Future Directions for Selected Topics in Mechanical and Civil Engineering

L. Cate Brinson and Jianmin Qu, Northwestern University

This report summarizes the findings of a workshop regarding frontiers in Mechanical and Civil Engineering as discussed by a panel of invited experts. The workshop was sponsored by the Office of the Assistant Secretary of Defense for Research and Engineering, Basic Science Office and was held at Northwestern University in Evanston, IL on April 23-25, 2012.

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FUTURE DIRECTIONS FOR SELECTED TOPICS IN MECHANICAL AND CIVIL ENGINEERING

L Cate Brinson and Jianmin Qu
Northwestern University

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1. Executive Summary

The Workshop on Future Directions in Mechanical and Civil Engineering was sponsored by the Office of the Assistant Secretary of Defense for Research and Engineering (ASD(R&E)) and was held at Northwestern University on April 23-25, 2012. The participants in the workshop included 34 invited scientists/engineers and 3 government observers, as listed in Appendix I.

The main objectives of the workshop were to identify specialized application-domain-based areas in the fields of mechanical and civil engineering that hold high promise for long-term (10+ years) technological breakthroughs and to identify the technological needs that will be required to meet these emerging challenges. These considerations were framed within an international context in order to provide recommendations to the ASD(R&E) regarding key areas of high potential growth that will be critical for ensuring that the United States continues to be a world leader within the realm of mechanical and civil engineering.

Over the course of the workshop, five application domains were pinpointed as holding particularly high potential for long-term growth in the fields of mechanical and civil engineering in light of recent and expected technological breakthroughs. The following list summarizes some of the key emerging challenges in these application domains (see Section 3 for more detail):

1) Energy
    - Energy conversion/storage devices and infrastructure
    - Energy efficiency of buildings
    - Efficiency of power generation
    - Enhanced multi-physics modeling and material design for enhanced energy recovery
    - Sensing systems in energy facilities
2) Water
    - Separation processes for obtaining potable water

- Monitoring/control systems (leak detection, water quality assessment, security, etc.) and structural health monitoring
- Water-energy nexus

3) Engineering for Human Health and Safety
   - Personalized, point-of-care disease diagnosis/treatment
   - Lightweight protective materials
   - Emergency response to disasters (man-made or natural)
4) Infrastructure
   - High-level risk management
   - Infrastructure planning for extreme events
   - Structural health monitoring via ubiquitous sensor network
   - Advanced modeling, simulation, and processing methods incorporating uncertainty analysis
   - Multifunctional infrastructure materials
5) Manufacturing
   - Development of new scalable/adaptive manufacturing methods
   - Multidimensional 3D manufacturing techniques with real-time feedback/control
   - Cloud processing to integrate modeling tools incorporating human behavior with enormous amounts of generated data
   - Distributed manufacturing

Meeting the challenges above will require the refinement or development of a number of cross-cutting technologies, as discussed in detail in Section 4 of this report:

1) Ubiquitous sensor network
   - Development of smart sensors
   - Rapid deployment of mobile sensor network
2) Cloud computing for storage/sharing
   - Cloud design and manufacturing
   - Modeling, simulation, and processing of sensor data
   - Materials genome development

3) Systems-level approaches
    - Tools for systems-level understanding/optimization
    - Interdependent infrastructure risk management
4) Multi-functional infrastructure materials
    - Self-healing
    - Sensing/actuating
    - Recycling/sustainability
5) Integration of experimental and modeling tools for multi-scale, multi-physics systems
    - Integration of advanced analytical models and experimental/ sensing techniques within a probabilistic framework, including uncertainty
    - Tools for meso-scale technology
    - Integration between social/behavioral and physics-based models
    - Far from equilibrium thermal and material systems
    - Understanding/controlling evolution of material behavior
6) Robot mobility and situation awareness
    - locomotion modes
    - map-building and localization
    - teleoperation
7) Adaptive and scalable manufacturing processes
    - Interface engineering
    - 3D characterization techniques
    - 3D fabrication methods
    - Part with integrated multi-functions and self-description

The challenges within the five application domains and technology development described in the lists above were all framed within an international context in which the United States was viewed as a leader in certain areas within the fields of mechanical and civil engineering, whereas U.S. leadership in other areas was determined to be unclear or in jeopardy. Section 5 of this report provides a detailed description of the international context for each of the five application domains listed above.

The remainder of this report summarizes the proceedings of the workshop in several main sections. First, Section 2 provides a brief overview of the logistics of the workshop. Section 3 goes on to describe the five major application domains determined to hold particularly significant long-term challenges within the fields of mechanical and civil engineering. Section 4 addresses the cross-cutting technological advances that will be required to meet the challenges described for the application domains discussed in Section 3. Finally, Section 5 describes the international context for both the current state and future growth of mechanical and civil engineering in the United States, and Section 6 offers some concluding remarks.

2. Background and Introduction

The fields of mechanical and civil engineering span a wide range of disciplines, as indicated by the Venn diagram in Figure 1. It is worth noting that this is only one possible breakdown of these larger engineering fields and that the disciplines noted are not exhaustive. In order to explore the full scope of these engineering fields within the workshop, scientists and engineers with expertise in each of the subdisciplines noted in Figure 1 were invited to discuss the current state of mechanical and civil engineering and the emerging areas within these fields with high potential for growth.

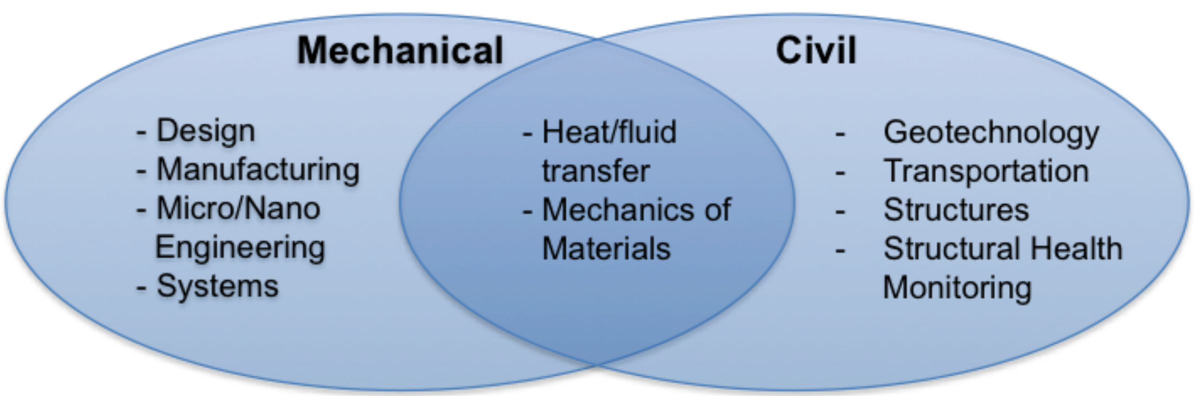


Figure 1: Venn diagram indicating the breakdown of disciplines within mechanical and civil engineering chosen for this workshop

The workshop began with a brief (5-minute) presentation by each invited participant outlining his or her work along with a recent breakthrough and emerging technological challenges within his or her area of expertise, with common themes summarized in Table 1. These ideas were used as a starting point for further discussions regarding challenges in broad application domains and the discipline-based technological advances required to meet those challenges.

