscopic techniques, but with an increasing level of chemical detail. Advances in proximal probes have demonstrated that STM operation at ultrahigh vacuum and low temperature can achieve spatial resolution to approximately to the atomic level. Microfabricated cantilevers allow AFM to be performed on soft sample surfaces without perturbation. Through intense laser sources and methods for generating small optical apertures chemical contrast mechanisms, dielectric spectroscopy and nonlinear spectroscopy have been demonstrated at length scales well below the diffraction limit of light.

A summary of some of the available technologies for nanomanufacturing is shown in Exhibit 3.1.2-a. Recent advances in TEMs have resulted in resolutions below 0.1 nanometer (nm). These tools are applicable to research and a limited set of manufacturing applications. For SEMs and CD SEMs in manufacturing, the primary problem is image artifacts (charging or scattering of secondary electrons). Although scanning tunneling microscopes have achieved resolution below 0.1 nm, they are not as effective for samples with any topography. Atomic force microscopes and CD atomic force microscopes are limited by the size and variability of tip geometry, which can cause large artifacts.

Exhibit 3.1.2-a Instrumentation for Nanomanufacturing

Scanning Probe-Based	Beam-Based	Photon-Based
Physical probes that either contact the sample directly or are controlled to be in near contact with the surface · Magnetic force microscope · Magnetic resonance force microscope · Chemical AFM · Dynamic force microscope · Cantilever sensors	*Particle beams interacting with the sample for determination of the properties of interest* · Scanning transmission electron microscope (STEM) · Electron energy-loss spectrometer (EELS) · Scanning electron microscope (SEM) · Aberration-corrected transmission electron microscope (TEM) · Focused ion beam (FIB)	*Photons of various energies ranging from optical to x- and gamma-ray sources* · Scanning near-field optical microscope · Scanning interferometric apertureless microscope · X-ray or gamma-ray scattering or diffraction methods · Photonic force microscope · Scatterometry

3.1.3 Key Barriers

Specific barriers limiting the understanding and characterization of nanomaterial surfaces, interfaces, and non-bonded interactions identified in the workshop are detailed in Exhibit 3.1.3-a. In summary, these include:

Regulatory, Legal, and Organizational Hurdles. In general, results from past research efforts are not readily available to the industrial and research communities. Many publications exist, but don't have adequate technical details to translate to manufacturing. Development of databases and publications with research outcomes would enable researchers to identify promising areas for further study and also learn from unsuccessful studies. Additionally, cross-cutting research needs are difficult to identify due to a prevailing lack of information-sharing across industrial sectors. Concerns over intellectual property ownership also contribute to this lack of collaboration. A legal framework that reduces R&D partnership risks would help overcome many of the barriers to cross-industry cooperation.

Effective Characterization and Measurement Methods and Tools. Several factors contribute to the inability to characterize nanomaterial chemistries and interactions, particularly the lack of standard protocols and measurement tools. Surface treatments often "mask" the nanoparticle, thereby modifying the raw particle's attributes and making it difficult to characterize. Better measurement techniques that ensure proper isolation of the nanoparticles would help to determine the effects surface treatments.

Modeling. Identifying ways to enhance modeling techniques is inhibited by a lack of coordinated R&D needs, information exchange, and systematic experimental structure-property data to develop and validate models. Modeling improvements would enable researchers to predict nanomaterial functionality and improve product reliability at lower cost and in less time. Other technical enhancements would address the nanomaterial properties for testing, such as controlling or shortening their half-life for optimal or shorter testing periods.

Environmental, Health, and Safety Issues (EH&S). Current research has not been able to establish a link between nanomaterial surface characteristics and toxicity. Further studies are needed to determine the influence of surface interaction on toxicity.

Performance Properties. Several challenges contribute to the inability to link nanomaterial surface characteristics to performance properties. Priority areas needing additional study include: preventing the time-dependent loss of functionality of nanomaterials and the development of processes that enable scaled-up production and testing. Other high priority areas include the inability to quickly characterize nanomaterials and to identify which nanomaterials are practical, safe, or reliable to use in manufacturing.

Process Control. Small variations in process conditions can result in nanomaterials with variable surface chemistry and structure that significantly impact performance and toxicological properties. When manufacturing products contain nanomaterials, these variations in surface chemistry can lead to nanomaterial aggregation and nonhomogeneous distribution that result in poor performance and product reliability. In composites, for example, uneven distribution of nanofillers can create weak areas that become points of failure. Currently it is a challenge to measure the surface characteristics and distribution of nanomaterials in a manufacturing stream or composite with the resolution and statistical significance required for reliable manufacture and performance that is essential for widespread commercialization.

Exhibit 3.1.3-a Key Barriers For Surface/Interfaces and Non-Bonded Interactions of Nanomaterials

Barriers	Needs	Priority
Regulatory/Legal/ Organizational	è Collaboration across disciplines	●●●●●
	è Databases or other publications that capture what works and what doesn't	●●●
	è Legal framework for companies to reduce risk	●●
	è Database for requirements and needs	
	è Published results for poorly characterized materials	
Characterization and Measurement	è Standard protocols/assays (instrumentation)	●●●●●
	è Nanoparticles – not a "masked", complex system – for dispersal · Blend particles without distorting attributes · Maintain functionality · Online or surrogate monitoring method and validation	●●●
	è Adequate measurement tools for chemists (for distribution, etc.)	●●
	è Field techniques to measure quality or characteristics · Practical methods, to lab and back	●
	è Better methods and standards for protocols	
	è Statistical significance of nanotechnology measurements · Atomic resolution · Cost effective tests	
	è Metrics to confirm that raw nanoparticles are being studied	
Modeling	è Modeling ex change, sharing of i nformation, and f ramework of v alidated experimental structure-property data to develop and validate models · Identify when nanotechnology takes over · 2D versus 3D	●●●●●●
	è Transferability – uncertainty of models available	●
	è Control or shorten half life (for functionality)	
	è Predict functionality over time · Model nanoparticle interaction with cells	
	è Understand interactions between various systems (e.g., food, other systems)	
EH&S	è Insufficient studies, basic science (is toxicity a result of surface interactions?) · Aspect ratio, diameter, functionality · Biocompatibility	●●●●●
	è Understand interaction and synergy with biological systems	●●●●
Performance Properties	è Basic science focused on market pull	●●●●●
	è Scalable process for complex, large areas	●●●
	è Maintain functionality over the long term	●●●
	è Determine what particles are practical and safe to use now	●
	è Reliable products	●
	è Cost models	
	è On-line measurement and characterization	
	è Control stability over full life cycle	
	è Ensure particles have desired/required characteristics and properties	

3.1.4 Priority Solutions

Cross-industry solutions to address the barriers were discussed and a list of topics identified, as follows:

- Developing new measurement science
- Developing new measurement tools
- Fostering collaboration across disciplines
- Modeling exchange and information sharing
- Measuring toxicity as a result of surface interaction
- Maintaining long-term functionality (for reliable products)
- Aligning research with market pull
- Information and property databases

Each topic was explored and the importance of possible solutions ranked (see Exhibit 3.1.4-a). While some of the solutions focus on a specific barrier, others can apply across multiple barriers (e.g., development of new measurement tools can improve modeling capabilities and enhance performance properties).

From the solutions identified in Exhibit 3.1.4-a, a set of priority solutions was selected and grouped as shown in Exhibit 3.1.4-b. Mini-roadmaps for each solution are shown graphically on the pages that follow.

Exhibit 3.1.4-a Cross-Industry Solutions to Accelerate Progress in Surface/Interfaces and Non-bonded Interactions of Nanomaterials

Topic	Solution	Priority
New Measurement Science		
	· For both measurement techniques and predictive models, develop an inventory, identify gaps, and drive solution development	●●●●●●
	o Identify existing tools and establish range of applicability	
	o Develop infrastructure framework of systematic experimental structure-property data to develop and validate predictive models	
	o Organize and maintain to identify gaps, range of size, classes of materials and surface interactions, accuracy and precision, range of physical properties	
	o Keep track of new developments in progress	
	o Focus on problems with market pull and link to fundamental science questions to coordinate activity and drive science forward	●
	· Learn/define what to measure, how to measure – from impacts to performance	
	o Test particles and precursors, ensure proper purification	
New Measurement Tools		
	· Identify surrogate measurement tools for online measurement (manufacturing) that can relate to research tools (laboratory)	●●●●
	o Standard protocols, assays (instrumentation) – field techniques to measure quality	
	o Property databases and information tools	
Fostering Collaboration Across Disciplines		
	· Integrate industry needs and academic funding – establish a mechanism to translate commercial needs into fundamental science	●●●●●●
	· Develop organization of labs that want to test, develop standards for nanomaterials characterization	●●●
	o Standard reference simulations for new users	
	o Known systems and validation for tools, limits and range of applicability	
	· Expand mechanisms for industry/Federal research, definition of important problems, co-funding	●●
	o Sharing best practices for university/industry collaborations/IP, etc.	

Exhibit 3.1.4-a Cross-Industry Solutions to Accelerate Progress in Surface/Interfaces and Non-bonded Interactions of Nanomaterials Continued

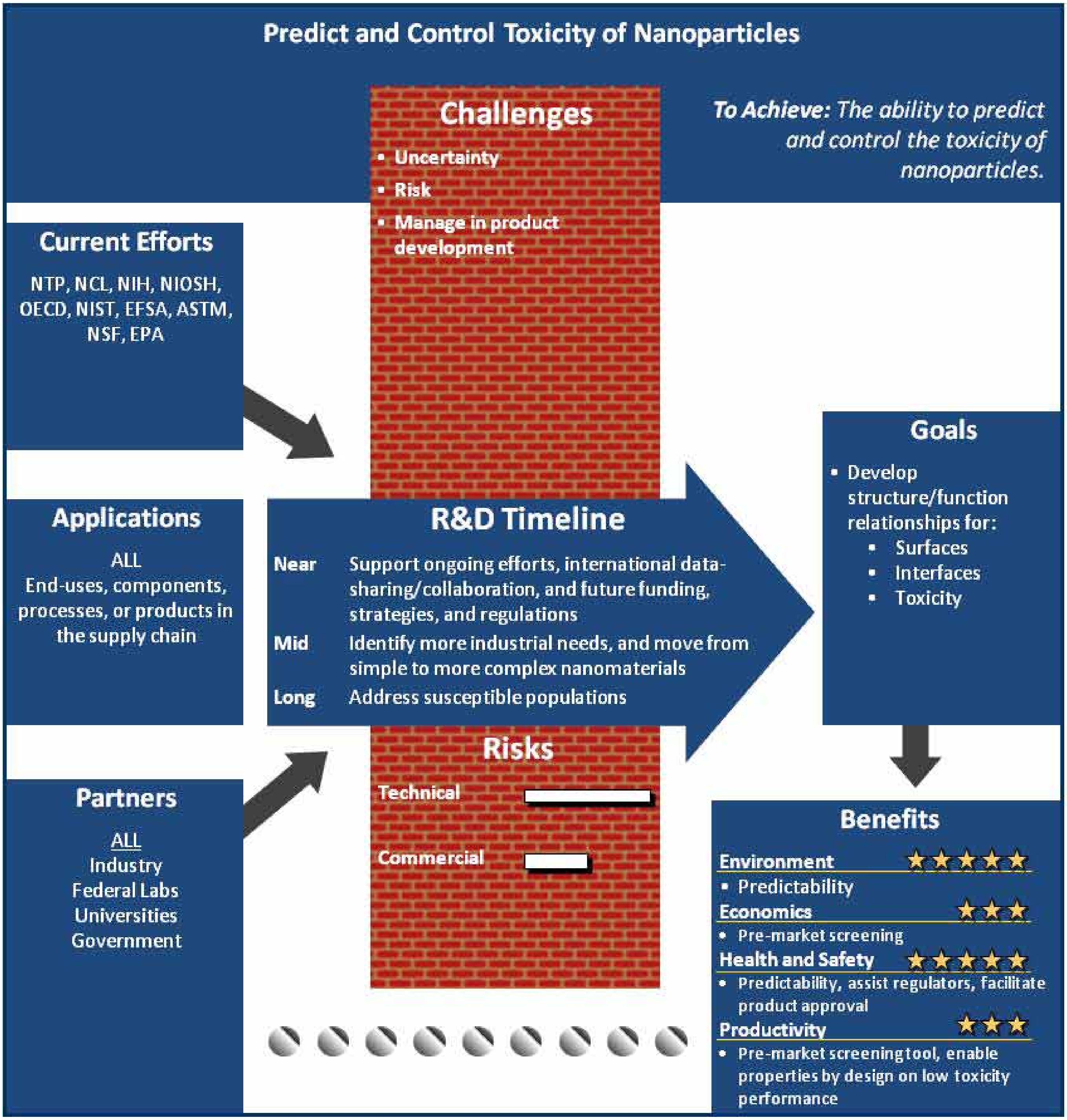
Topic	Solution	Priority
Modeling Exchange and Sharing of Information		
	· Integrate modeling and experiments – increase collaboration	●●●●
	· Initiate model verification/validation for nanomaterial surface interactions (e.g., nanoparticle/cell membrane interactions; nanoparticle-solvent interactions to validate pair-potentials to quantify noncovalent interactions in atomistic simulations)	●●●
	· Need blind modeling competition, mapping space for a well-known nanocomposite systems	●●
	· Create programs that will generate basic properties needed for models	●
Toxicity and Surface Interaction		
	· List existing toxicity interactions/assays	●●●●
	· List existing measurement tools efforts	
	· Inventory existing modeling efforts before going forward o Pose issue/problem, call for ideas/solutions – establish an interactive working group process to achieve this o Protect competitive aspects o Model known systems to validate modeling; understand limits and range of applicability o Utilize standard reference simulation to train new users	
Maintaining Functionality/Reliability Long Term		
	· Correlate fundamental nanoparticle surface understanding to performance properties o Understand surface and interfacial properties to ensure, control, and measure dispersion – initially and in the long term	●●●●●●
Market Pull		
	· Develop reference systems relating to market needs	●●●●●●
	· Need mechanism to facilitate/encourage university/academic research and strengthen collaboration on market-relevant materials	
	· Identify nanotechnology attributes that clearly relate to specific market space	
General		
	· Fund basic research on surface/interface properties and relationships with toxicity	●●●
	· After problems are defined, develop infrastructure to carry out research	●
	· Fund fundamental research on surface and interfaces of nanoparticles – hydrophophic, chemical, Van der Waals, etc.	
	· Fund basic research to develop new measurement tools	

Exhibit 3.1.4-b Priority Cross-Industry Solutions
Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

- **Predict and control toxicity of nanoparticles**
- **Develop reference systems relating to market needs**
- **Establish a network of labs that test and develop standards for nanomaterial characterization**
- **Research on surface interface properties relevant to performance**
- **Collect list of existing models, measurement tools, and biological interaction assays**
- **Identify or develop surrogate measurement tools for on-line measurements that relate to research tools**
- **Integrate industry needs and academic funding—mechanism and framework to translate commercial needs into fundamental science questions**
- **Correlate fundamental nanoparticle surface understanding to performance priorities**
- **Improved computational models for nanomaterial surface interactions**
- **Measurement techniques and predictive models interaction: identify gaps and devise solution development**
- **Increase collaboration in modeling and experimentation**

Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

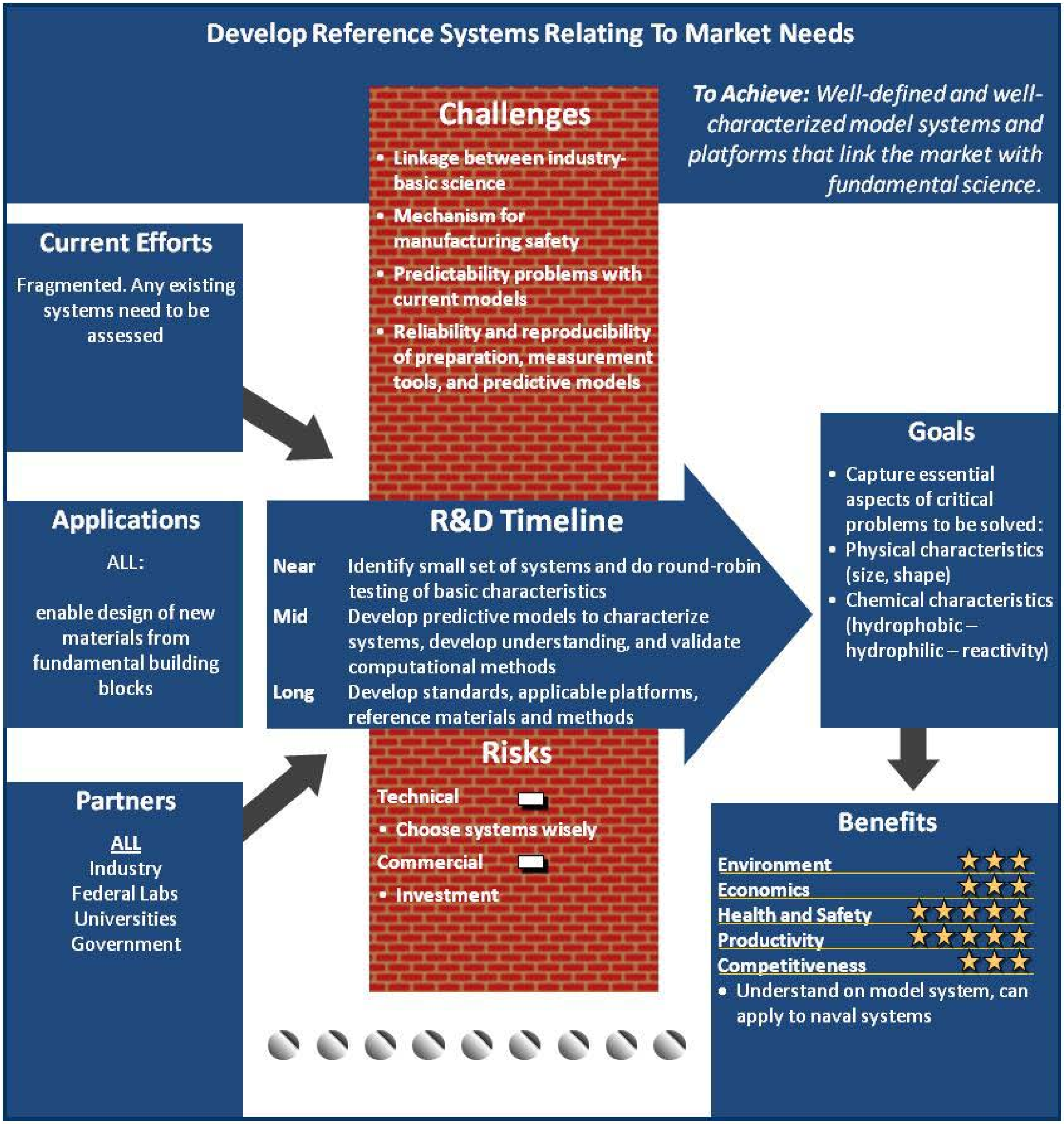
Priority Solution: Predict and Control Toxicity of Nanoparticles



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

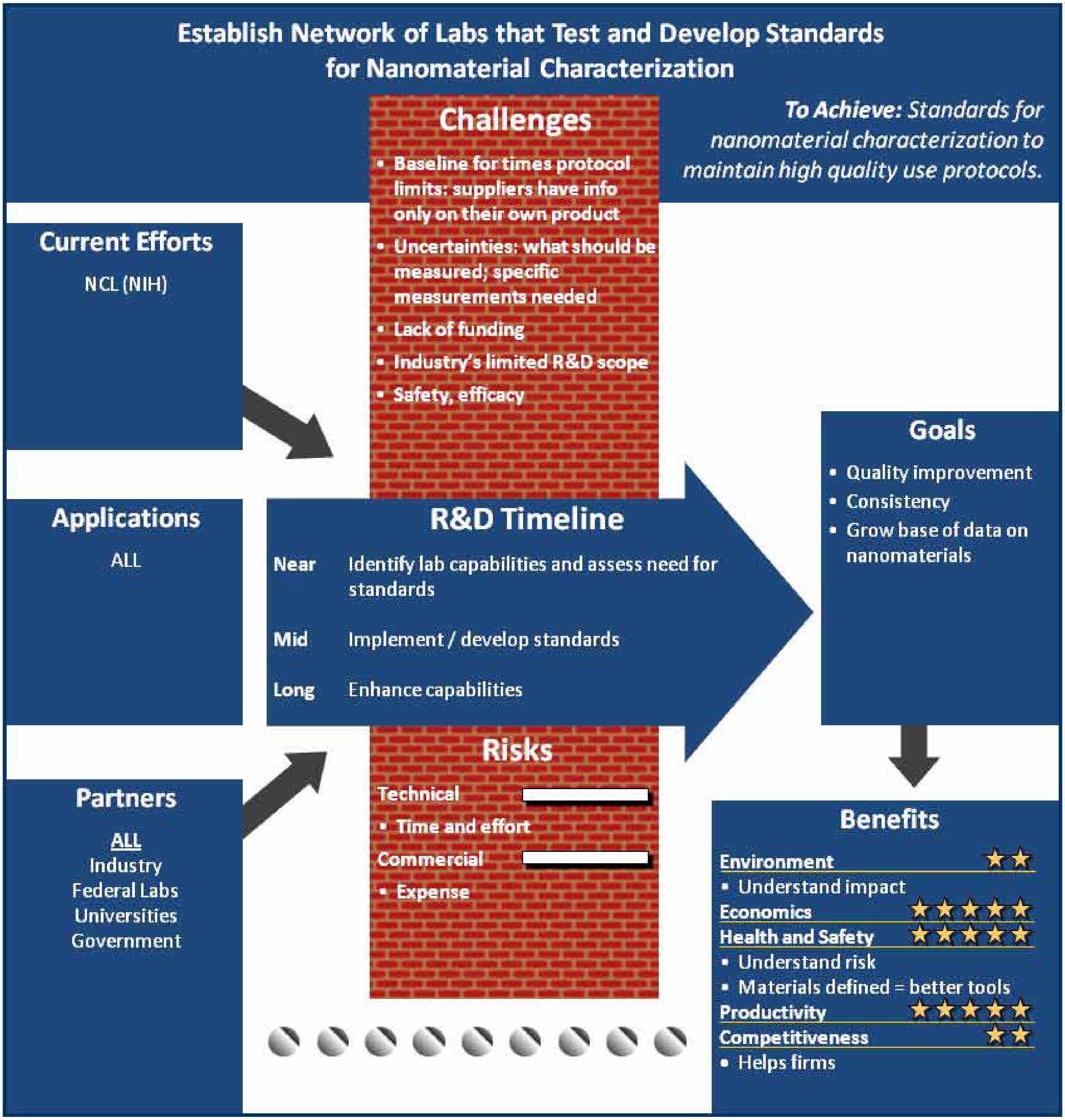
Priority Solution: Develop Reference Systems Relating To Market Needs



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

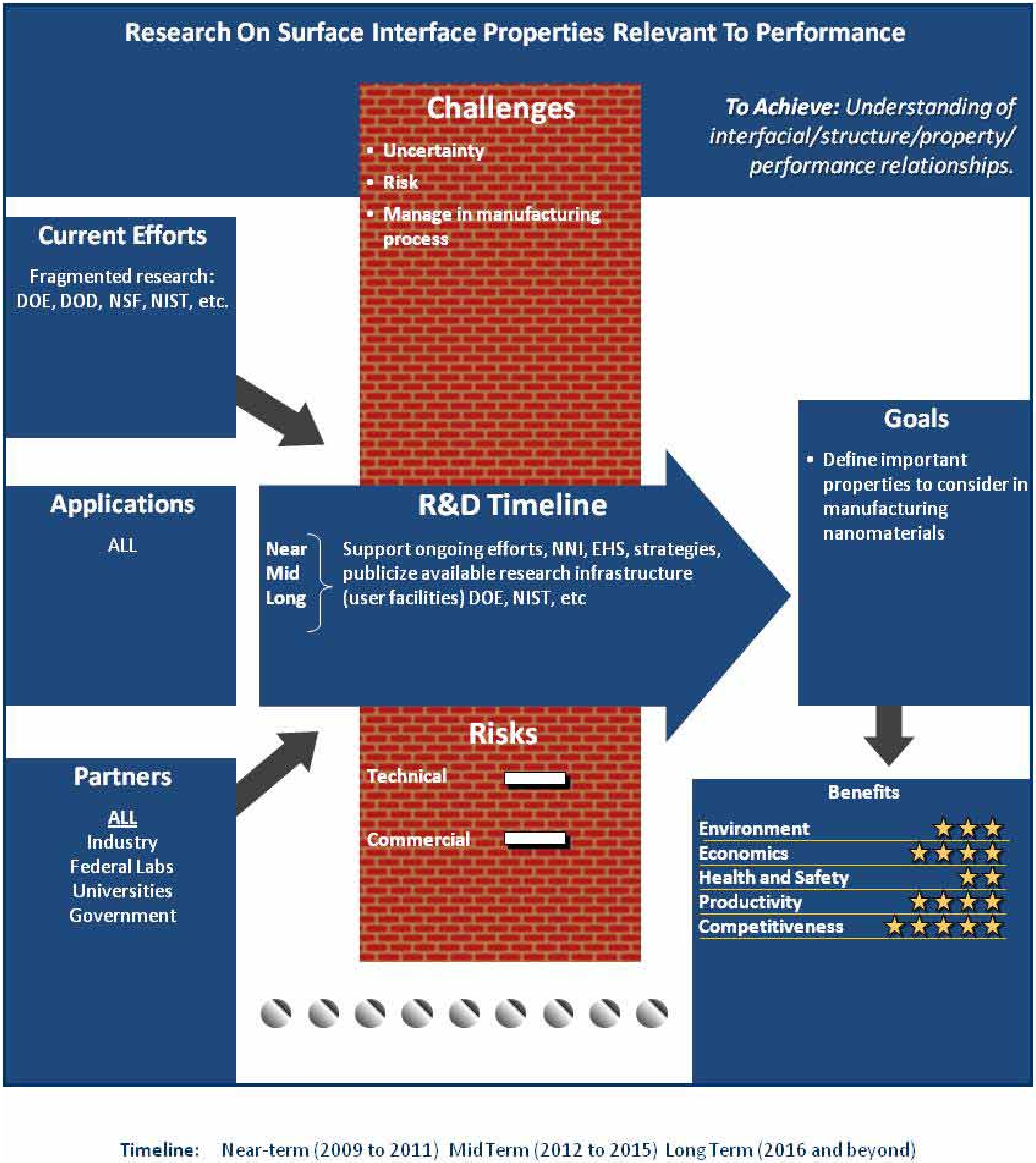
Priority Solution: Establish Network of Labs that Test and Develop Standards for Nanomaterial Characterization



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

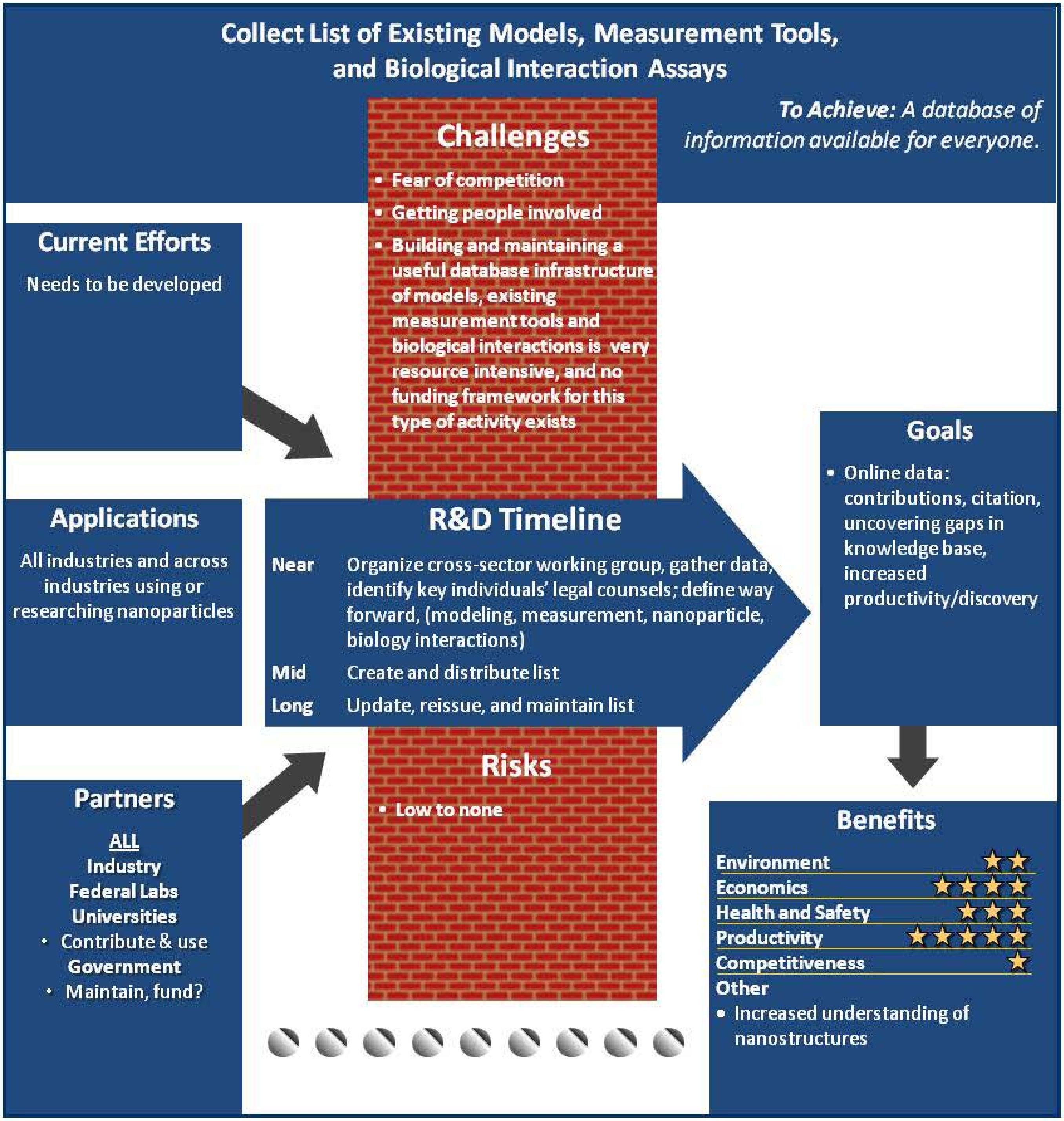
Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

Priority Solution: Research On Surface Interface Properties Relevant To Performance



Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

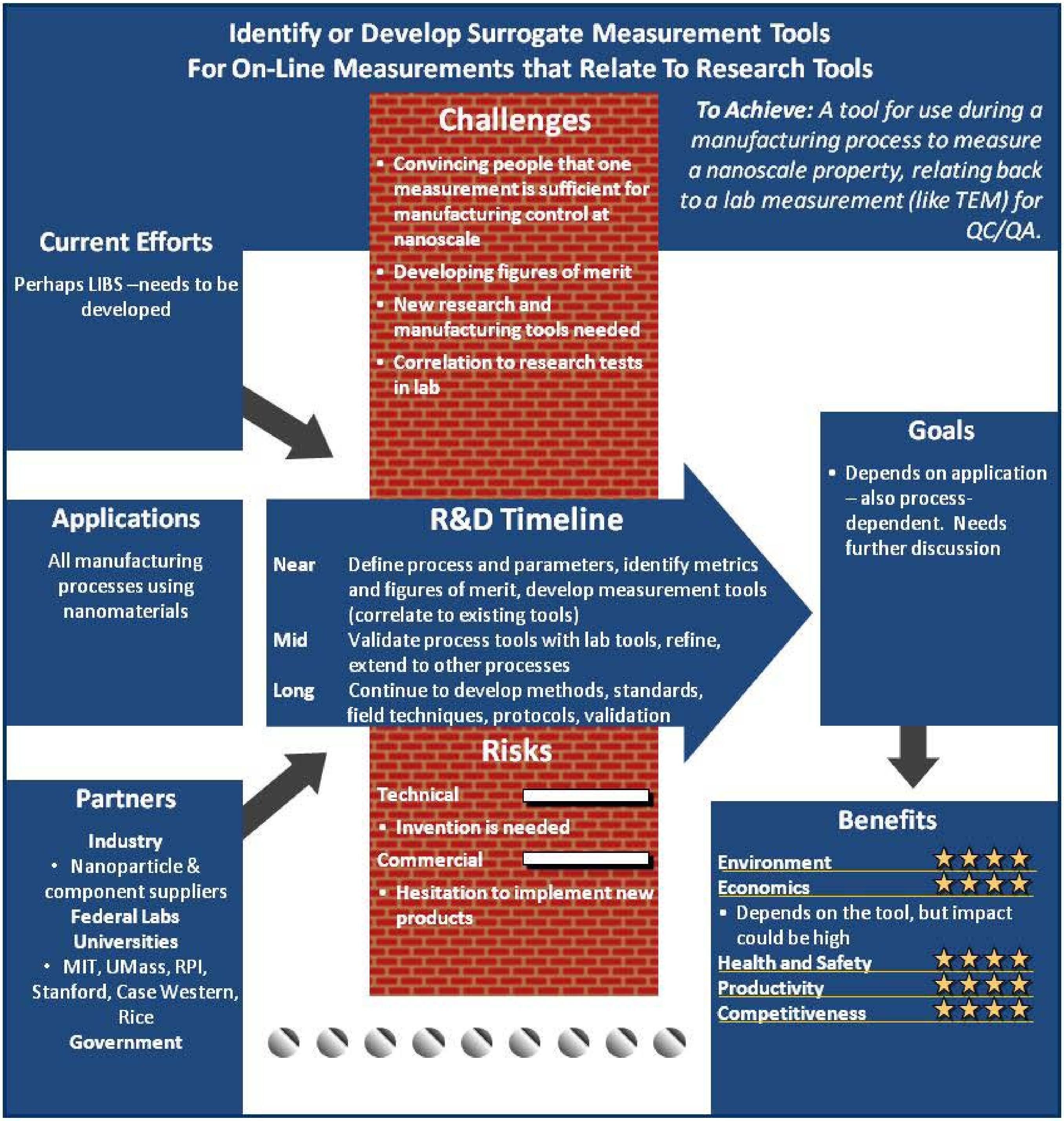
Priority Solution: Collect List of Existing Models, Measurement Tools, and Biological Interaction Assays



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

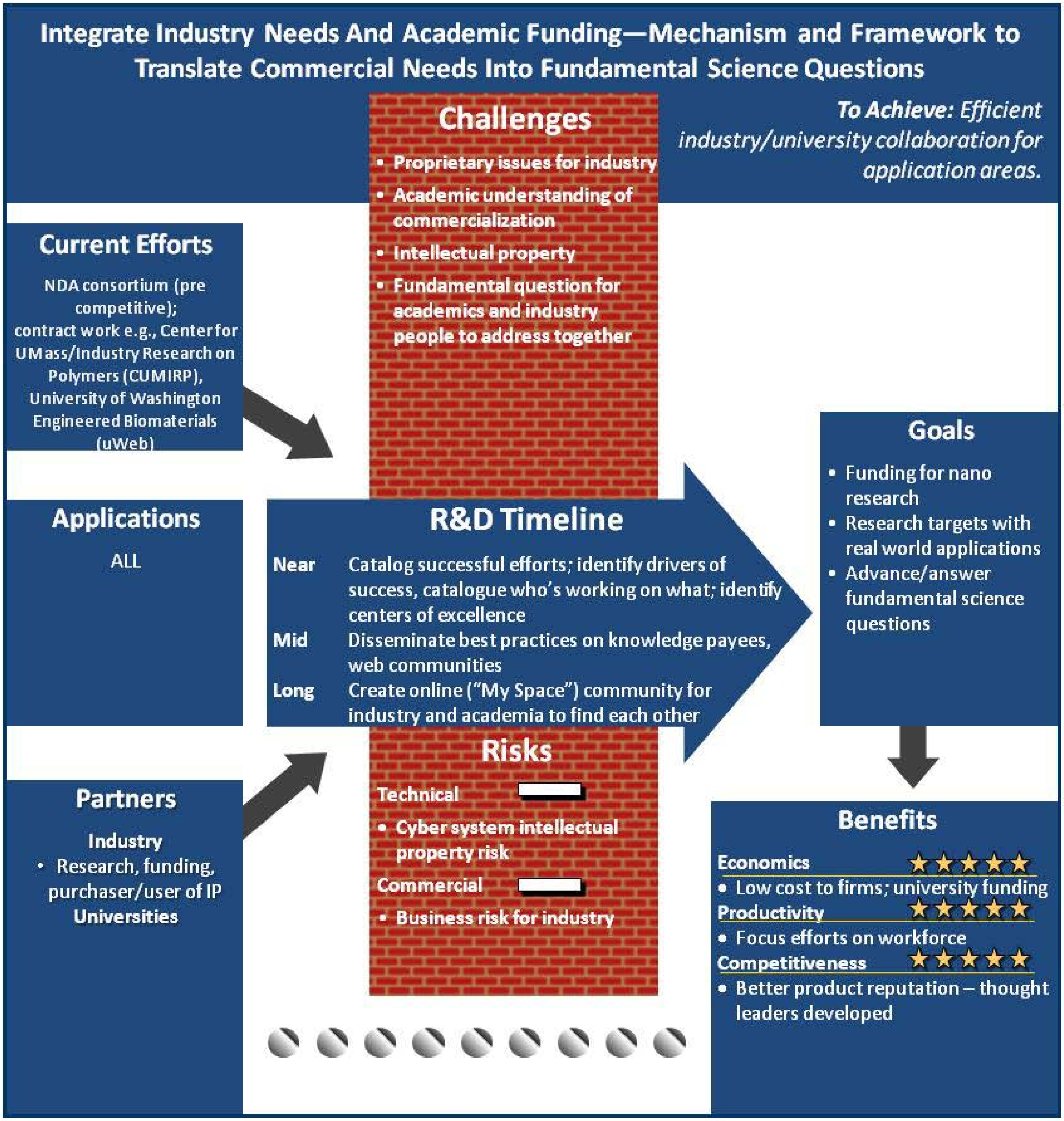
Priority Solution: Identify or Develop Surrogate Measurement Tools For On-Line Measurements that Relate To Research Tools