Table 1: List of discipline-based recent breakthroughs and emerging technological needs outlined by workshop participants

Disciplinary Domain	Recent Breakthrough	Emerging Technological Challenge
Structural Health Monitoring	Damage-sensing materials	Sustainable, self-healing, "smart" materials
Design	Structural topology and material design	Design via cloud processing
Manufacturing	Globalized manufacturing	Adaptive/scalable processes; 3D manufacturing
Micro-Nano Engineering	Multi-scale fabrication/characterization	Materials genomics; interface engineering
Systems	Nanotechnology-based sensors	Ubiquitous sensor network for real-time systems assessment
Heat/Fluid Transfer	Microfluidics	*High-power* work via waste heat recovery; control of far from equilibrium systems
Mechanics of Materials	Quantitative Nanoscale in-situ and 3D Characterization	Integrated multi-scale modeling techniques
Geotechnology	Multi-phase modeling methods; Self-learning simulations; Subsurface imaging	Multi-physics modeling; Adaptive integrated design-construction-monitoring
Transportation	Intelligent transportation systems	Real-time control/management of transportation systems
Structures	Composite materials with increased functionality	Multi-functional, sustainable Infrastructure materials

Figure 2 illustrates the flow of the workshop, which proceeded by a combination of round-table group discussions and breakout sessions in which the participants were divided into four discipline-based or application-domain-based groups. A detailed description of the organization of the workshop is provided in Appendix 2.

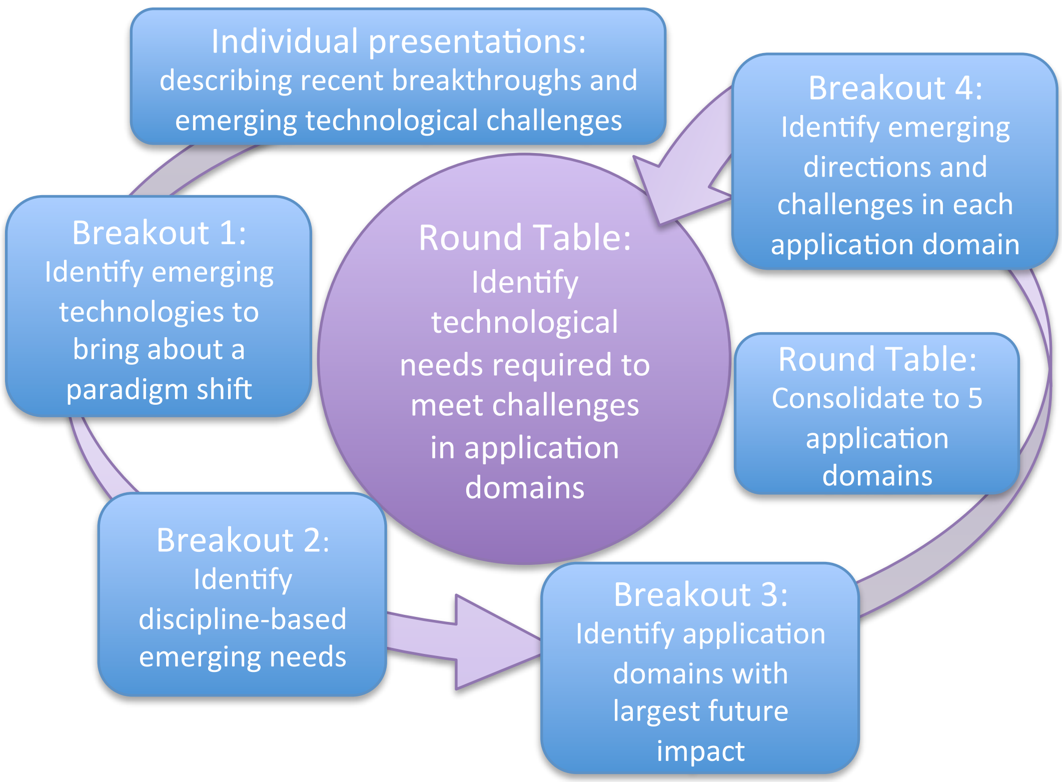


Figure 2: Flow chart illustrating the objectives of the various workshop sessions

3. Application domains with high impact and emerging challenges

While numerous application domains were discussed as holding significant importance in the near future and long-term, five broad application domains emerged as the most significant drivers for future growth, as shown by representative images in Figure 3. These domains were defined as:

1) Energy
2) Water
3) Engineering for Human Health and Safety

4) Infrastructure
5) Manufacturing

These application domains were each discussed within the context of significant emerging technical challenges. The following subsections provide an overview of the foreseen challenges in each of these domains, and the technological developments that will be required to meet these challenges are subsequently described in Section 4.