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

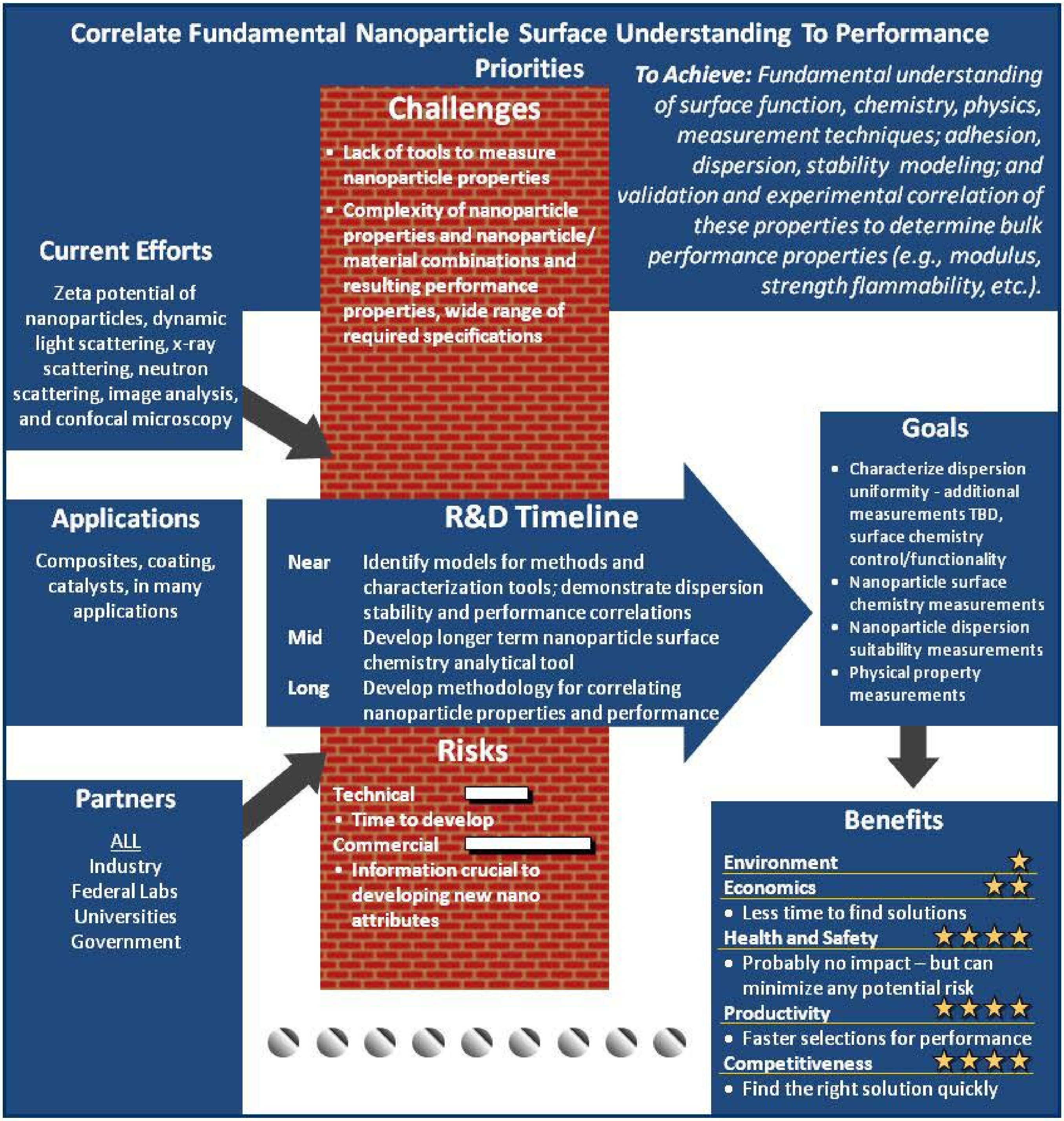
Priority Solution: Integrate Industry Needs And Academic Funding—Mechanism and Framework to Translate Commercial Needs Into Fundamental Science Questions



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

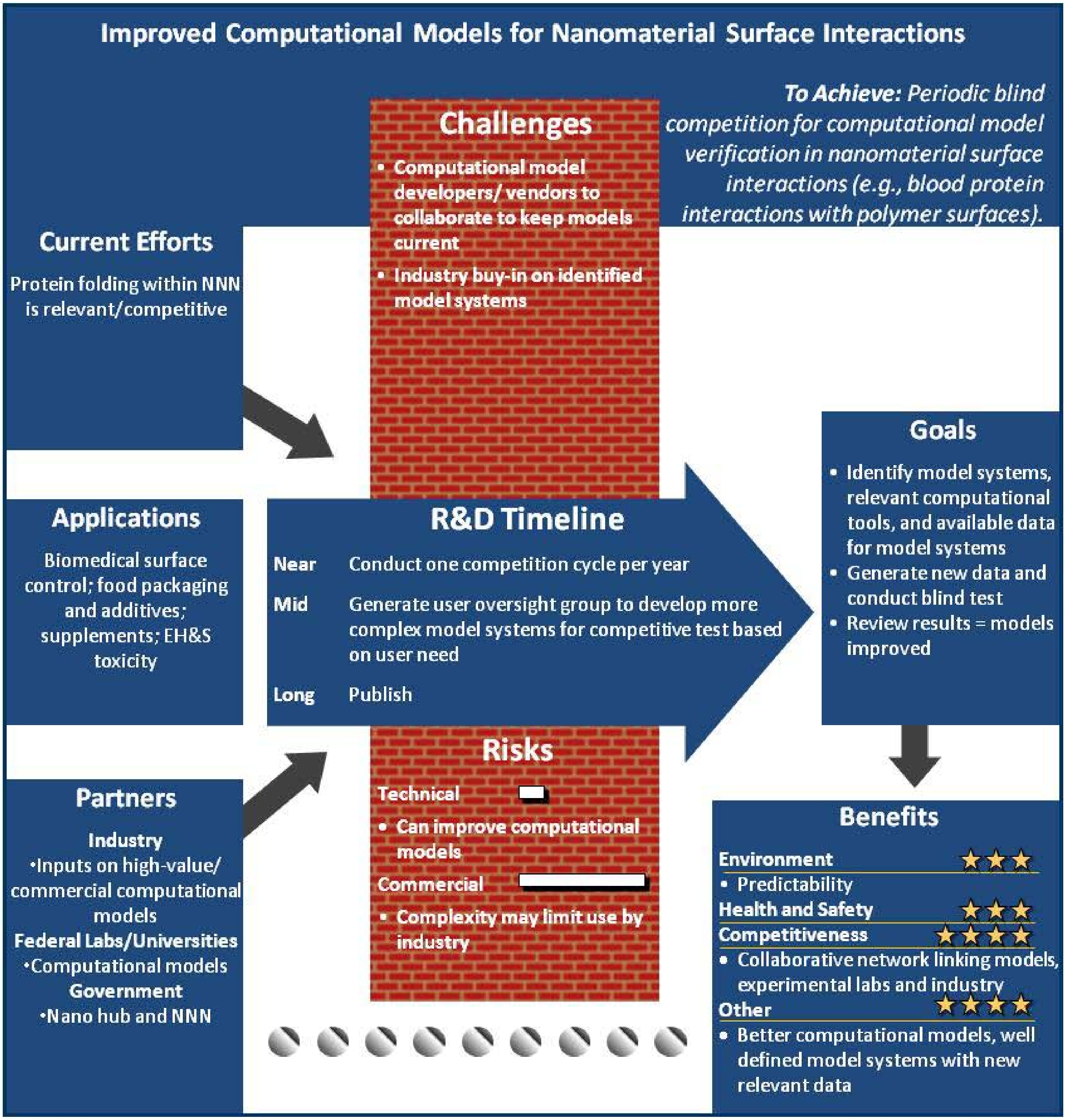
Priority Solution: Correlate Fundamental Nanoparticle Surface Understanding To Performance Priorities



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

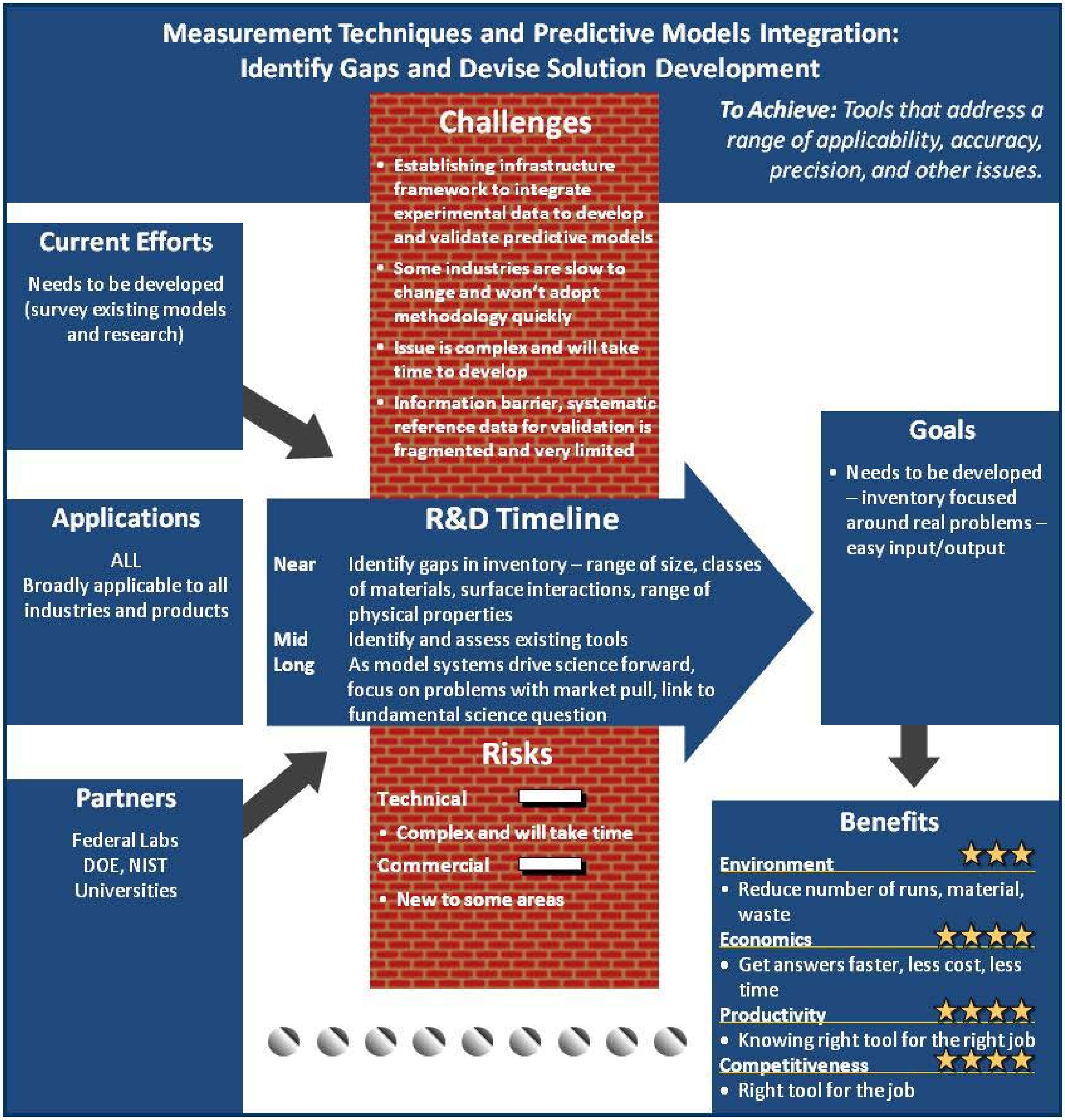
Priority Solution: Improved Computational Models for Nanomaterial Surface Interactions



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

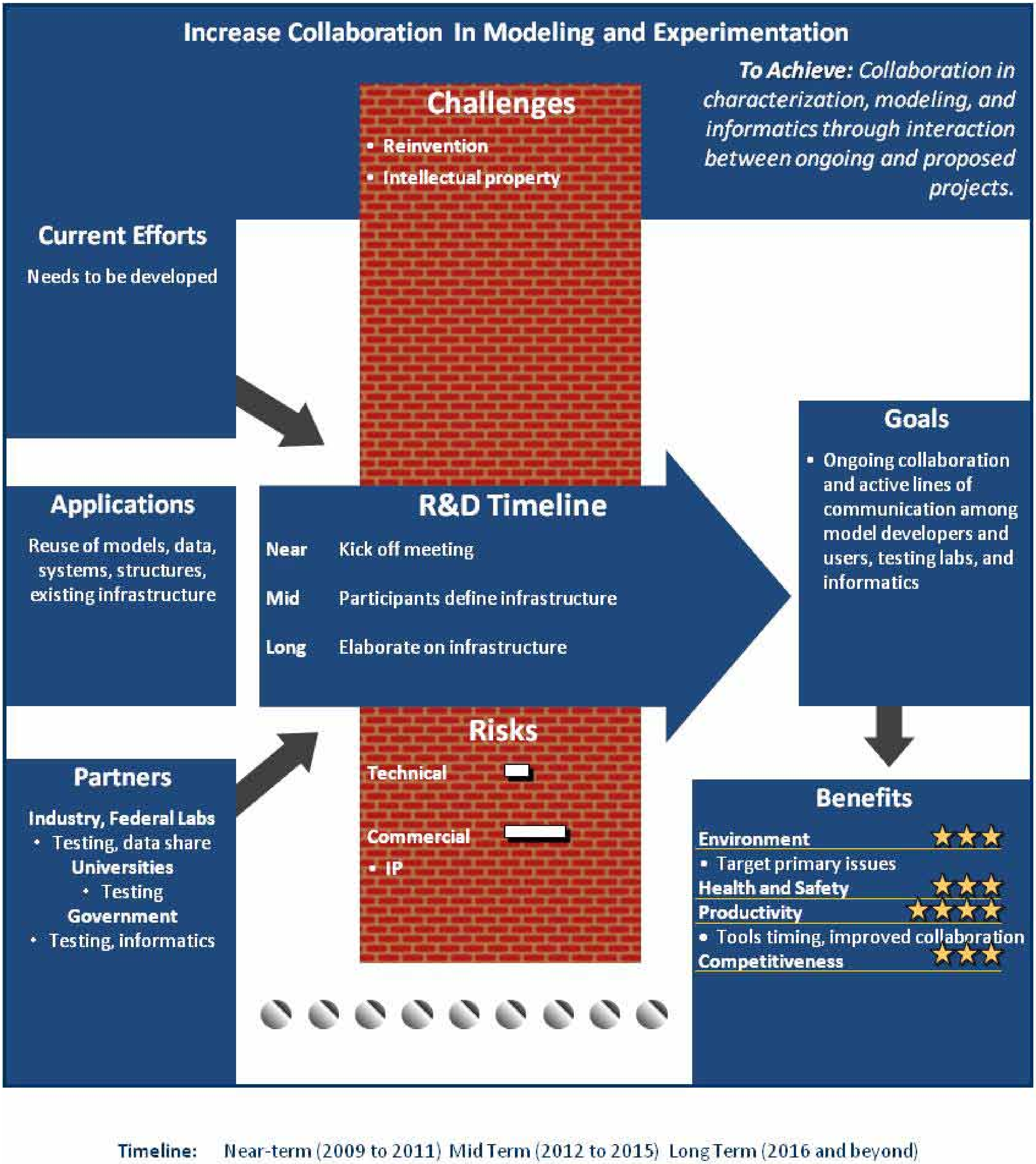
Surfaces, Interfaces, and Non-Bonded Interactions of Nanomaterials

Priority Solution: Measurement Techniques and Predictive Models Integration: Identify Gaps and Devise Solution Development



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Priority Solution: Increase Collaboration In Modeling and Experimentation



3.2 Nanotechnology-Enabled Composites and Matrices

One of the keys to unlocking the benefits of nanotechnology is building the nanomanufacturing science and technology base to the point where nanomaterials exhibiting unique nanoscale properties can (1) be designed based on existing and emerging science; (2) routinely be placed into components or systems; (3) retain and combine their unique nanoscale properties in a matrix of other materials; and (4) result in superior and controllable composite performance. In developing the needed nanomanufacturing technologies, greater commercial influence and awareness serves to guide research into the highest priority and most productive areas.

> **Session Scope**
>
> - Identify science foundation needed to enable nanocomposite materials with unique properties
> - Develop knowledge and models to enable design of nanocomposites with multiple properties optimized simultaneously within these topical areas
> - Discuss and refine these needs and arrive at a prioritized list of fundamental science gaps with respect to the needs
> - Develop knowledge to enable scale-up of nanomanufacturing (may be a competitive capability)
> - Define the challenges and barriers for filling these gaps and propose solutions

Nanomaterials can boost energy efficiency in a wide range of applications by offering such properties as light weight, high mechanical strength, unique color, electrical properties, and high reliability in extreme environments. Applications could be as diverse as biological implant materials, electronic packages, and automotive or aircraft components. Although some properties will be common among applications, others will need to be quite different. For example, an electronic package polymer composite must be electrically insulating, while an aircraft component may need to be electrically conductive to dissipate charges from lightning strikes.

The addition of small amounts of nanoparticles to polymers can enable new properties in the composite material, but results are highly dependent on the surface treatment of the nanoparticles and processing used. It will be valuable to determine whether nanomaterials could be integrated into nanocomposites to enable multiple desirable properties required for a given application.

While industry is seeking materials with unique properties to address difficult challenges, no "rule of mixtures" exists as a guide for mixing multiple nanomaterials to obtain all required properties in a composite structure. Nanomaterials often have unique properties that could enable composite materials with multiple unique properties simultaneously, yet it is often challenging to achieve these properties in large-scale nanocomposite materials. Furthermore, nanomaterials should provide desirable properties that cannot be achieved through use of conventional chemicals and materials.

3.2.1 Current Advances

Progress in nanocomposites is varied and covers many industries. Nanocomposites can be made with a variety of enhanced physical, thermal, and other unique properties. They have properties that are superior to conventional microscale composites and can be synthesized using simple and inexpensive techniques. To assess the potential value of nanocomposites, developers must determine which nanomaterials can be effectively integrated into nanocomposites and what new or improved properties this enables. This process entails determining the effectiveness of dispersion of the nanoparticles in the matrix and how this affects the structure of the polymer to enable optimization of the desired property. Once the basic models of this process are developed, it must be determined how the mixing of multiple nanomaterials in a polymer affects the resulting structure and properties of the nanocomposite. One nanomaterial may be required to improve the mechanical property, and another may be required to change the electrical properties. However, the addition of the electrical material may also change the mechanical properties of the nanocomposite through interactions with the polymer and nanoparticles.

In general, two idealized polymer-layered nanocomposite structures are possible: intercalated and exfoliated. The greatest property enhancements are generally observed for exfoliated nanocomposites. These consist of individual nanometer filler layers suspended in a polymer matrix. In contrast, intercalated hybrids consist of well-ordered multilayers with alternating polymer/nanometer filler layers with a repeat distance of a few nanometers. In reality many systems fall short of the idealized exfoliated morphology.

Existing Materials. A few nanocomposites have already reached the marketplace, while others are on the verge. The global nanocomposites market is projected to reach 989 million pounds by the end of the decade.[10] The United States and Europe dominate the global nanocomposites market, with a collective share of over 80% of the volume sales for 2008.

Nanocomposites influence many industries, such as computers, electronics, plastics, coatings, magnets, water remediation, energy, and medical equipment. For example, a nanoscale memristor switch has been developed using nanocomposites. The memristor—short for memory resistor—could make it possible to develop far more energy-efficient computing systems with memories that retain information even after the power is off, so there's no wait for the system to boot up after turning the computer on. It may even be possible to create systems with some of the pattern-matching abilities of the human brain.[11]

The uses for nanocomposites are highly diverse, as the following examples illustrate. Using a nanocomposite ZnO/polymer nanocomposite, Applied Nanomat, Inc. (ANI) scientists have invented the world's first nanoscale electric generator. This ground-breaking invention is a revolution that allows us to harvest mechanical energy from various microenergy sources in the environment and human body, then convert them into electric energy.[12]

Progress has also been made in solar power based on nanostructures and nanocomposites. For example, dye-sensitized solar cells using micro/nanocomposite TiO porous films resulting in cells with enhanced light collection, have been fabricated. This technique opens an alternative way for manufacturing solar cells on an industrial scale. Other solar developments include development and manufacture of revolutionary nanostructured ultra thin film solar (photovoltaic-PV) products that increase the total PV surface area by an incredible 6-12 times over other thin film products on the market today.

Graphene nano-platelets have been developed as additives for advanced composites, as a substrate for advanced electrical or electronic applications, as the conductive component in specialty coatings or adhesives, and as a component of e-inks or printable electronic circuits. Low-cost processes have been engineered that provide the ability to tailor multi-functional materials that take advantage of exceptionally large surface area to mass ratios of active metals and metal oxides for applications such as catalysis, lithium-ion battery electrodes, supercapacitors, solar cells, and energy storage.[13]

Nanocomposite permanent magnet materials are a new type of permanent magnet material consisting of magnetically hard and soft grains, both in nanometer size. These materials have a high potential to be developed into high-performance permanent magnets with very high energy production.[14]

Instrumentation/Equipment. There are many current efforts underway in manufacturing, testing, and simulation technology for nanocomposites. A few are outlined below.

For *manufacturing of composites*, plasma coupling technology provides the capability forming carbon nanotube/fiber systems that are highly flexible and reproducible (singlewall/multiwall), and of nanofiber deposition. Capacitive coupling requires a high capacitance between the electrode and the plasma (large amplitude radio frequency (RF) voltages). The inductive coupling requires a high inductance between a coil and the plasma (large RF currents).[15]

Nonradiative energy transfer (incoherent) relies on *long-range electrostatic* Coulomb interactions that can potentially enable highly parallel, defect tolerant, and easily scalable communicating structures. On the other hand, strong electrostatic "plasmonic" interactions can be used for controlling energy flows in metal nanoassemblies. The ability to predictably control interfacial electrostatic interactions can lead to such important applications as electrically pumped tunable light emitters, on-chip plasmonic circuitry, artificial photosynthesis, low-cost photovoltaics, Terahertz detectors, and bio/chemical sensors.[16]

Molecular Vapor Deposition (MVD®) technology enables the growth of ultra-thin films with a wide range of functionalities on a broad spectrum of substrates. MVD is a breakthrough proprietary nanotechnology technique that allows for room temperature vapor deposition of several types of organic and organometallic molecules. This innovative technique has facilitated many new emerging applications with small feature sizes that have been difficult or impossible using traditional liquid synthetic techniques.[17]

For *testing of composites*, the mechanical response of nanoscale materials and structures has important implications, from understanding biological recognition and development of lightweight structural materials, to exploration of new concepts for switches and chemical sensors. While instrumentation such as nanoindentation exists to measure mechanical properties of nanostructured films on substrates, the development of techniques to reliably measure mechanical response of structures with nanometer-scale architectural dimensions such as nanowires, nanotubes, nanodots, nanofilms, nanopillars, nanoporous, etc, remains a challenging problem in nanomechanics.

New Materials and R&D Advances. Ongoing research generally focuses on state-of-the-art developments and the possible environmental impact of nanocomposites. For example, a new class of optical materials known as left-handed (or negative index) metamaterials that are not found in nature are being explored. These structures can focus light down to dimensions that are far beyond the classical diffraction limit.[18]

In other areas, research is ongoing to leverage attributes of carbon nanotube-based conductive coatings to solve real world problems for the security, medical, and performance coatings markets. This includes materials that can significantly improve the performance of commercial and military lithium ion batteries through the development of new salts.[19]

New Y-Carbon technology allows production of nanoporous carbon of uniform and controlled pore size. By varying different precursor and processing parameters, pore size can be tuned to sub-nanometer (about ten billionth of a meter) precision, something that is unattainable with the conventional route of carbon synthesis.[20]

Research is also ongoing to evaluate the impacts of nanomaterials in general on the environment, health, and safety. There is a significant body of work in this area, and numerous efforts are in progress to identify and define an effective approach for assessing the potential impacts of these new materials.[21]

3.2.2 Key Barriers

Specific barriers limiting the development of nanotechology-enabled composites and matrices identified in the workshop are detailed in Exhibit 3.2.2-a. In summary, these include:

Achieving nanotechnology-enabled composites/matrices with multi-functional properties. Industry requires better understanding and control over the functionality of nanomaterials in matrices before it can cost-effectively use their unique combinations of properties (e.g., strength, optical, magnetic, and electrical) to improve final products. Industry wants to better understand how performance properties vary as a function of size and surface area. Advances in this area could potentially enable breakthrough applications such as load-bearing windows, lightweight drilling rigs, super capacitors (high charge density batteries), and drug delivery.

Modeling properties across dimension scales. A key enabling technology would be to have predictive modeling capability that accurately relates material properties (mechanical, electrical, thermal, etc.) and the combinations of properties from the atomic- to the macro-scale. What is needed is a series of modeling techniques, each experimentally verified, that bridge across the atomic to macroscopic length scales, such as, but not limited to, quantum mechanics, molecular dynamics, meso-dynamics, phase fields, and finite element analysis. High-quality models would make it possible to accurately predict composite properties from the nanotechnology additives. Success in this area would mean fewer materials to be tested and simulations that could accurately predict unexpected properties.

Measuring the mixing and dispersion of nanoparticles. Thorough dispersion of nanoparticles within a matrix or composite is essential to deliver the intended properties of a nanomaterial, yet current tools are inadequate to provide the required level of quality assurance for such dispersion. A key difficulty is the inability to assure true dispersion and the absence of agglomeration of such tiny particles throughout an entire matrix or composite. A tool is needed to provide an accurate and realistic characterization of the dispersion of nanoparticles.

Scaling up for large-scale production/manufacture. Techniques for precision control of the scale-up process are needed to reliably preserve nanomaterial properties in large-scale manufacturing. Batch, continuous, and campaign industrial manufacturing applications require that large amounts of nanomaterials be completely and predictably consistent in makeup, properties, and quality over extended periods of time. Process control measurements and processes designed to take advantage of nanoscale interaction are needed, as well as processes that direct nanotechnology self assembly.

Effectively assessing and communicating EH&S risk. Industrial manufacturers are necessarily concerned about exposure to liability. They need to know what the risks of exposure are to human health and safety and to the environment. They need a way to reliably measure the presence of both manmade and preexisting nanoparticles in the work environment and in end-use environments. Supporting analyses may require methods for artificially aging or accelerating effects of time and weather on nanoparticles and nanomaterials.

Bonding nanofibers for high strength. Enhanced strength is a desirable property often associated with nanomaterials. The ability of nanotechnology to deliver on this promise requires a better understanding of the best ways to connect the nanofibers. Controlled self-assembly techniques that deliver high strength would enable multiple manufacturing applications, potentially including enhanced electrical conduction via nanotubes.

Establishing valid value proposition. Manufacturers require a clear and quantifiable demonstration of the value added by incorporating nanomaterials into their products or processes. In most cases, use of a nanomaterial must be shown to either deliver valuable added functionality at the same or only slightly higher cost than the current process or must deliver the same functionality at a lower cost. While the process for determining value proposition is well established, it has not been applied to nanomaterials. Extensions of the value proposition as it relates to nanomaterials include quality assurance, materials certification, EH&S issues, cost, final properties, and the properties as they affect processing (e.g., nanoparticle loading level in a matrix affects cost, viscosity, flow rate, and processing time). One value-added application could help sell industry on nanomaterials and get them widely invested in the effort.

The results in Exhibits 3.2.2-a and 3.2.3-a indicate that a combination of multi-scale modeling and experimental characterization techniques and informatics are needed to enable the capability to produce nanocomposites with properties-by-design criteria. As this capability is developed, it will be important to assess the potential degradation of nanocomposite properties throughout the life cycle and characterize the interactions of nanocomposites with environmental conditions, such as moisture, temperature, and mechanical stress.

Exhibit 3.2.2-a Key Barriers to Use of Nanotechnology-Enabled Composites and Matrices Across Industry

Barriers	Needs	Priority
Value	è Valuable early prototypes	●●●●●●●
	· Making even one useful nanotechnology-enabled material (e.g., aerospace)	
	· Results to justify continued or expanded Federal funding	
	· Sufficient information to enable decisions by corporate managers	
	è Valid value propositions	●●●●●●●
	· Show value in use	
	· Define market needs	
	· Acceptable changes to customer's production process	
	· Define cost structure	
	· Overcome cost concerns about engineered nanomaterials	
	è Certification/approval authorizing agents unaware of differences between composites and metals	●●●●
	· Stringent government regulation will stifle/inhibit research, development, and deployment (RD&D)	
	è Under-developed supply chains	●
	· Gap between nanomaterials producers and application companies	
	è Finding applications for lab results	
Multi-Scale Modeling	è How to relate properties from the nano- to the macro-scale	●●●●●●●
	· Finite element analysis to define relationship of structure to molecular properties	●●●●●
	· Deduce composite properties from nanotechnology additives	
	è Predict interactions between filler and matrix	
	è Models of nanomaterial effects and usage	
Characterization	è Property barriers: Inability to	●●
	· Determine solubility in polymers	
	· Measure leachants and extractables	
	· Measure permeability with small sample sizes	
	è Achieve/prove consistent synthesis	●
	è Fundamental understanding of phase separation at nanoscale	
	· Interaction of nanoparticles with polymer phases not understood	
	è Multi-functional instrumentation	
Measurement	è Accurate measurement of mixing or dispersion	●●●●●●●
	è Ability to measure time-dependent properties and capture effects of aging	●●
	· Appropriately accelerate conditions (aging) for all elements in nanocomposite	
	· Measure dynamic heterogeneity in nanocomposite	
	· Better understanding of properties of semi-crystalline nanocomposites	
	è Need database of standardized nanomaterial properties	●
Performance Properties	è Ability to build composites with multi-functionality	●●●●●●●
	· Multi-functional properties	●●●●●●
	· Preserving functionality of nanomaterials (e.g., strength, optical, magnetic, etc.) in matrices	
	· Improvement to final product	
	· Control of multiple properties	
	è Better understanding and control over electrical and optical properties	●●

Exhibit 3.2.2-a Key Barriers to Use of Nanotechnology-Enabled Composites and Matrices Across Industry Continued		
Barriers	**Needs**	**Priority**
	è Better understanding of performance properties as a function of size and surface area	●●
Processing	è Scale-up for industrial use	●●●●●●●
	· Controlled technology change needed in existing process, formulator	●●●●
	· Large-scale manufacturing infrastructure	
	· Process changes/impacts	
	è Challenges in bonding of nanofibers	●●●●●●●
	è Poor flow of nanoparticles at large scale	
	è Ability to control and use *in-situ* formation	
	è Ability to control meso-structure (porosity, homogeneity)	
EH&S	è Mechanism for communicating EH&S risk (real or perceived) along the supply chain	●●●●●●●
	è Better information on sustainability	●
	· Determine options for proper disposal/ reuse/recycling	
	è Reliable, available methods to measure or detect engineered nanoparticles in the workplace or environment	
	è Identification of best models/assays for preclinical and toxicological assessment of nanomaterials	

3.2.3 Priority Solutions

Cross-industry solutions to address the barriers were discussed and a list of topics identified, as follows:

- Informatics
- Communication
- EH&S
- Research
- Pre-Production (Process, Pilot, Value)
- Measurement
- Computing

Science needs within these topical areas were interactively discussed and the importance of possible solutions ranked (see Exhibit 3.2.3-a). While some of the solutions focus on a specific barrier, others apply across multiple barriers and industries.

Exhibit 3.2.3-a Cross-Industry Solutions to Accelerate Progress in Nanotechnology-Enabled Composites and Matrices

Topic / Solution	Priority
Informatics	
· Develop searchable database for nanomaterials and their properties	●●●●●●●●●
o Develop nanoinformatics database on current understanding of interfaces at nanoscale	
o Enable cross-field/industry knowledge-sharing and idea fertilization, focused on science/engineering organizations	
o Extend Toxnet[22] database with added nanomaterial searching method	
o Communicate "failures" to research community	
· Informatics (broken up by materials class)	●●●●●●●
o Launch major effort (like moon shot)	
· Develop better IP technology transfer models	●●●
o Improve technology transfer: communication, dissemination, matching	
· Develop central "nanomanufacturing hub"	
o Gain knowledge and reduce number of networks for nanotechnology	
· Perform knowledge gap analyses and focus research on criteria gaps	
Communication	
· Create better academic/government lab/industrial communication structure	●●●●●
o Improve industry coordination in communicating research needs to research community	
o Forge better connections between scientists and industry	
· Create awareness (pros and cons)	●●●
o Promote public relations to "advertise" nanotechnology successes to public	
· Improve communication of material needs through the value chain	●
· Create on-line magazine like *MIT Technology Review* on nanotechnology subjects	
EH&S	
· Harmonize and validate toxicology testing protocols	●●●
o Validate *in-vitro* test protocols to correlate to *in vivo* effect (nanotoxicology)	
o Employ cross-disciplinary approach to assess issues (e.g., biochemistry, engineering, materials, toxicology, etc.)	
o EH&S test protocols validated across multiple labs	
o Bridge gap between National Institutes of Health (NIH) funding (toxicology) and NSF funding (creation of nanocomposites)	
· Develop tool kits	●●●
o Collect, review, and disseminate best and most practical EH&S practices – tool kit	
o Develop a method for containing nanoparticles – EH&S	
o Categorize EH&S risk with focus on worker, consumer, general population	
o Build EH&S concepts into product launch model/ business plan	
· Metrology	
o Identify chemistry/physics properties most useful for risk management decisions along material life cycle (develop methods)	●●
o Develop good metrics for determining exposure (environmental, health, etc.)	●
o Develop well-characterized toxicology samples (mono disperse particles)	
· Regulatory	
o Be proactively involved with regulators and legislators in setting standards for nanomaterials	
§ Inform/decide/communicate/influence EH&S regulations ASAP	

Exhibit 3.2.3-a Cross-Industry Solutions to Accelerate Progress in Nanotechnology-Enabled Composites and Matrices Continued

Topic	Solution	Priority
Research		
	· Surface modification – bonding	●●●●●●●●
	o Binding covalently to the matrix	
	· *In situ* formation precipitation, self assembly, gas/water phase dynamics	●●●●
	· Develop material templates to help control the dispersion	●
	o Develop material templates to control structure	
	o Address dispersion issues on an industrial scale	
	· Focus on set of composites	
	o Understand how various composite formation methods (e.g., extraction/casting/high shear) impact matrix properties	
	· Enhance interaction between synthetic and bi-focused programs on nanotechnology interfaces	
	· Analyze relationship between nanoscale and discontinuous, amorphous phase	
	· Develop high-throughput (lab-on-chip) method to characterize >2 properties simultaneously	
Pre-production		
	· Scale up	●●●●●●●●
	o Low cost raw materials	●●●●
	o Consider scale-up issues from product development outset	
	o Incorporate linking/bonding with current materials or processes	
	o Create programs for scale-up facilities	
	o Strategic centers of excellence in nanomanufacturing (nanomaterials and nano technology products)	
	· Customer needs/value	●●●●●●●●
	o Collaborate with customers and others in value chain to develop robust systems	
	o Prioritize commercial needs and increase their influence on research funding allocations	
	o Clearly define value of nanotechnology	
	· Manufacturing needs/value	●●●●●
	o Process-focused program, well understood markets and technologies	
	o Provide access to pilot-scale manufacturing equipment for process validation and demos	
	o Develop generic business case plans/templates for risk assessment and sensitivity analysis	
	o Enable low-cost production	
	o Understand process-structure (engineering properties)	
	· Modify certification process	
	· Develop tool kit with measurement systems for nano- to micro-scale	●●●●●
	o Develop "labeling" technology to assist measurement of mixing/dispersion	
	o Develop improved metrology/imaging for nanocomposites	
	· Gain knowledge of real-time and accelerated aging of well-characterized nanomaterial systems (prioritization needed)	
	· Develop robust, real-time, *in situ* composite characterization and monitoring tools	
	· Develop analytical method for non-ideal/complex material systems	

Exhibit 3.2.3-a Cross-Industry Solutions to Accelerate Progress in Nanotechnology-Enabled Composites and Matrices Continued

Topic	Solution	Priority
Computing		
	· Petascale computing o Develop modeling tool kits on "nanoHUB.org" to simulate multiple different properties of nanocomposites · Model properties and map them across size scales o Engineering and science map o Structural o Strategic targets	●●●●

To hold commercial value for industry, a nanocomposite must offer specialized properties at lower cost than traditional materials or provide multiple new and unique properties for a specific application. These properties must not degrade significantly through the life of the material. Developing these capabilities will require significant research into the interactions of the nanomaterials in the polymer matrix and how these interactions change over time and under various conditions.