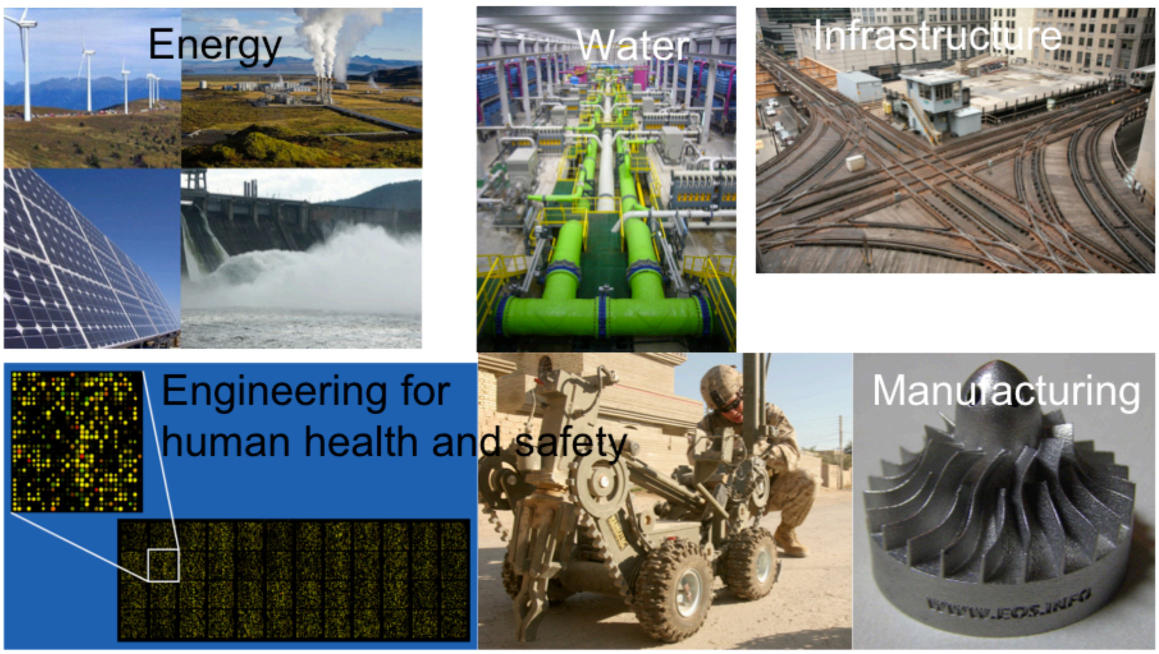


Figure 3: Representative images of the five application domains deemed as the most significant drivers for change: Energy (wind, geothermal, solar, hydroelectric), Water (desalination plant), Infrastructure (Chicago "El" cross junction), Engineering for Human Health and Safety (DNA microarray; IED detonator), and Manufacturing (miniature 3D-printed turbine)

3.1. Energy

The energy domain provides many grand challenges for the disciplines of mechanical and civil engineering. Several areas of key importance (with details to follow) can be summarized as:

- High-power alternative energy conversion/storage devices

- Increased energy efficiency of buildings
- Interface engineering by design for efficient power generation
- Enhanced multi-physics (i.e., chemo-thermo-hydro-mechano-electro) modeling
- Enhanced sensing network for energy infrastructure

There is growing demand for energy conversion and storage devices such as batteries and fuel cells, which require the design of efficient and durable material systems. Furthermore, as the prevalence of these devices expands, there will be significant infrastructure needs for electric and hydrogen vehicles as related to the sources, storage, and transport of fuels. An efficient, flexible grid infrastructure based on intermittent renewable power sources will need to be set in place, directly relevant to Department of Defense interest in more efficient power systems in deployments such as emergency response. A supply chain challenge regarding the increased pervasiveness of energy conversion and storage devices lies in securing resources for the constituent materials from overseas (e.g. rare earth metals, phosphorous, etc). While government investment in fuel cells is on the rise in countries such as Japan, there was concern among the workshop participants that government investment may be declining domestically.

A second energy-related challenge is the energy efficiency of buildings. Sensor and control systems, along with the further development of multi-functional materials, will prove invaluable for making optimal use of available energy and reducing the amount of wasted energy.

Another challenge is the energy efficiency of power generation. Increased efficiency requires low-friction surfaces via a new age of tribology for reduced losses in energy, as well as precise nano-scale control over surface functionalization (e.g., super-hydrophobicity). The development of manufacturing techniques towards up-scaling of this nano-scale control over large surface areas remains a further challenge.

Enhanced multi-physics models incorporating coupled chemo-thermo-hydro-mechano-electro properties provides a challenge to improve control of existing hydrocarbon resources and new energy sources for such concerns as enhanced oil recovery (EOR), gas shales, and enhanced geothermal systems (EGS). The design of materials with improved high-temperature and high-pressure properties, as well as corrosion and abrasion performance, remain a challenge for deep drilling of fuel resources (and other applications in the energy industry) that are currently unattainable by current technologies.

The role of sensing systems in energy facilities remains a challenge. Systems that can detect and evaluate damage are required to reduce the risk to human life and health, and the environment in the event of man-made or natural disasters. This requires both embedded systems of sensor networks and deployable systems that can improve long-term performance through detection and response of corrosion, fatigue, and other sources of damage.

3.2. Water

The grand challenge in the realm of water relates to finding or generating abundant clean and sustainable water, which entails meeting the following goals as discussed in detail below:

- Development of separation processes for desalination and water recycling
- Enhancement of monitoring/control systems for water infrastructure
- Water-energy nexus (water harvesting, reduced thermal pollution, etc.)

A few challenges along this endeavor were proposed for the next 5-10 years. One such challenge pertains to developing separation processes for the derivation of potable water from municipal waste water, industrial waste water, and ocean salt water. Such separation processes include the design of functional membranes for desalination, the design of functionalized anti-fouling surfaces with reduced cost and enhanced energy efficiency, and the development of advanced phase-change processes (e.g., far-from-equilibrium phase changes). Another water-related challenge lies in the monitoring and control systems for water systems, which include enhanced sensor technology for leak detection, real-time assessment of water quality (e.g., toxins, treatment by-products, etc.) in water distribution networks, security from malicious attack (biological, chemical, cyber, etc.) against water systems, and enhanced thermo-fluid processes. Structural health monitoring of critical flood protection infrastructure systems (e.g., dams, levees, etc.) offers another challenge for the next 5-10 years. Among the concerns for these systems is climate change, which applies additional stress on these systems.

The water-energy nexus acts as a longer-term challenge (10-20 years), with concerns such as control over thermal pollution via water discharge from industrial and power plant cooling processes, as well as water harvesting (i.e., reduction of evaporation through recapture). In all of these water-related challenges, advanced simulation and modeling of fluid systems is required to inform design and control.