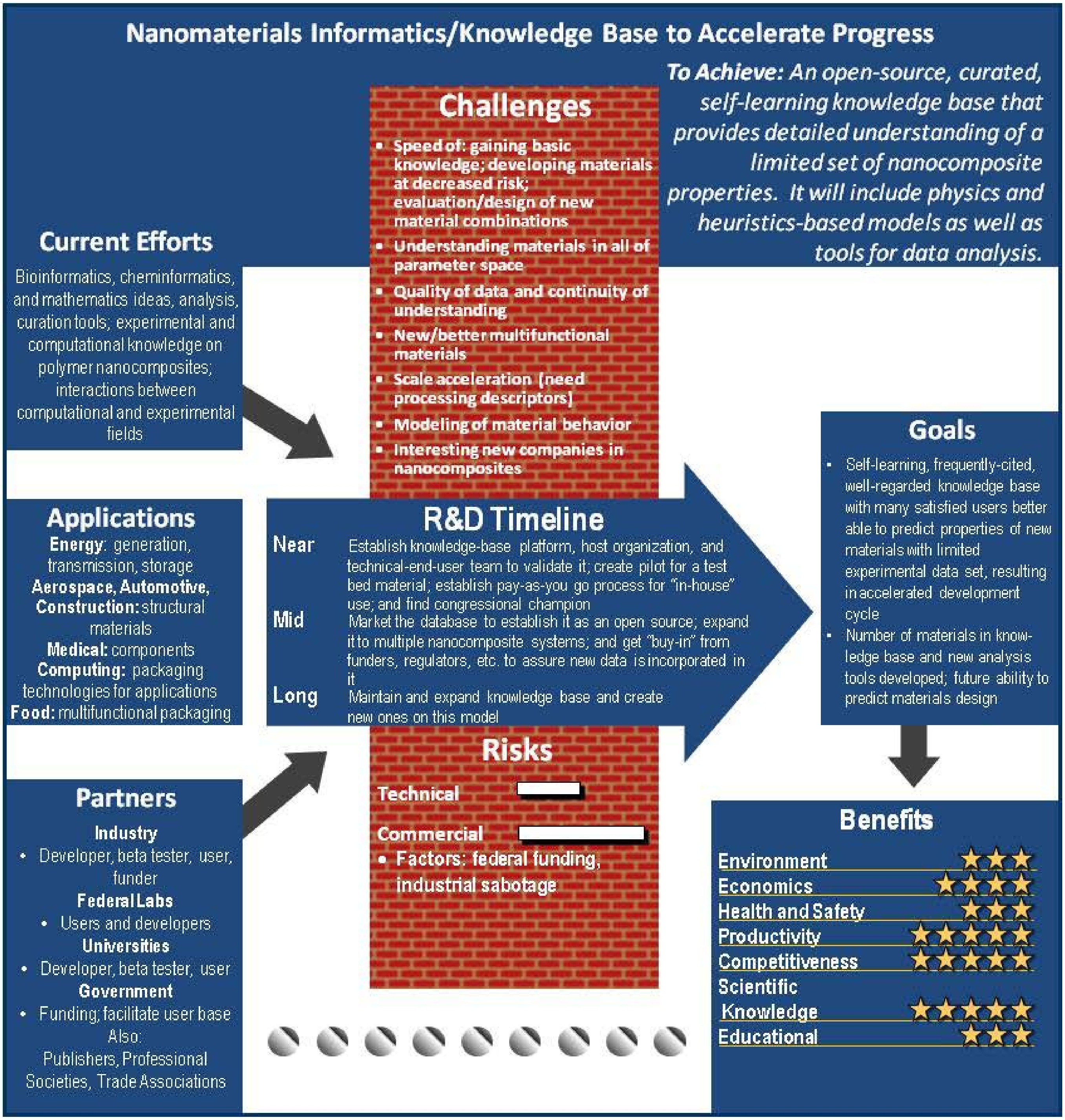
From the solutions identified in Exhibit 3.2.3-a, a set of priority solutions was selected and grouped as shown in Exhibit 3.2.3-b. Mini-roadmaps for each solution are shown graphically on the pages that follow.

Exhibit 3.2.3-b Priority Cross-Industry Solutions
Nanotechnology-Enabled Composites and Matrices

- Nanomaterials informatics/knowledge base to accelerate progress
- Develop methodology to control reactions/bonding of nanoscale particles within a matrix and across interfaces
- Build value proposition for nanomanufacturing to meet customer needs
- Develop tool kit enabling measurement at nano- to micro-scale (including dispersion of nanoparticles within a matrix and at interfaces)
- Predictably scale up lab-scale processes to manufacturing-scale for production of nanomaterials and products
- Optimize manufacturing processes
- Coordination of research on nanocomposites and matrices across industry, universities, Government, and Federal laboratories

Nanotechnology-Enabled Composites and Matrices

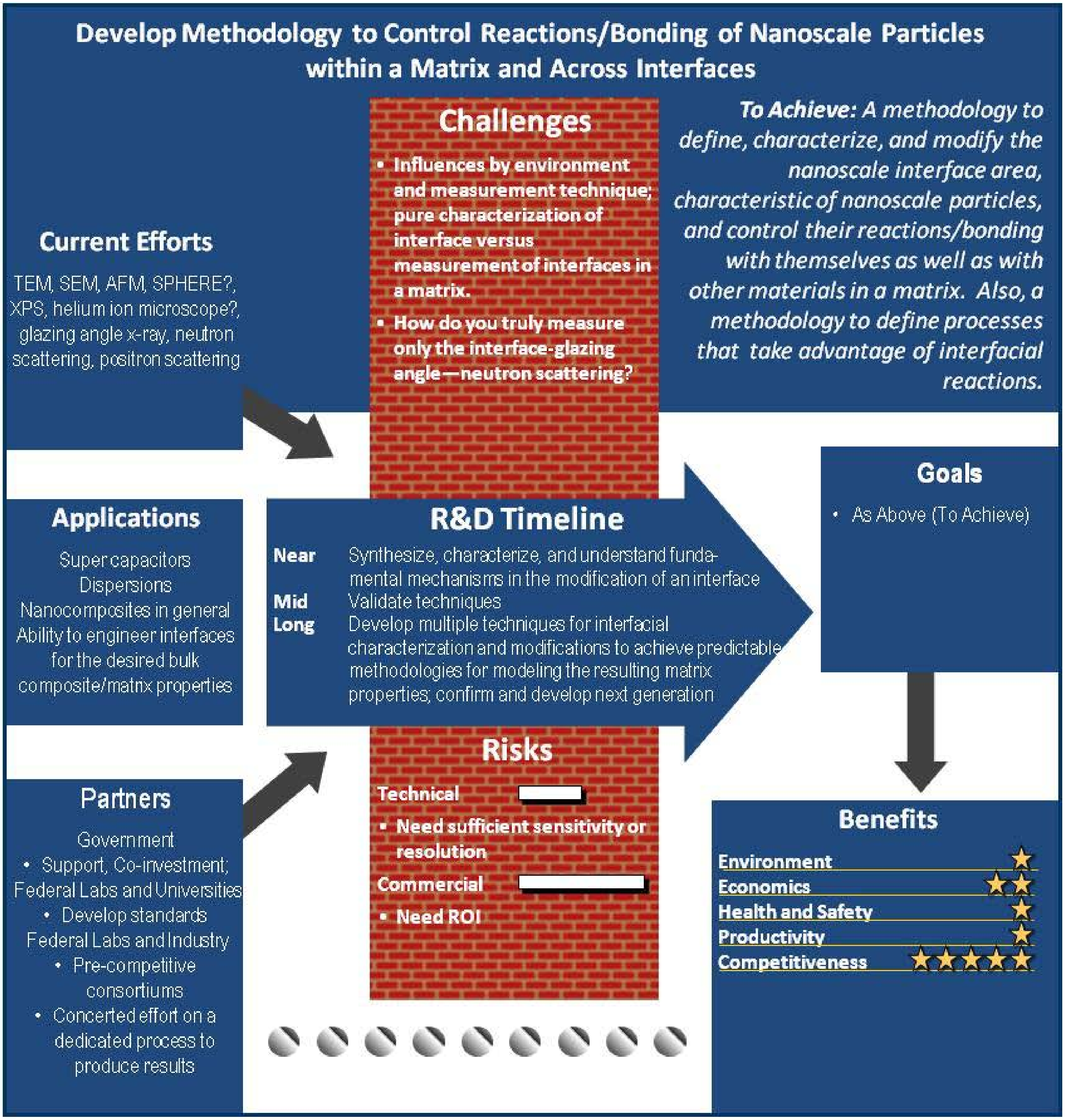
Priority Solution: Nanomaterials Informatics/Knowledge Base to Accelerate Progress



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Nanotechnology-Enabled Composites and Matrices

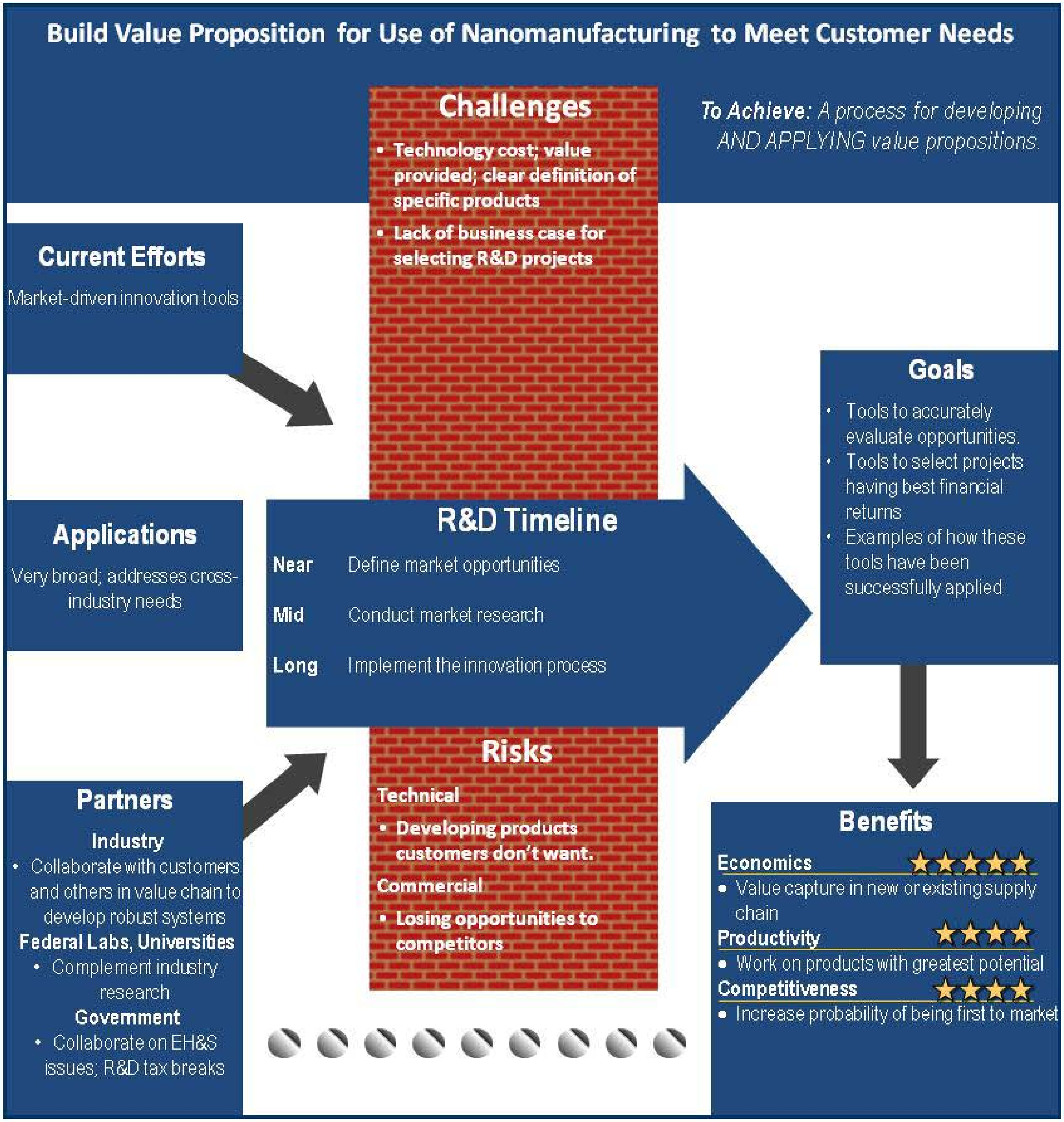
Priority Solution: Develop Methodology to Control Reactions/Bonding of Nanoscale Particles within a Matrix and Across Interfaces



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Nanotechnology-Enabled Composites and Matrices

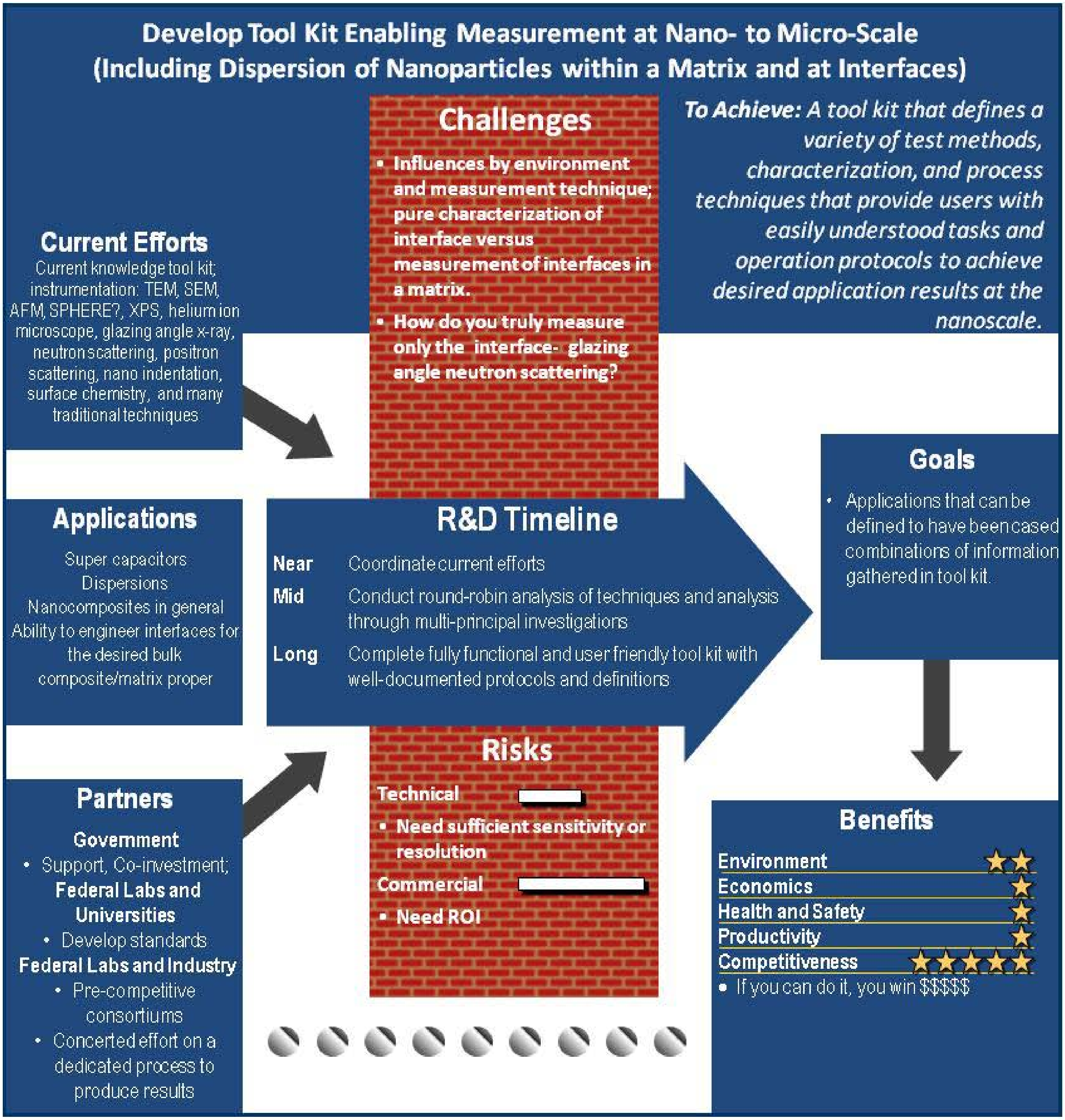
Priority Solution: Build Value Proposition for Use of Nanomanufacturing to Meet Customer Needs



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Nanotechnology-Enabled Composites and Matrices

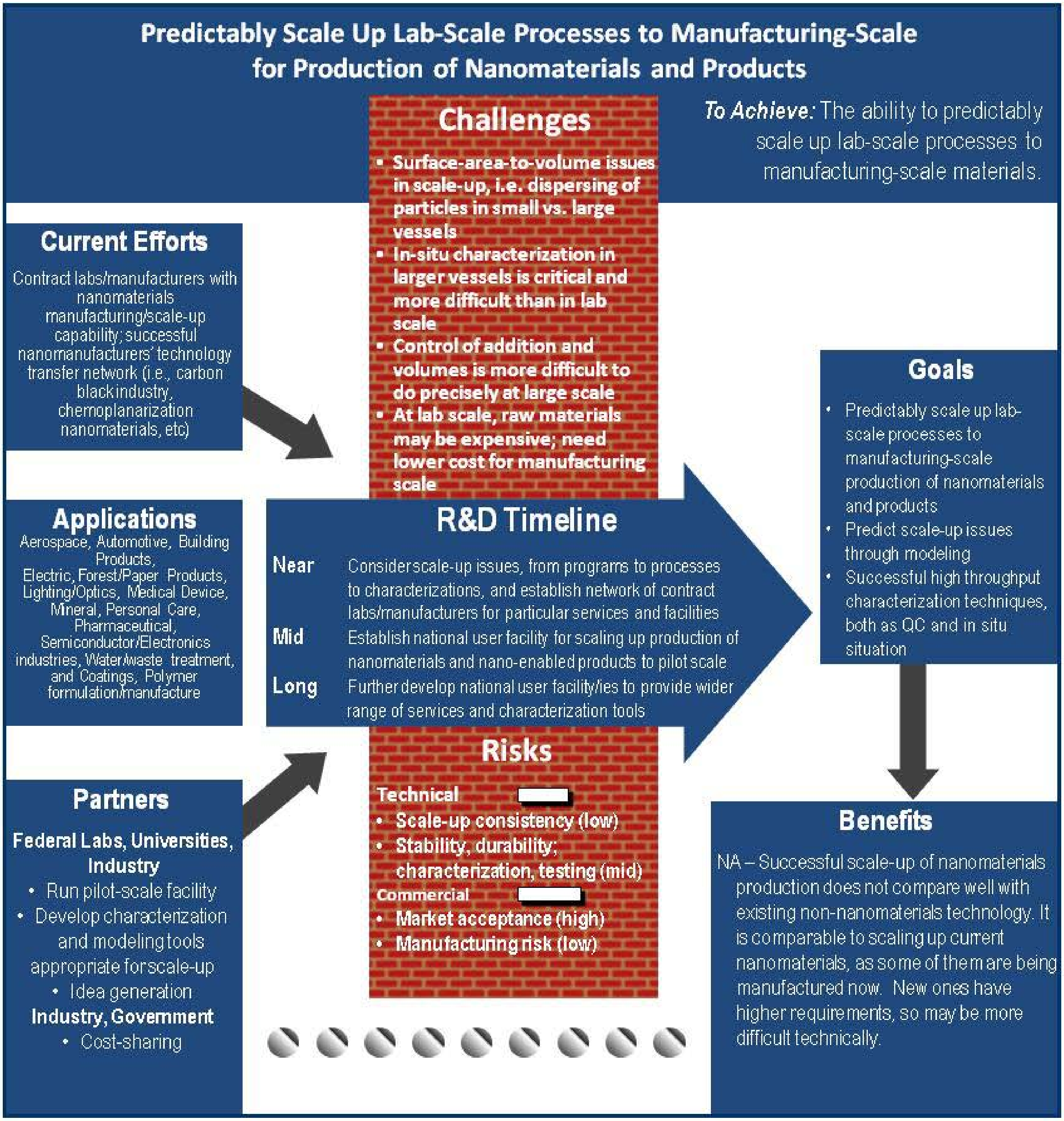
Priority Solution: Develop Tool Kit Enabling Measurement at Nano- to Micro-Scale (Including Dispersion of Nanoparticles within a Matrix and at Interfaces)



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Nanotechnology-Enabled Composites and Matrices

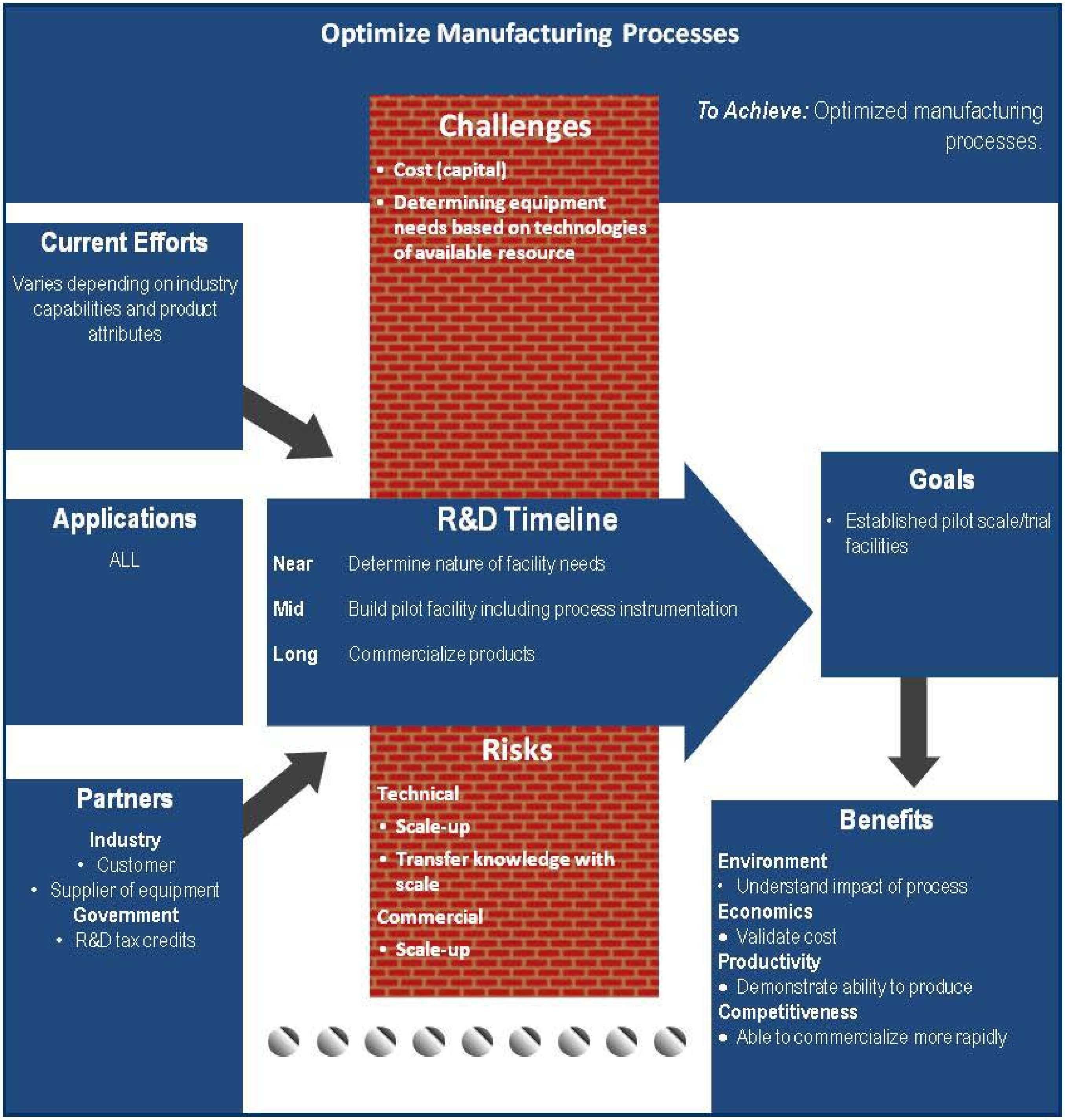
Priority Solution: Predictably Scale Up Lab-Scale Processes to Manufacturing-Scale for Production of Nanomaterials and Products



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

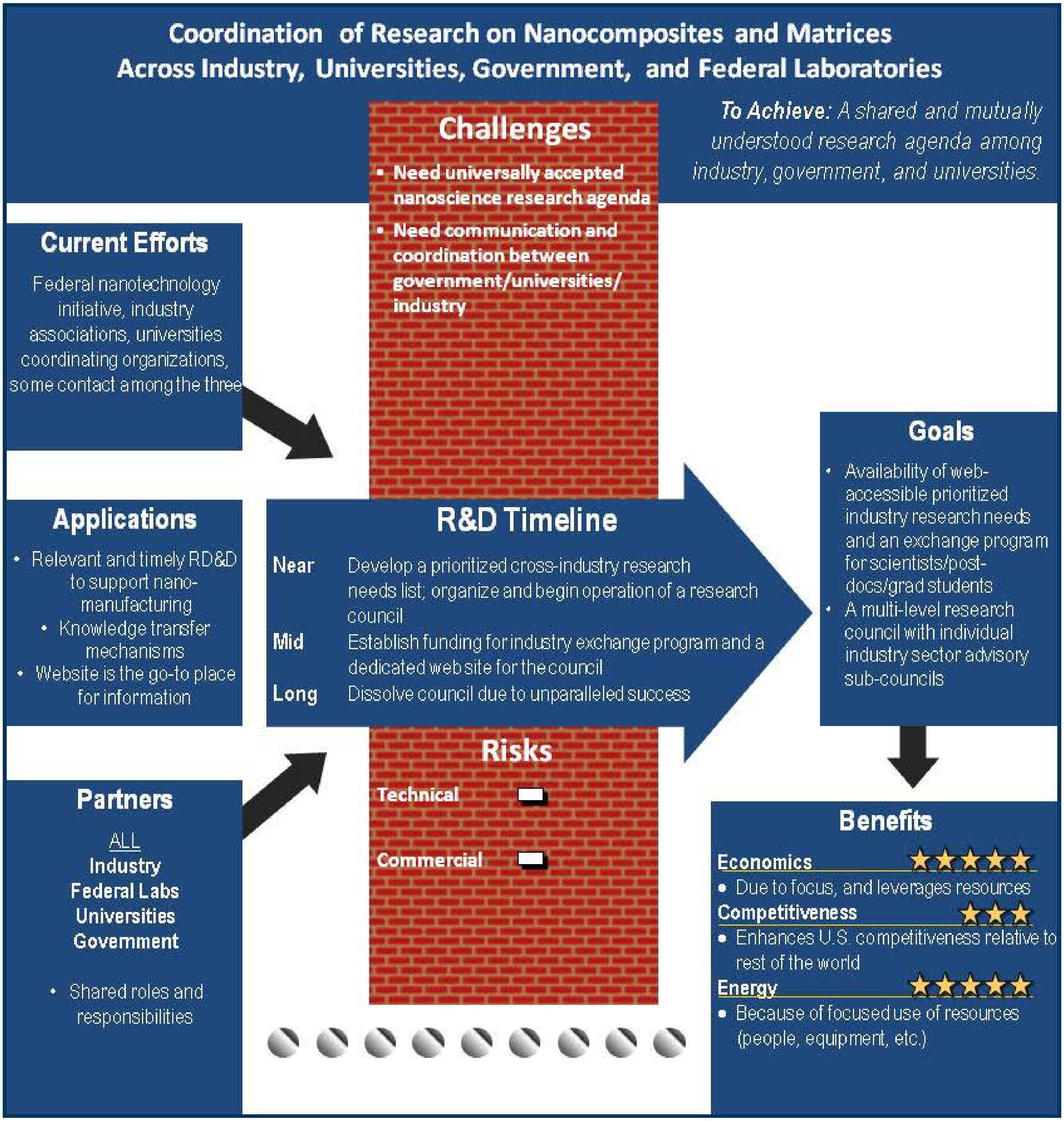
Nanotechnology-Enabled Composites and Matrices

Priority Solution: Optimize Manufacturing Processes



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Priority Solution: Coordination of Research on Nanocomposites and Matrices Across Industry, Universities, Government, and Federal Laboratories



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

3.3 Separations and Fractionation

> **Session Scope**
>
> - Identify what separation, purification, and fractionation issues are critical to nanotechnology
> - Define what kinds of separations and fractionalizations are used to get formulations needed for products and current limits
> - Identify challenges and barriers for improving current separations and fractionations to improve yields

Techniques and industry processes related to separations and fractionation of nanomaterials are critical for characterization and stabilization of many materials during manufacturing. Nanomaterial applications in medicine, food production and packaging, chemical pigment production, bio-fuel processing, and the forest industry have specific needs to improve methods and techniques of separations and fractionalizations. Purifications in particular are a targeted emphasis.

This group was tasked with identifying the challenges and prioritizing the needs for advancing separations and fractionation techniques for commercial production of uniform, high quality, stable, and consistent nanomaterials in high volume. It is recognized that separations and fractionation methods are specifically applicable to the production of nanoparticles, which might be functionalized and used for applications such as nanomedicines, or mixed with other materials to form nanocomposites.

Two basic production strategies for nanoparticles were discussed: (1) large volume, batch fabrication, where the application of filtration techniques is used to purify the formulation from undesired byproducts; and (2) emerging microfluidic methods that could produce high-purity formulations that require little purification.

3.3.1 Current Advances

There are a range of techniques that can be applied to the separation and fractionation of nanoparticle formulations. These include filtration, chromatography, electrophoresis, ultracentrifugation, and field flow fractionation. The techniques each have their advantages and disadvantages that are dependent on the type of particle of interest, and the cost, quality, and efficiency of the separation.

Filtration methods have the potential to provide high-speed, high-volume fractionation capability. The basic approach is to set up a series of filtration steps with increasingly smaller pores in order to extract or separate larger-sized materials or debris that would clog the membrane filter for the particles of interest. In addition, each filtration step would yield particle size fractions in the size range of the filters that are upstream and downstream of that step. Examples of state-of-the-art membrane filtration techniques include the use of ordered porous materials (for example, see M. E. Davis, Nature 417, 813, 2002).

The separation of materials by chromatography was first reported by Mikhail Tsvet in 1906. In a chromatographic separation the material of interest is dissolved in a solvent (mobile phase) gas or liquid, and is passed over a solid adsorbent (stationary phase), which is typically packed in a chromatographic column. The differing affinities between the material, the solvent, and the solid adsorbent will separate the material of interest into its constituent parts. One advantage of this technique is that it is well established and has been expanded for application to a host of materials. A disadvantage is that it is not applicable for high-volume production. Techniques include normal phase (NP-HPLC), reverse phase (RP-HPLC), size-exclusion or gel permeation (SEC or GPC), and ion exchange (IEC), and fast protein liquid chromatography (FPLC).

Another well-established separation method is electrophoresis, discovered by Ferdinand Friedrich Reuss in 1806. Electrophoresis is a primary technique for biomolecular separations because it is powerful yet reasonably easy and inexpensive to implement. It can be carried out in a rectangular slab of material, a capillary tube, and in planar microchip formats. Electrophoretic separation techniques include free-solution and gel electrophoresis, micellar electrokinetic, and isoelectric focusing. This technique can yield high-quality separations of materials for laboratory analysis but is also not amenable to high-volume production.

Separations have also been demonstrated using a technique called analytical ultracentrifugation, invented in 1923 by Theodor Svedberg. The separation is carried out in a device called an ultracentrifuge, which is optimized for spinning a rotor at very high speeds that are capable of generating acceleration as high as 1,000,000 G. The sample being spun can be monitored in real time using ultraviolet light absorption and/or an interference optical refractive index sensitive system. A hazard associated with analytical ultracentrifugation is the tremendous rotational kinetic energy where a catastrophic failure of the rotor is a serious concern.

The last method of common use is separation by field flow fractionation (FFF), discovered in 1965 by J. Calvin Giddings. An excellent review of this technique can be found in the reference: J.C. Giddings, Science, 260 (1993), 1456. The separation method is based on the differing retention of materials in a stream of liquid flowing through a thin channel while applying a force (by centripetal, electric, or magnetic field) at right angles to the flow. The technique will allow a sample to elute through the system and separate by size. This technique has been demonstrated to give high-performance separations of nanoparticles but is not scalable to high-volume production at this time.

3.3.2 Key Barriers

Specific barriers for improving current separations and fractionations to improve yields identified in the workshop are detailed in Exhibit 3.3.2-a. In summary, these include:

Manufacturability. The main challenges and problems in separations and fractionation are in the area of manufacturability.[23] A consensus was reached that improved in-line measurements and characterization of nanoparticles was needed. Filtration techniques typically require a multiple step process. In-line measurements at each filtration step would yield improved understanding of the process so that it could be used to develop models to optimize the process for high throughput and lowered cost. In-line measurements were also desired for the microfluidic techniques, which could lead to improved understanding of how nanoparticles form and could drive massively parallel production techniques to bring throughput to commerically viable volumes.

Characterization. Key characterization issues that present challenges are simultaneous sorting of size, shape, and charge; and temperature and chemical compatibility. It was recognized that the ability to not only characterize nanoparticle size, but to also simultaneously determine shape and charge, would be a highly useful improvement in characterization.

Purification and Removal of Non-Nanomaterials. Purification is a key step in the development of nanomaterials with the desired properties and functionality. Purification and fractionation first take place in the removal of non-nanomaterials. The main issues that need to be addressed in this area are preparative purification, sample preparation, and the removal of debris. There are also challenges in assuring the purity of the material produced for use in final products, including the sensitivity of the process and selectivity.

Measurement Methods. Key measurement issues encompass the ability to measure the properties of interest with enough precision, selectivity, sensitivity, and tolerance in the manufacturing environment. Proven calibration techniques that are reliable for production and reference materials are also needed to ensure reproducibility.