3.3. Engineering for Human Health and Safety

Within this application domain there exist challenges in medical technology, personal safety and protection, and emergency response:

- Personalized point of care disease diagnosis and treatment, including molecular sensors/therapies and robotic surgery
- Advancements in biomanufacturing
- Development of lightweight protective materials
- Optimization of emergency response logistics

Since the late 1980s, significant advancements have been made in micro- and nano-scale manufacturing technologies that enable the development of sensors and actuators on scales close to those of bio-molecules or complex cellular systems. These capabilities provide new opportunities for revolutionizing diagnostic and therapeutic techniques for significantly improved human health care. Nanotechnology-based drug delivery using gold nanoparticles, nanodiamonds, or hydrogels can significantly increase the efficacy of drugs. These nanoparticles can provide advantages in targeted delivery, reduced toxicity and extended drug release. Associated advancements in rapid, real-time, local biomanufacturing methods will be required for realization of these potential therapies to patients.

Additionally, microfluidic systems enable processing of minute amounts (microliters or less) of samples from blood, urine or saliva to extract bio-markers. Current molecular sensors can detect bio-markers with single molecule sensitivity in tens of minutes. Thus, a challenge lies in integrating microfluidic devices and sensors into point-of-care diagnostic systems with high sensitivity and specificity at the patient's bedside.

Cell signaling and regulatory molecular assemblies may behave or interact aberrantly in diseased cells compared to their healthy counterparts. Often, it is most effective to treat the cellular machines in this complex network on multiple fronts by combinatorial drugs. However, searching the optimal drug combination in the large drug-dosage parameter space is like finding a needle in a haystack. The feedback system control (FSC) scheme and high throughput methods are beginning to make rapid drug screening possible, but more work is needed for much improved therapeutics.

Additional challenges within the realm of medical technology include improvement in teleoperated surgery brought about by advanced robotics. Challenges in improved teleoperated surgery include reducing the cost of the systems to make it feasible to carry the expertise of trained surgeons to remote or hazardous locations; improving haptic feedback and general situation awareness for the surgeon; and increasing the autonomy of the remote surgical robot system to compensate for variable communication time delays.

An important personal safety and protection challenge for both military and civilian arenas is the development of lightweight materials for protection against ballistic, chemical, biological, and radiation attacks. Another important area is human factors and information delivery as related to in-vehicle sensor systems and displays.

There are also challenges in emergency response to both natural and man-made disasters. First, there is a challenge in optimizing emergency response logistics. More sophisticated functionality and fine motor control of robots remains a challenge for rapid autonomous creation of three-dimensional situational awareness maps describing visual, chemical, structural, radiation, and thermal factors in the wake of an emergency in order to minimize human risk. These awareness maps will require autonomously deployable sensors with multiple modes of locomotion (flying, crawling, walking, leaping, deforming, slithering, etc.) to cross any situational barrier, as well as buildings that can self-describe through passive embedded sensors which can be interrogated for local structural stress as well as global building blueprints. Finally, rapid stabilization of infrastructure in the wake of an emergency is a major challenge both in terms of physical structures as well as communication networks.

3.4. Infrastructure

In this report we focus on the physical infrastructure required for modern urban societies. As we live in an increasingly urbanized world, the sustainability and resiliency of individual infrastructure components and larger systems – particularly in relation to major natural or man-made hazards - represent a grand challenge heading into the future. Some specific challenges include:

- Development of smart sensors and deployment in a ubiquitous network
- Development of modeling/processing methods for sensor data
- Design of new multi-functional, sustainable infrastructure materials
- Infrastructure planning for extreme events
- Risk management

Infrastructure refers to the constructed physical facilities that support the day-to-day activities of our society and provide a means for distribution of resources and services, for transportation of people and goods, and for communication of information. Examples of infrastructure include roads, bridges, water and sewer systems, airports, ports, public buildings, schools, health facilities, jails, recreation facilities, electric power production, dams, levees, communication services, pipelines, railroads, along with the power plants, trains, planes and other machines that are integral to the societal function in each sector.

There are a number of challenges that must be met in order to enhance the sustainability and resiliency of current U.S. infrastructure. A significant contribution to this challenge is the development and deployment of a ubiquitous sensor network for structural health monitoring in both new and existing infrastructures. Furthermore, new methods for modeling, simulation, and processing of the data provided by complex, large-scale, distributed sensor networks, along with associated uncertainty analysis, must be developed for optimized decision-making. For new structures, an ongoing challenge lies in the development and design of new sustainable, lightweight, multi-functional structural materials and associated manufacturing methods. At the root of all of these challenges is a need for continued development, management, and protection of the existing infrastructure to pave the pathway for meeting societal needs heading into the future.

Extreme events, either natural (flood, earthquake, hurricane, tsunami, etc.) or man-made (terrorist attacks, human errors, etc.), present another significant challenge to modern infrastructure systems. To deal with this challenge, research developments are needed in advanced warning of impending disasters, and in real-time information processing and decision making to minimize human casualty and property damage. Advanced warning systems need breakthroughs in sensing and sensor systems. Real-time decision making requires breakthroughs in logistics, resilient communication and transportation systems, and reconfigurable infrastructures, so that when an extreme event occurs, communication channels remain open, evacuation can take place via alternative transportation means, and infrastructure systems can be reconfigured to meet the emergency needs. An essential part of developing reconfigurable structure is modeling the interdependency among different sub-infrastructure systems (e.g., how water supply may depend on power generation and vice versa) so that when one sub-system is damaged, its effects will not cascade through the entire infrastructure system. To this end, we need new frameworks for understanding systems of sub-infrastructure systems as a basis for modeling the complex behaviors of individual sub-infrastructure systems as well as coupled systems.

3.5. Manufacturing

With the emergence of new materials with complex structures at a variety of length scales, there must be efficient, precise, flexible manufacturing tools and techniques capable of producing them. Some of the major challenges in the realm of manufacturing include:

- Development of 3D manufacturing and characterization techniques
- Real-time feedback and control to balance tolerance and uncertainty
- Development of scalable cascaded manufacturing techniques
- Implementing cloud processing for information sharing and point-of-need manufacturing
- Distributed manufacturing