Exhibit 3.3.2-a Key Barriers for Separations And Fractionation

Barriers	Needs	Priority
Measurement Methods	è Calibration and reference materials	●●
	è Sample collection method; getting enough of the item of interest	
	è Measuring the metric of interest to needed tolerance	
	è Instrument selectivity	
	è Instrument sensitivity	
	è Detection limit	
	è Precision	
Removal of Non-Nanomaterials	è Preparative purification	●●●
	è Sample preparation removing debris	●●
	è Soluble fraction – separate	
	è Semi-preparation, application/purification	
Manufacturability	è In-line measurements and visualization	●●●●●●●
	è High-throughput methods	●●●●●●
	è Efficiency	●●●
	è Avoid aggregation, recognize change in extract	●●●
	è In-line characterization	●
	è Filtration rates	●
	è Making stable dispersions	●
	è Reproducibility, consistency	●
	è Quantity (large) processing (scale-up)	●
	è Mature manufacturing, large scale, process availability	
	è Longevity, i.e., get enough product made without blocking	
	è Yield	
	è Affordability of existing filtration & separation methodologies	
Purification	è Probes selectivity	●
	è Sample and final product purity	
	è Process sensitivity	
	è Purity of raw material produced	
Characterization	è Simultaneous sorting of size, shape, and charge	●●●●●●●
	è Temperature and chemical compatibility	●●
	è Size determination in water	
	è Defined attributes for separation/fractionation	
	è Verification of separation/fractionation	
	è Matrices (air, liquid, biofluid)	
	è Compatibility – no fouling/blocking	
	è Chemical composition	
	è Modeling the system	

3.3.3 Priority Solutions

Cross-industry solutions to address the barriers were discussed and a list of topics identified, as follows:

- Avoid aggregation; recognize change in extract
- Efficiency
- Preparative purification
- Modeling
- High throughput methods
- In-line measurements and visualization
- Simultaneous sorting of size, shape, charge

Research needs within these topical areas were further explored and the importance of possible solutions ranked (see Exhibit 3.3.3-a). These solutions are mostly unique to separations and fractionation, but many could be applied across multiple industries.

Exhibit 3.3.3-a Cross-Industry Solutions for Separations and Fractionation

Topic	Solution	Priority
Avoid Aggregation; Recognize Change In Extract		
	Plate reader high throughput approach	
	Agitation/shaking, additives/surfactants, flow aids	
	Use micro-bubble reactor to avoid aggregation	
Efficiency		
	Sharp cutoffs so that multiple passes are not needed	●
	Easy to clean	●
	Filter sized correctly for particle size required	
Preparative Purification		
	Filter or centrifuge sized correctly to remove debris, junk, contamination	
	Particle size required (nm)	
Modeling		
	Models of modules for system design. Optimization by modeling – solvent, charge, interaction	●●●●●●●●
	Sizing determined by modeling – feed, reaction and reaction profile, required final product	
	Model for efficiency – feed, reaction profile, required final product	
	Model correctly – feed, reaction, final product	
High Throughput Methods		
	High-throughput production/scalable	●●●
	Investigate massively parallel microfluidic methods	●●●
	Combine synthesis and separation to increase process throughput/efficiency	●●
	Centrifugation filtration chromatography	●
	Investigate use of rotating packed beds for materials separation	

Exhibit 3.3.3-a Cross-Industry Solutions for Separations and Fractionation Continued

Topic	Solution	Priority
In Line Measurements and Visualization		
	· Adapt anal ytical m ethods t o i n-line. Filter t o nm r ange, c harge c apture r elease < 50 nm, s ide stream/sample port, zeta potential laser	●●●●●●●● ●●
	· Use ultrasound attenuation spectra in line for measurement/control	●●
	· Dynamic light scattering (DLS)	●
	· 3D measurement and visualization	●●
	· Develop microfluidic method and measurement techniques	
	· Automated microscopic sampling and analysis	
	· Side stream filter to <50 nm, laser, zeta, microfluidic channel, print out real time on size distribution	
Simultaneous sorting of Size, Shape, Charge		
	· Standard reference materials, size, shape, charge, chemistry	●●
	· Modify electro-zone sensing for size, shape, and charge sorting	
	· Investigate nanofluidic methods	
	· In-line mass spectroscopy, enhanced mass spectroscopy	
	· Microfluidics with detection capabilities	

From the solutions identified in Exhibit 3.3.3-a, a set of priority solutions were selected and grouped as shown in Exhibit 3.3.3-b. Mini-roadmaps for each solution are shown graphically on the pages that follow.

Exhibit 3.3.3-b Priority Cross-Industry Solutions
Separations and Fractionation

Develop parallel microfluidic methods

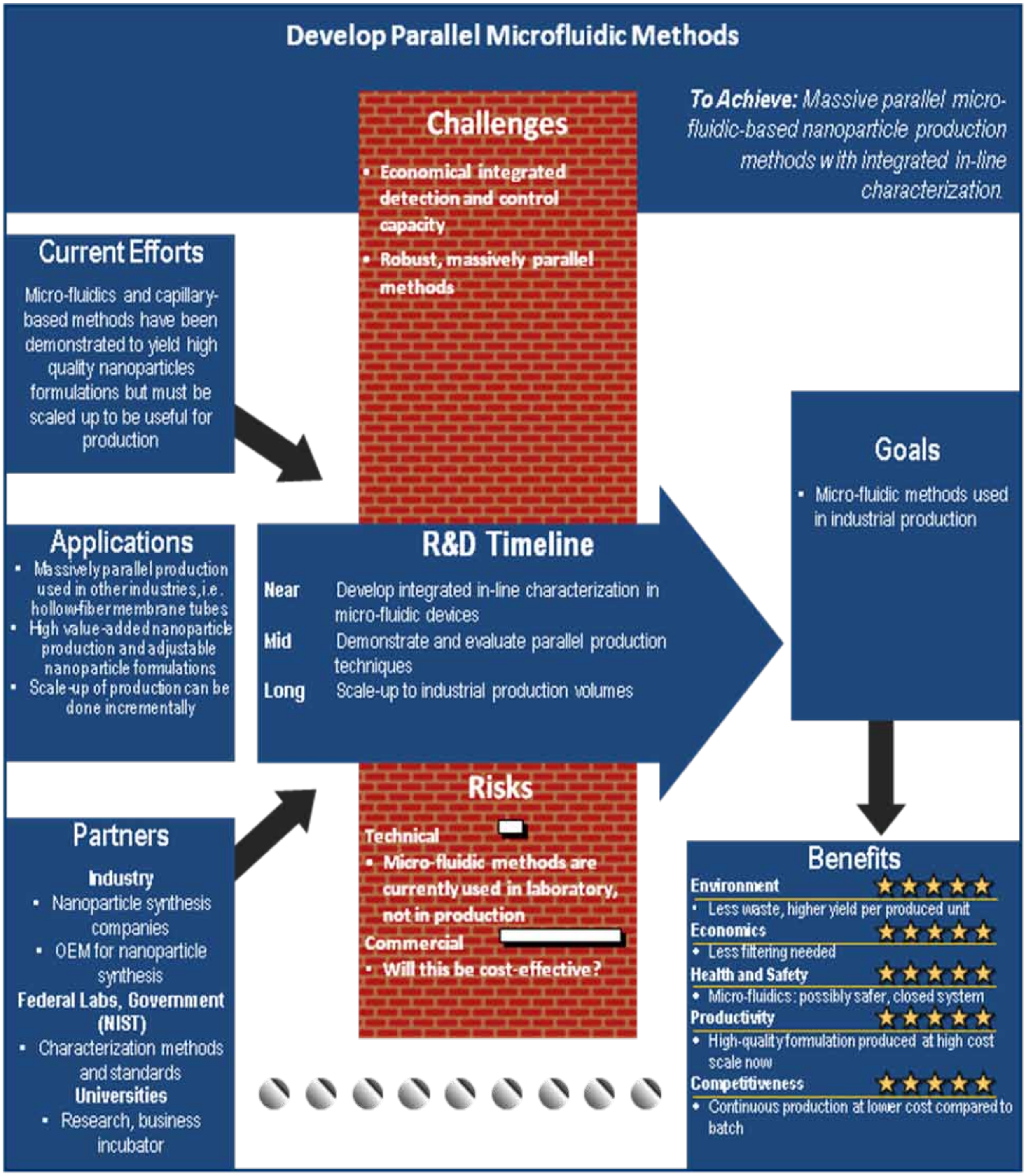
Build high-throughput production/scalable methods

Enable modeling to predict process/material characteristics

Develop in-line measurements and visualization: transfer laboratory analytical methods to in-line

Separations and Fractionation

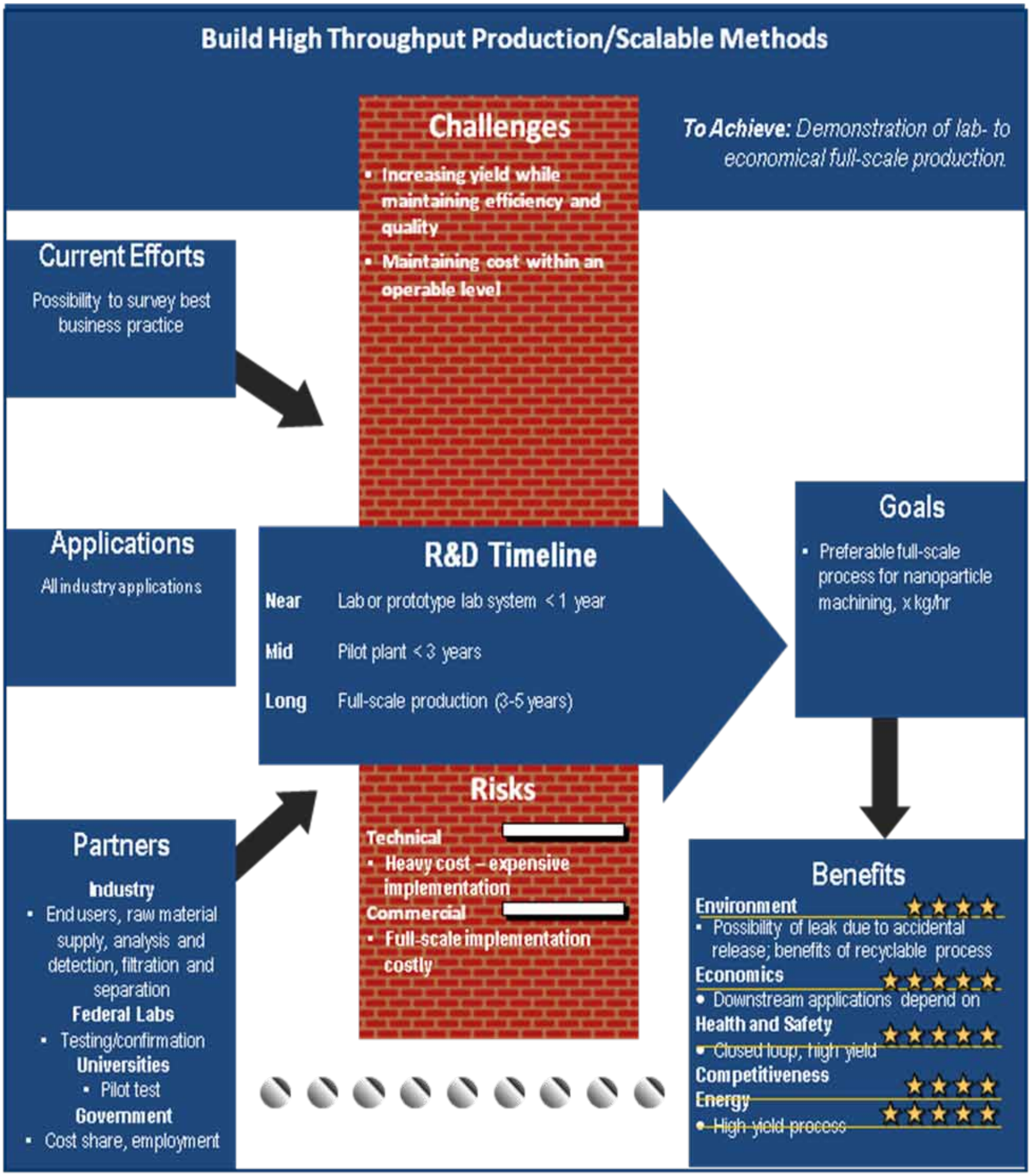
Priority Solution: Develop Parallel Microfluidic Methods



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Separations and Fractionation

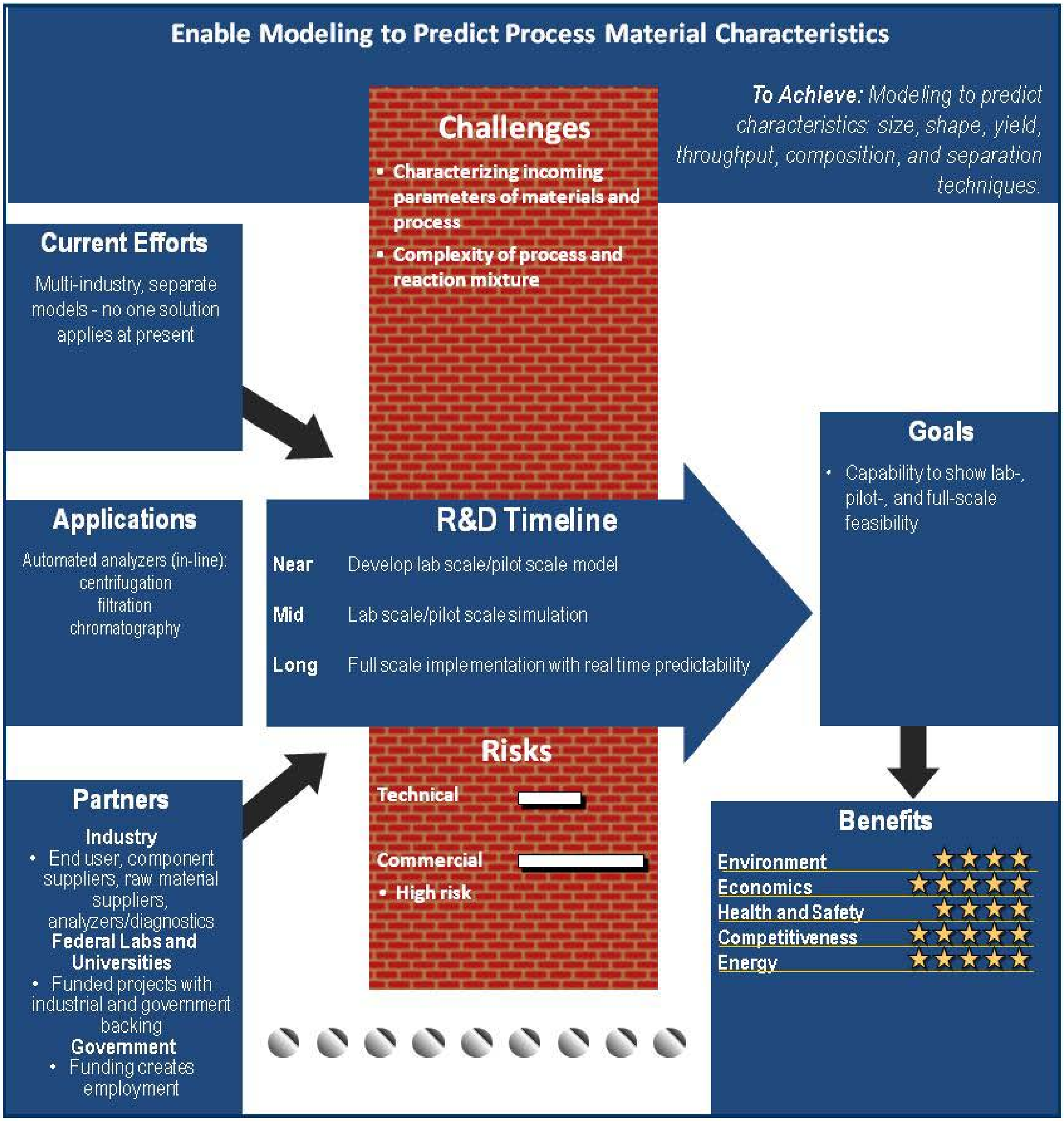
Priority Solution: Build High Throughput Production/Scalable Methods



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

Separations and Fractionation

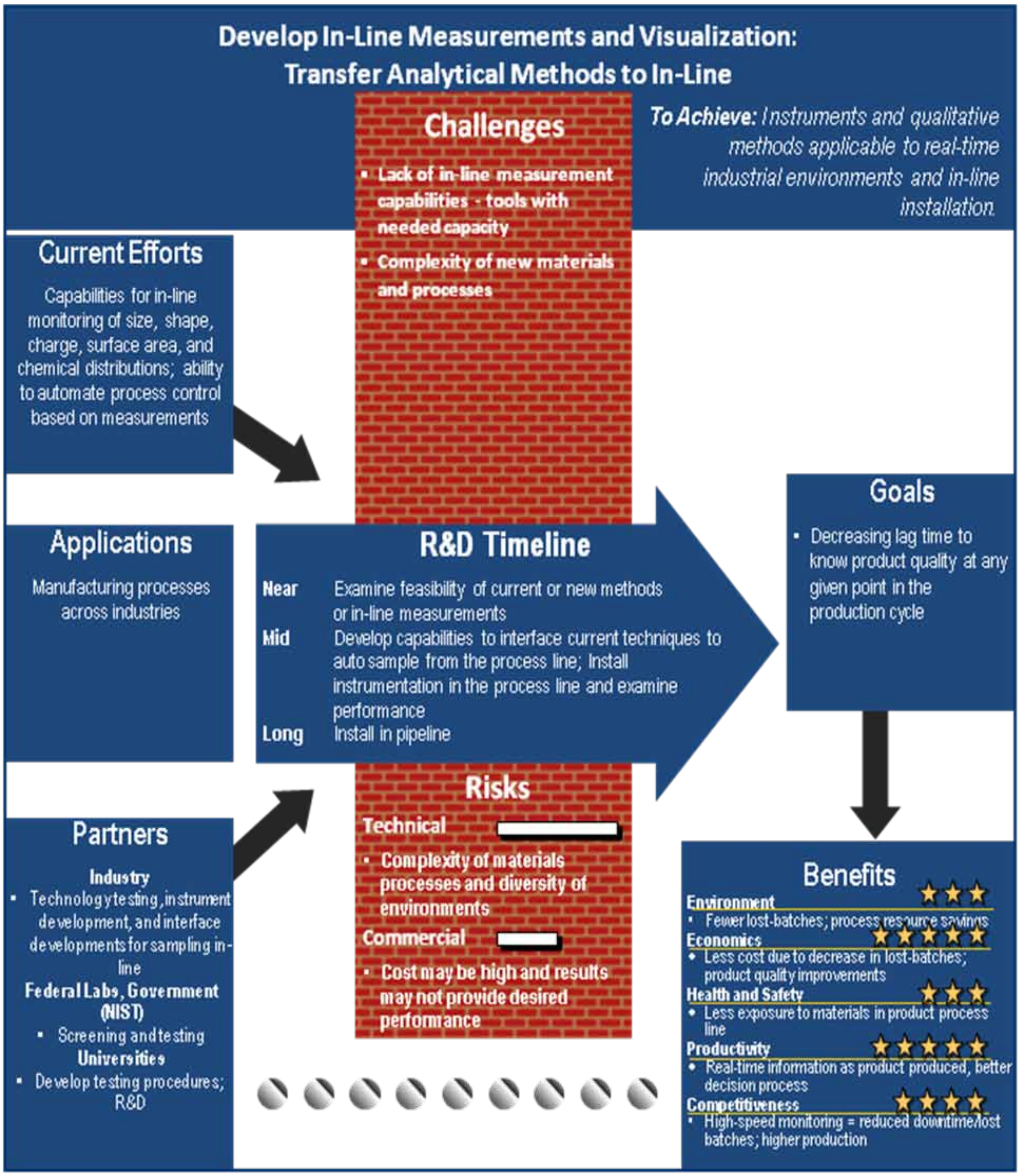
Priority Solution: Enable Modeling to Predict Process/Material Characteristics



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

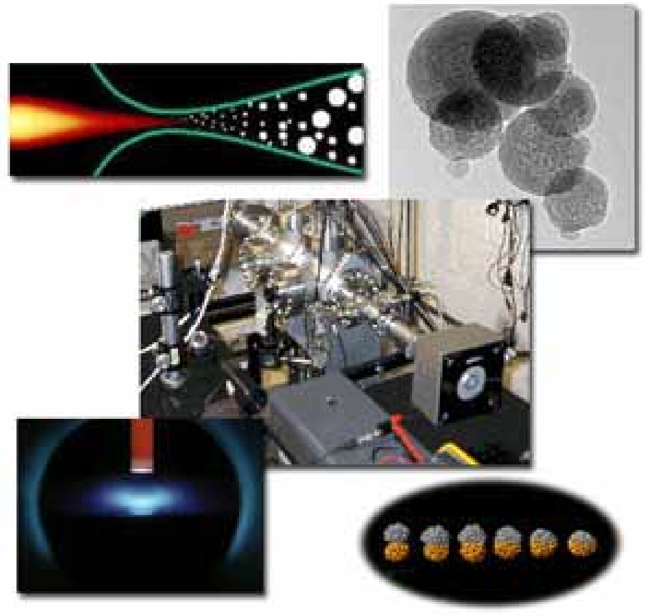
Separations and Fractionation

Priority Solution: Develop In-line Measurements and Visualization: Transfer Laboratory Analytical Methods to In-Line



Timeline: Near-term (2009 to 2011) Mid Term (2012 to 2015) Long Term (2016 and beyond)

4. The Path Forward



Figures courtesy of The University of Maryland
(http://www.enme.umd.edu/cnmm/)

Identifying and better understanding the cross-industry challenges is a step toward coordinating research, disseminating common knowledge and that could serve all industries, and improving the knowledge foundation and data infrastructure needed for cost-effective, world-competitive nanomanufacturing. Currently, multiple industries and sectors are producing nanotechnology roadmaps, often with similar or cross-cutting needs. Multiple databases of information are beginning to emerge, along with technical successes in commercial nanotechnology. Along with these developments is a strong consensus on the need for evaluating the environmental, health, and safety impacts of nanotechnology-based products. Modeling, measurement, and process control, based on high throughput measurement, have been established as critical parameters to the safe commercial utilization of nanotechnology on a broad scale.

While there is a large Federal investment in nanotechnology research, the challenge remains in prioritizing what needs to be done, and how to leverage the outcomes (gaining the most benefit for dollars spent). Many government agencies are making a push toward cross-industry programs to expand the reach of R&D. The need for coordination in nanomanufacturing R&D and information dissemination across the public and private sectors has never been stronger, and is critical to attaining and maintaining global leadership.

As the results of this workshop illustrate, there are numerous cross-industry challenges related to nanomanufacturing that could begin to be addressed through a concerted, integrated, public-private effort. The following guiding concepts were considered to be an essential foundation for the framework for a coordinated effort:

- Enable cross-fertilization and identification of best practices using currently available science and technology to deliver short-term impact,
- Define collaborative research programs that cross industrial sectors, government agencies, and academic disciplines to address the more difficult challenges and long-term needs,
- Identify challenges that are appropriate for Federal and/or industrial funding, and lay the groundwork for formation of consortia and multi-organizational R&D projects to achieve the desired outcomes,
- Establish a reference data infrastructure that links nanoscale structure and composition to properties and performance to enable more effective R&D, advance fundamental understanding, and the development and validation of reliable predictive models, and
- Establish a knowledge database of work conducted at universities and national labs that captures structure/manufacturing process/performance relationships, as well as predictive capabilities of models and simulations.

Ideas for creating a coordinating nanomanufacturing group were presented and explored. One important idea that emerged was an umbrella alliance that would be industry-driven (industrial decision makers with long-term commitment, trade associations, individual companies) and government-facilitated and government-supported. The purpose of this alliance would be to help consolidate multi-industry research needs, map existing research and capabilities, consortia, and initiatives, and build a nanomanufacturing knowledge base in targeted areas.

Implementing an umbrella alliance will require the development of planning committees and an organizational charter. Tentatively this would include an executive committee, advisory committee, administrative group, and technical committees/subcommittees – all with members from both the public and private sectors. Discussions have taken place post-workshop to build an Umbrella Alliance for Nanomanufacturing. As this organization evolves, it is expected that the benefits of a coordinated approach to this critical area of nanotechnology will begin to emerge.

Appendices

Appendix A. List of Participants and Contributors

Clare Allocca
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Michael Wolcott
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Appendix B. Workshop Agenda

Cross-industry Issues in Nanomanufacturing Workshop
National Nanotechnology Initiative Affiliated Workshop
Workshop Agenda
NIST Campus, Gaithersburg, MD, USA 20899
May 20 – 22, 2008

<table>
<tr><th colspan="3">Tuesday, May 20: “The Problem”
Convener: Anne Chaka (NIST)</th></tr>
<tr><td>7:00 -7:30 am</td><td colspan="2">Continental Breakfast</td></tr>
<tr><td rowspan="4">7:30 -8:45 am
Plenary Session</td><td colspan="2">“Set the stage for the workshop: What are we intending to accomplish and why and what are the Deliverables”</td></tr>
<tr><td>7:30 – 7:50 am</td><td>Introductions, antitrust, purpose of workshop, deliverables, workshop logistics, facilitated breakout sessions orientation: Anne Chaka (NIST)</td></tr>
<tr><td>7:50 – 8:00 am</td><td>Working with NIST: Terry Lynch (NIST Office of Technology Partnerships)</td></tr>
<tr><td>8:00 – 8:45 am</td><td>Overview of outcomes and follow-up from recent relevant Nanotechnology conferences and workshops: Mike Postek (NIST)</td></tr>
<tr><td rowspan="8">8:45 am -12 noon
Morning Plenary Speakers</td><td>8:45-9:10 am</td><td>Nanomanufacturing Overview: Mohan “Mano” Manoharan (Manager, Surface and Coatings Technology Laboratory at GE Research)</td></tr>
<tr><td>9:10-9:35 am</td><td>Forest Products: Steve Masia (Sappi Fine Paper)</td></tr>
<tr><td>9:35- 10 am</td><td>Automotive: Xingcheng Xiao (Senior Researcher, General Motors R&D)</td></tr>
<tr><td>10:00—10:15 am</td><td>Break</td></tr>
<tr><td>10:15—10:40 am</td><td>Pharmaceuticals and Medical Devices: Gary Fletcher, (Advanced Technology Leader / R&D, Becton Dickinson)</td></tr>
<tr><td>10:40—11:05 am</td><td>Chemicals and Semi-Conductors: Mike Garner (Intel)</td></tr>
<tr><td>11:05—11:30 am</td><td>Aerospace: Keith McIver (Boeing)</td></tr>
<tr><td>11:30 am—12:00 noon</td><td>Food Science: Bernadene Magnuson (Senior Scientific & Regulatory Consultant, Cantox Health Sciences International)</td></tr>
<tr><td>12:00 – 1:15 pm
Lunch and EH&S Speaker</td><td colspan="2">Speaker: Paul Schulte (Director of the Education and Information Division at NIOSH, and coordinator of the agency’s Nanotechnology Research Program)</td></tr>
</table>

Afternoon Plenary Speaker 1:15-1:140	Mohamad Al-Sheikhly, Department of Materials Science and Engineering, University of Maryland, College Park "Challenges in the Synthesis of Nanomaterials for a Wide Variety of Applications"	
1:40 -3:15 pm **Concurrent breakout groups A, B, and C**	Group A	**Surface/Interfaces and Non-Bonded Interactions of Nanomaterials** Session Chairs: Gary Fletcher (Becton Dickinson); Christine Mahoney (NIST)
	Group B	**Nanotechnology-enabled Composites and Matrices** Session Chairs: Steve Masia, (Sappi); Ted Wegner and World Nieh (USDA Forest Service); Gale Holmes (NIST)
	Group C	**Separations and Fractionation** Session Chairs: Michael Gaitan (NIST); Ron Rossner (Wyatt Technology Corp.)
3:15 – 3:30 pm	**Break**	
3:30 – 4:30 pm	**Breakout groups prepare report**	
4:30 – 5:00 pm **Joint session**	**Highlights of breakout reports.** Each presentation is at most 10 minutes (5 min presentation and 5 minutes Q&A)	
Dinner	**Dinner at Holiday Inn.** Speaker: Michael Holman (Lux Associates)	

Wednesday, May 21: *"The Solution"*

Convener: Michael Postek (NIST)

7:00 -8:00 am	**Continental Breakfast**	
8:00 – 12 noon **Expert speakers to address the nanomaufacturing areas of focus**	8:00-8:05 am	**Call to Order and Announcements**
	8:05-8:40 am	**Nanomanufacturing Overview:** Mark Tuominen (University of Massachusetts-Amherst)
	8:40-9:10 am	**Separations/Fractionation:** Wyatt Vreeland (Biochemical Science Division, NIST)
	9:10-9:40 am	**Composites:** Jeff Gilman (NIST), Huber
	9:40-10:10 am	**Surfaces/Interfaces:** Linda Schadler (RPI)
	10:10-10:30 am	Break
10:30 am – 12 noon **Concurrent breakout sessions** **Groups A, B, and C**	Group A	**Surface/Interfaces and Non-Bonded Interactions of Nanomaterials** Session Chairs: Gary Fletcher (Becton Dickinson); Christine Mahoney (NIST)
	Group B	**Nanotechnology-enabled Composites and Matrices** Session Chairs: Steve Masia, (Sappi); Ted Wegner and World Nieh (USDA Forest Service); Gale Holmes (NIST)
	Group C	**Separations and Fractionation** Session Chairs: Michael Gaitan (NIST); Ron Rossner (Wyatt Technology Corp.)

12 noon – 1:00 pm	**Lunch. Speaker: "The United States Measurement System and Measurement Needs for Nanotechnology and NanoEH&S"** Clare Allocca (NIST)
1:00-3:15 pm	**Groups A, B and C reconvene**
3:15 – 3:30 pm	**Break**
3:3 0 – 4:30 pm	**Breakout groups prepare report**
4:30 – 5:00 pm **Joint session**	**Highlights of breakout reports.** Each presentation is at most 10 minutes (5 min presentation and 5 minutes Q&A)
5:00-5:30 pm	"**The Way Forward: Potential interaction models for collaboration and cross-fertilization"** Anne Chaka (NIST) and Mike Garner (Intel)
Dinner	**Picnic Barbeque at Smokey Glen Farm.**

Thursday, May 22: *"The Way Forward"*

Convener: Dianne Poster (NIST)

7:00 -7:00 am	**Continental Breakfast**	
8:00 to 9:00 am **Session Chairs present the Deliverables from their session.**	8:00 – 8:20 am Group A	**Surface/Interfaces and Non-Bonded Interactions of Nanomaterials.** Session Chairs: Gary Fletcher (Becton Dickinson); Christine Mahoney (NIST)
	8:20 – 8:40 am Group B	**Nanotechnology-enabled Composites and Matrices.** Session Chairs: Steve Masia, (Sappi); Ted Wegner and World Nieh (USDA Forest Service); Gale Holmes (NIST)
	8:40 – 9:00 am Group C	**Separations and Fractionation.** Session Chairs: Michael Gaitan (NIST); Dirk Rossner (Wyatt Technology Corp.)
9:00-9:15 am	Break	
9:15-11:45 am Next steps	***"Set the stage for the next steps: What are we intending to accomplish next and how who does what, when"*** ***Session Chairs: Gerard Closset (AF and PA), Mike Garner (Intel), Anne Chaka (NIST)***	
	· Follow-up action plan · Model for collaboration · Timeline	
11:45 am – 12 noon	**Concluding remarks.** Workshop ends. (Anne Chaka)	
12:00 noon	**Lunch** (Optional)	
12:30-2:30 pm	**NIST tour** (Optional)	

Appendix C. List of Presentations

The following presentations were made at the workshop. Those marked with a ˜ are posted on the permanent website: http://www.mel.nist.gov/div821/webdocs-14/events/cri-nano-workshop-05-2008/NIST-Nanomanufacturing-Workshop-Presentation-Schedule.pdf.

Introductions, antitrust: Anne Chaka

˜ ***Welcoming remarks:*** R. Kayser (NIST Chief Scientist)

˜ ***Purpose of workshop, deliverables, workshop logistics, facilitated breakout sessions orientation:*** Anne Chaka (NIST)

˜ ***Working with NIST:*** Terry Lynch (NIST Office of Technology Partnerships)

˜ ***Overview of outcomes and follow-up from recent relevant Nanotechnology conferences and workshops:*** Mike Postek (NIST)

˜ ***Nanomanufacturing Overview:*** Mohan "Mano" Manoharan (Surface and Coatings Technology Laboratory, GE Research)

˜ ***Forest Products:*** Steve Masia (SAPPI Fine Paper)

Automotive: Xingcheng Xiao (Senior Researcher, General Motors R&D)

˜ ***Pharmaceuticals and Medical Devices:*** Gary Fletcher, (Advanced Technology Leader/ R&D, Becton Dickinson)

˜ ***Chemicals and Semi-Conductors:*** Mike Garner (Intel)

˜ ***Aerospace:*** Keith Dan Humfield (Boeing Phantom Works)

˜ ***Food Science:*** Bernadene Magnuson (Senior Scientific & Regulatory Consultant, Cantox Health Sciences International)

˜ ***Occupational Safety and Health Issues and Nanotechnology:*** Paul Schulte (Director of the Education and Information Division at NIOSH, and coordinator of the agency's Nanotechnology Research Program)

˜ ***Challenges in the Synthesis of Nanomaterials for a Wide Variety of Applications:*** Mohamad Al-Sheikhly, Department of Materials Science and Engineering, University of Maryland, College Park

Nanotechnology Commercialization and Nanomanufacturing: Evgenia Pekarskaya (Lux Associates)

International Standards: Impact on Nanomanufacturing: Angela Hight-Walker (NIST)

˜ ***NIST Combinatorial Methods Center:*** Kathryn Beers (NIST)

˜ ***Nanomanufacturing Overview:*** Mark Tuominen (University of Massachusetts-Amherst)

Separations/Fractionation: Wyatt Vreeland (Biochemical Science Division, NIST)

Composites: Jeff Gilman (NIST), Huber

Surfaces/Interfaces: Linda Schadler (RPI)

˜ ***The United States Measurement System and Measurement Needs for Nanotechnology and NanoEH&S:*** Clare Allocca (NIST)

NIST Center for Nanoscale Science and Technology: Lloyd Whitman (NIST)

˜ ***NIST Technology Innovation Program***: Margaret Phillips (NIST)

˜ ***The Way Forward: Potential interaction models for collaboration and cross-fertilization:*** Anne Chaka (NIST) and Mike Garner (Intel)

Appendix D. Acronyms

AF&PA	American Forest and Paper Association
AFM	atomic force microscopy
ANI	Applied Nanomat, Inc.
CD	chromatic dispersion
DLS	dynamic light scattering
DNA	deoxyribonucleic acid
EELS	electron energy-loss spectrometer
EH&S	Environmental, Health, and Safety Issues
FFF	field flow fractionation
FIB	focused ion bean
FPLC	fast protein liquid chromatography
GPC	gel permeation chromatography
IEC	ion exchange chromatography
MVD®	Molecular Vapor Deposition
MIT	Massachusetts Institute of Technology
NCN	Network for Computational Nanotechnology
NIH	National Institutes of Health
NIST	National Institute of Standards and Technology
nm	Nanometer
NNI	National Nanotechnology Initiative
NP-HPLC	normal phase-high performance liquid chromatography
NSF	National Science Foundation
NSOM	near-field scanning optical microscopy
PV	photovoltaic
QC/QA	quality control/quality assurance
R&D	research and development
RD&D	research, development, and deployment
RF	radio frequency
RP-HPLC	reverse phase-high performance liquid chromatography
SEC	size-exclusion permeation chromatography
SEM	scanning electron microscopy
SPMs	scanning probe microscopes
STEM	scanning transmission electron microscope
STM	proximal probe microscopies such as scanning tunneling microscopy
TEM	transmission electron microscopy
USFS	U.S. Forest Service
XPS	X-ray photoelectron spectroscopy
ZnO	zinc oxide

Endnotes

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[23] The degree to which a product can be efficiently, cost-effectively and accurately produced using modern manufacturing methods; sometimes achieved through "design for manufacturability."

Cross-industry issues in nanomanufacturing: May 20-22, 2008, National Institute of Standards and Technology, Gaithersburg, Maryland. [Gaithersburg, MD : National Institute of Standards and Technology, [2010?]. 76, A8 p