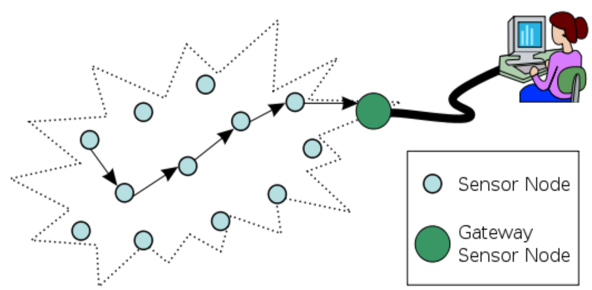
A significant challenge in the realm of manufacturing is to develop automated, three-dimensional prototyping and manufacturing techniques to enable the generation of designed materials with desired surface, interface, and bulk properties. Further development of manufacturing techniques such as 3D printing at both large and small length scales, guided self-assembly, roll-to-roll processing, surface texturing methods (both bottom-up and top-down), and interferometric lithography remain a challenge. The highly complex nature of these manufacturing techniques will require real-time feedback and control, integrating performance tolerance to uncertainty, in order to create precise structures, especially at the micro- and nano- scales. Scalable "cascaded" manufacturing techniques must be developed to allow for meter-scale assembly with micro-scale or even nano-scale surface resolution. Taking advantage of cloud processing is necessary for the integration of enormous amounts of data with modeling tools incorporating human behavior. Distributed manufacturing remains a challenge for flexible hybrid machinery and supply chain management in response to natural disasters, man-made (including political) interruption, or point-of-need manufacturing.

4. Technological developments required to meet emerging challenges

In order to meet the challenges described for the five application domains outlined in section 3, a number of technological breakthroughs will need to be developed or refined. The following technological needs were identified as being particularly important across the application domains, as discussed in detail below. While the needs described herein do not constitute an exhaustive list, they highlight some of the major points discussed during the workshop.

4.1. Ubiquitous ***sensor*** network

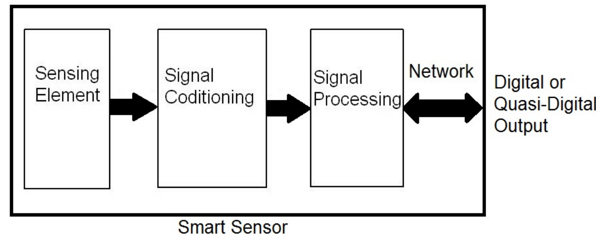
For each of the application domains discussed in Section 3, enhancements in sensing technology is expected to be a major factor in meeting the proposed long-term challenges. These technological enhancements are described below and include:



- Development of smart sensors (multi-functional, energy-efficient, wireless, etc)
- Rapid deployment of a high-resolution mobile sensing network into both new and existing infrastructure

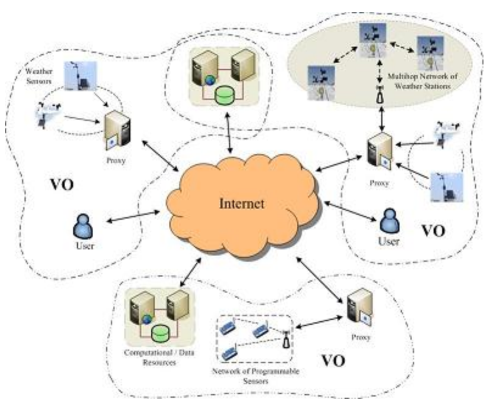
4.1.1. Development of smart sensors

There is dire need for a new generation of sensors with unprecedented functionality to fully realize the vision of structural health monitoring. In concert with sister disciplines (*e.g.*, electrical engineering), sensors must be developed that are capable of sensing damage directly. There are also tremendous opportunities to learn



from biological systems that have compact and energy-efficient sensor transduction mechanisms; bio-inspired sensors could revolutionize the field of sensors for structural health monitoring. While wireless sensors have shown promise, the technology and their deployment is still in early stages. Efforts aimed towards reducing both the size and cost of wireless sensors is necessary to ensure their deployment in high-density networks can be realized. Furthermore, a long-standing challenge with wireless sensors is their dependence on batteries. Thus, new and innovative power harvesting technologies with unprecedented levels of energy capture efficiency are also needed.

4.1.2. Rapid deployment of mobile sensor network



The ability to rapidly deploy a low cost sensor network to mitigate uncertainties in unknown environments is critical in emergency situations (e.g., the Fukushima nuclear disaster, hurricane Katrina, the Gulf Oil spill, etc.), as well as in challenging dynamic environments such as manufacturing. The deployment and integration of new sensors into the aging infrastructure already in existence is also of critical value. In each of these areas, the sensor network should be able to create three-dimensional, multi-agent maps that capture the distribution of temperature, stress, motion, chemicals, radiation, etc. at different time scales, thus allowing for the inclusion and integration of a broad range of sensor types into different environments. Key challenges include the ability to make high resolution spatial and temporal measurements across a large area (e.g., nano- and micro-scale resolution across meter length scales) at the rates needed to capture the evolving states of various systems (e.g., microstructure, damage, etc.), as well as “real-time” analysis to inform effective process control, diagnostics, and prognostics.

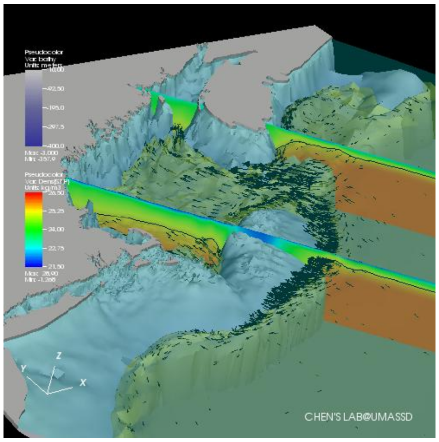
4.2. Cloud computing for storage, sharing and processing

In order to process the enormous and ever increasing amounts of generated data into usable information, advancements must be made in the following areas, as discussed in detail below:

- Modeling, simulation, and processing methods of sensor data
- Cloud design and manufacturing for collaborative design methods
- Development of materials genome for the *design* of new materials with desired properties

4.2.1. Modeling, simulation, and processing of sensor data

The ongoing revolution in sensors places civil and mechanical systems on a trajectory of unprecedented levels of sensor deployment. The sensor systems of tomorrow will be defined by high dimensionality, multimodality (i.e., multiple sensing techniques), and heterogeneity and will provide real-time data regarding the state of the system, including microstructure or damage evolution, as discussed in Section 4.1.2. This scenario creates a number of vexing technological issues including how large-scale datasets can be aggregated, managed, and processed. To fully harness the potential of these massive datasets, new methods of data processing for real-time and near real-time diagnosis are necessary. Structural diagnosis methods based on physical principles and mechanics-based simulations must be developed that can take full advantage of the available sensor data. This requires the explicit coupling of sensor data with simulation tools through a new generation of inverse and self-learning simulation methods. Furthermore, there is a need to adopt emerging computational statistics, bioinformatics, data mining, and machine learning methods for rapid interrogation of massive sensor datasets. Inherent to these efforts is the explicit incorporation of stochastic analyses and methods aimed toward uncertainty quantification (further discussed in Section 4.5.3). A critical need in this area is the development of cloud computing, which offers a system for data collection, storage,



distribution, and searching (similar to a materials genome approach toward materials design, Section 4.2.3) to facilitate model development and structural health monitoring.

4.2.2. Cloud design and manufacturing

The cloud is envisioned to have at least two elements or levels. The first is the software cloud that stores and processes designs. It is in this level where analysis will be executed on both the design and manufacturing processes, whereby modifications will take place as informed through the sharing of information. The second element of the cloud is the hardware necessary for the actual manufacturing of a design. A critical link will be the ability to translate design content into manufacturing protocol, and then to take manufacturing information and integrate it back into design content.

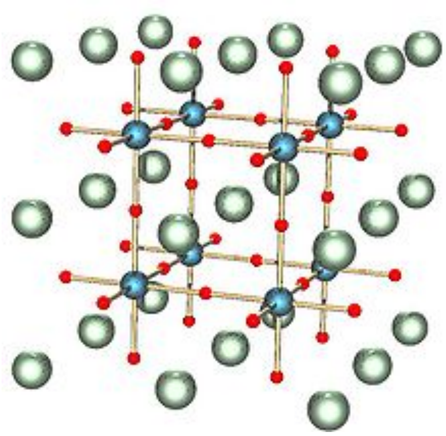
Connectivity will enable significant collaboration in the design of products and in manufacturing. These designs will be easily and ubiquitously shared by a broad community. Knowledge gained from prior designs and components of designs will be more accessible, leading to faster improvements across all application domains or industry sectors. These designs will not necessarily be only geometric representations, but may also include performance specifications and analyses, material information, and manufacturing protocols. These designs may also act as building blocks toward larger scale systems. An example of such a building block-based system is a car, for which one could select and install the desired engine, transmission, seating and infotainment system. Once the designs are produced, already incorporating manufacturability via the cloud, they can be shared via the cloud with a variety of manufacturing locations. New technologies, such as additive manufacturing and flexible processes or reconfigurable machines, will ultimately realize the ability to rapidly produce these designs in local facilities. For simple, low performance systems, a home-based 3D printer may suffice. However, it is envisioned that a distribution of higher-end manufacturing systems will be readily available through local suppliers. The production of picture prints offers an excellent parallel example. Today, most homes are capable of printing digital color images, yet consumers often defer to commercial vendors (e.g., Walmart, Shutterfly, etc.) for final high resolution copies of a picture.

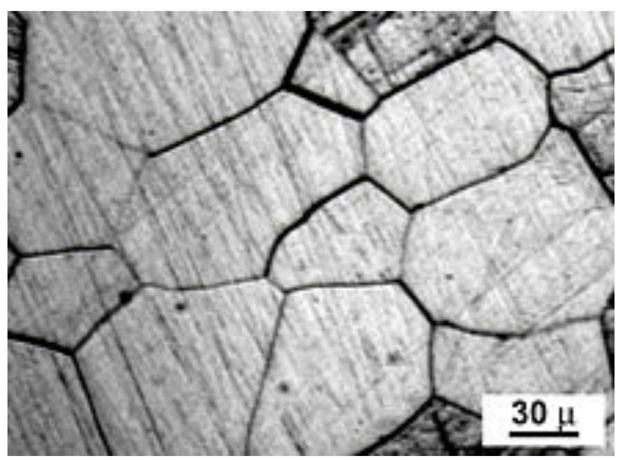
Several very interesting issues should be highlighted in this area. First, there are significant IP issues that must be addressed. Once a design is made available in the cloud, what is to stop other individuals from copying or making unauthorized usage of those designs or elements thereof? Other considerations include:

1) Cloud design and manufacture enable point-of-need manufacture. One can download the design and produce it close to where it will be used, eliminating inventory of high-value-add components and shipping needs.
2) The cloud is a two-way information path. Thus, lessons learned through design and manufacture can be "uploaded" into the cloud for further improvements. This is analogous to open source programs, and, of course, also has its implications from an IP and a safety perspective. Organizing this information is a nontrivial problem.
3) This concept is not limited to mechanical or civil engineering systems. Cloud computing could also be executed for electrical and mechatronic systems, and it may also be expanded to bio systems and chemical systems. For example, rapid manufacture of customized drugs could happen at local pharmacies, where automated pharmacological systems may produce prescription drugs to exact specifications for individuals. Also, it can be imagined that highly specific bandages are produced in regional health centers to specifically fit the needs of patients.

4.2.3. Materials genome development for hybrid system design (bottom-up)

The increasing complexity of materials information available from both experimental and computational tools across many length and time scales, has created an enormous opportunity to rapidly develop "designer materials" tailored to specific application needs. At the same time, the infinite property design space and the sheer quantity of data and models present a challenge to access and assess the available information to initiate new material design concepts or optimized application of existing materials. Material data is often isolated in PhD theses and journal articles with no integrated method to access the information on a given system. Taking inspiration from revolutionary successes in the biological genomics field upon embracing a rigorous informatics approach, a new approach is needed. In this approach, data must be vetted and curated into centralized resources, which will enhance accessibility and therefore ability to apply data mining and information science to speed discovery and innovation. Current researchers in mechanical and civil engineering have limited exposure to information science and promotion of interdisciplinary teaching in this area is critical to development of the materials genome. In this new approach, information based models such as QSPR (quantitative structure property relationships), heuristic analyses and other data mining methods will be married with improved physics based models, from atomistic to continuum, to discover new mechanistic relationships, and to navigate the design space for materials efficiently.





In this context, there is a strong need for new computational methods in materials science. The information based models need to be transferred from other domains and tuned to materials needs and physics based models for responses at multiple length scales need to be improved and in many cases used as input to the information models. This new materials genome approach can be considered a bottom-up approach which complements top-down fabrication technologies. Such modeling is needed not only in understanding and designing of solid materials but is also of particular significance for designing tailored working fluids with specific thermodynamic, transport, chemical, and electrochemical properties, such as materials for refrigerants and battery electrode materials. In addition, new materials or new surface functionalization approaches to yield desired interactions between components in composite systems and solid/liquid interactions will yield substantial performance advantages. Phase-change (solid-liquid, liquid-vapor, solid-vapor) materials and tailored nanocomposites are expected to be enablers for high power and energy density storage. In the health sector, new drug screening techniques and drug delivery materials are needed for personalized medicine. In all of these examples, a cloud-based materials genome approach will enable a much more rapid exploration of possible material and response combinations and will hasten the discovery of new solutions.

4.3. Systems level approaches

Tools must be developed on a systems level for the top-down design of engineering systems with control via real-time feedback, as well as in interdependent infrastructure risk management, as discussed below.

4.3.1. Tools for systems-level understanding and optimization (top-down)

Many micro/nano engineering systems are based on a bottom-up design approach, but in thermal/fluid/bio systems there is a need to complement this with a top-down systems-level understanding. Understanding the sensitivity of the system to small-scale features would then enable a refined control approach in which one includes real-time feedback and control of multivariable systems. For example, it is possible in this way to build in control of phase change behavior via photocatalysis. Another example is the use of combinatory drugs to treat diseased cells. Like other similarly complicated systems in bioengineering, it might be possible to drive a system toward a desired state even if the transfer functions are highly empirical or even unknown.

Additionally, in the design of large scale engineering products (e.g., vehicles for civil or defense), systems level optimization approaches that can simultaneously incorporate modeling and data on subsystems (e.g., transmission, frame, armor, electronics, etc.) and performance characteristics (e.g., speed, payload, maneuverability, size/weight constraints, etc.) will enable advances in materials and energy technologies to be realized in vehicles with radically improved forms and functions.

4.3.2. Interdependent systems approach for infrastructure risk management

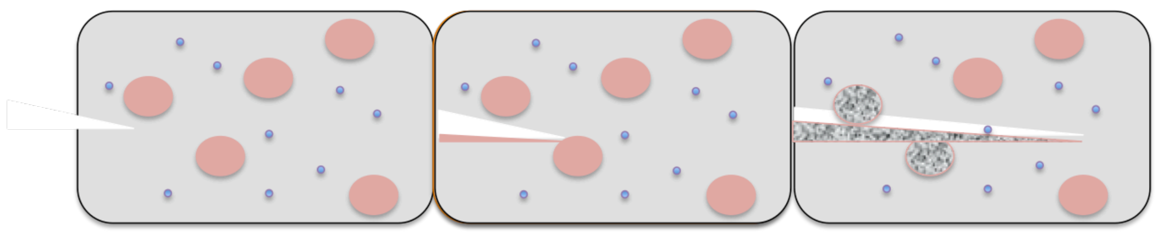
The well-being of modern communities depends on proper functioning of infrastructure systems, such as water, power, communication and transportation systems, as well as systems of facilities providing health care, police, government and emergency services. The management of such systems requires monitoring, assessment and decision making for actions such as routine maintenance, prioritizing repair or replacement alternatives, preparedness for natural and man-made hazards, and emergency response for post-hazard events such as rescue operations and closure or operation of facilities. Monitoring systems based on dense sensor networks installed in such infrastructures can provide immense amounts of data. Advanced and efficient methods for interpreting these data and accounting for the prevailing uncertainties are needed. Furthermore, the complexity of infrastructure systems, including the interdependence of different infrastructures (e.g., the water distribution system being dependent on the power network) requires new methods for system performance and risk assessment. Decision support systems will be needed to process the vast amount of information gathered and provide support to operators for the management and operation of the infrastructure.

4.4. Multi-functional infrastructure materials

Sustainable, “smart” materials with increased functionality (damage-sensing, self-healing, etc) are required to meet growing infrastructure demands.

Recent advances in material science and chemistry have provided engineers with unprecedented ability to manipulate materials at their most fundamental length scales in order to create entirely new materials for civil and mechanical engineering systems, including those subjected to extreme or aggressive environments.

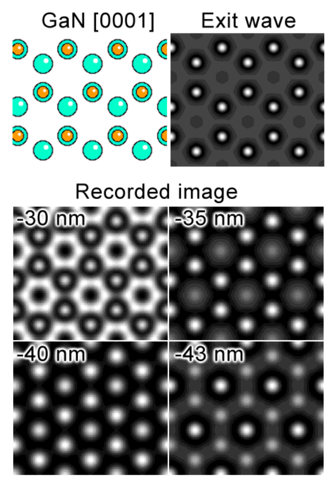
Multifunctional materials, endowed with functionalities beyond load carrying capacity, must be advanced. To this end, there are significant opportunities to learn from biology to create bio-inspired materials with multiple functionalities. For example, self-healing materials that can heal themselves when damage occurs and adaptive materials that can sense and respond to their environment would enhance the durability and "smartness" of infrastructure. Additionally, materials that can respond to load/temperature/humidity with shape changes or internal stress changes offer the ability to design new types of adaptive structures, optimized for in-use needs, while at the same time removing external actuators and motors, enabling improved, optimized designs. Furthermore, in order to minimize the carbon footprint of new engineering systems and structures for a sustainable future, focus should be aimed at developing environmentally friendly materials with capabilities such as carbon dioxide absorption or energy harvesting.



While the concept of multifunctional materials is not new, the possibilities of yet unrealized potential are vast: smart paints that will "bleed" when damage or high stress occurs to facilitate crack identification and repair; materials with self-sensing capabilities that can send advanced warning to the operator for impending disasters; shape-memory materials for retrofitting damaged structures that can reduce the repair time from weeks to hours, critical for extreme events; anti-freezing pavements that can reduce winter driving hazard and eliminate the use of salts; piezoelectric pavements that can convert traffic motion into electricity; thermoelectric materials that can harvest low-grade heat from parking decks; self-lighting paints that eliminate the need for light bulbs; window glass that reflects the sun's thermal radiation in the summer without affecting the visible light, and can, with an applied voltage, be switched so that the thermal radiation is reflected back to the house during winter time. To realize these visions for smart infrastructure requires that sustainable infrastructure technology pass through revolutionary changes similar to nanotechnology, microelectronics and biomedicine in the past few decades. Indeed, the progress made in these “high tech” areas has generated a treasure chest of innovations that enables a revolution in multi-functional infrastructure materials.

4.5. Integration of experimental and modeling tools for coupled multi-scale and multi-physics systems

Advances in both experimental and modeling tools enable unprecedented understanding of coupled systems at multiple length scales. Optimal integration between experimental and modeling techniques will prove invaluable toward developing advanced materials and engineering systems. This integration will require:



- Integration of advanced analytical models and experimental/sensing techniques within a probabilistic framework including uncertainty
- Development of modeling tools for meso-scale technology (bridging the nano- and macro- scales)
- Development of physics-based models incorporating social/behavioral patterns
- Development of far from equilibrium thermal/material systems
- Better understanding and control of material evolution over time

There is great need for better models and experimental tools for understanding material behavior phenomena such as transport, energy conversion, etc., in these coupled systems. For example, transport models in battery systems must include the physics of heat generation and dissipation. Materials constitutive models for these systems must also consider electrode charging, discharging, and aging. Advanced spectroscopic methods that permit the observation of electrochemistry at surfaces, for example, could have a significant impact on the development of new technologies in this area. Ultimately, diagnostic tools that could be inexpensively and widely distributed in the field would enable cloud-based applications in these systems.

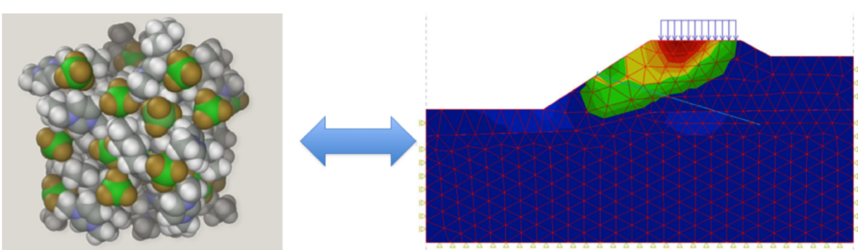
4.5.1. Integration of Advanced Methods of Mechanics, Probability, and Experiments

The last decade has been characterized by significant breakthroughs in the understanding and modeling of the intricate, multi-scale, and multi-physics behavior of infrastructure materials and structures. Significant advances have been made in the analytical description and computational modeling of many phenomena spanning several length and time scales. Concurrently, advanced experimental and sensing technologies continue to emerge and provide an unprecedented opportunity for the characterization of material and structural behavior. In addition, sophisticated statistical methods have been developed to analyze and process the intrinsically stochastic character of experimental data as well as numerical data obtained from complex analytical theories.

While research focus on further development in the aforementioned areas should be maintained, there is an emergent need for a paradigm shift in which advanced analytical models, advanced experimental and sensing techniques, and advanced probabilistic methods are integrated into a single coherent scientific framework. Advancement in this direction will benefit the engineering community at large and will make possible a broader impact for scientific research through, for example, the formulation of better design codes based more on scientific principles rather than through empirical means.

4.5.2. Tools for meso-scale technology

New methods to bridge the gaps between experiments, simulations, and manufacturing on the nano-, micro-, and macro-scales are needed. The scale intermediate with respect to nano- and micro- is often referred to as the “meso-scale”. In

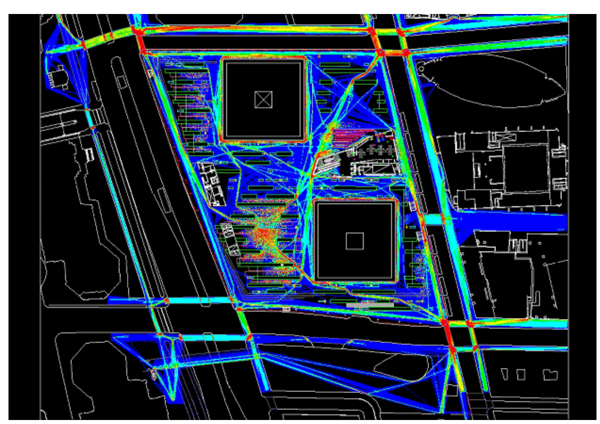


solid mechanics, significant effort has been devoted to developing meso-scale models, but such methods are lacking in fluid mechanics and thermal systems. Such new modeling methods should be accompanied by new diagnostic tools with high spatial and temporal resolution. One example for which these tools would be valuable is in monitoring phase nucleation. Inexpensive, distributed sensor networks are needed for deployment in the field, where such meso-scale sensor networks are envisioned to link to cloud-based diagnostics and information systems.

4.5.3. Tools for addressing uncertainty (UQ and VV)

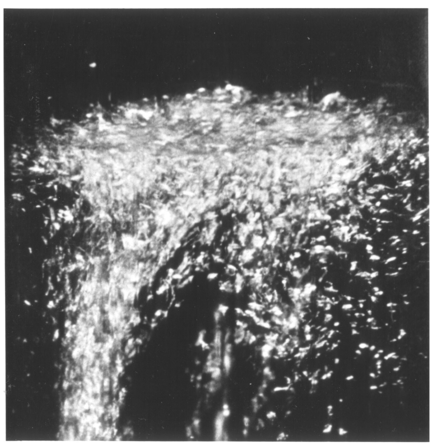
New approaches for carrying out uncertainty quantification (UQ) and verification and validation (VV) of predictive models are needed. Uncertainty quantification can be understood as quantifying the impact of various sources of uncertainty and error on the uncertainty of a model-based prediction. Verification studies the agreement between the computational result and the underlying mathematical model, while validation relates to the agreement between experiment and model prediction. The impact of modifications in performance of one device or material in a system on the performance of other components and the overall system must be better understood in all complex mechanical and civil engineering systems. In fundamental solid and fluid mechanics, better training and model development in statistical mechanics and statistical thermodynamics is required. In complex thermal-fluid systems with multiple parallel and series branches of single and multi-constituent fluids, better understanding of uncertain aspects of micro/nano and fluids/thermal systems is needed and new tools are needed for understanding physics and flow-regime mapping of two-phase flows.

4.5.4. Integration between social/behavioral and physics-based models



This topic targets integrating physics-based models that are commonly used in engineering with societal models to design products and their production systems that better address the needs of society. This entails more than the simple incorporation of biomechanical models into designs, in that societal behaviors must also be integrated into the design process, thereby resulting in the production of manufactured goods that are better suited for consumption, while minimizing the potential for misuse, unintended use, or unexpected failure modes due to human interactions.

The ability to link these models together will provide a higher level of design as it identifies potential uses of products and operations of systems, and it links them to product performance and specifications. Social and behavioral models might come in the form of market analysis or specifications that can be considered early in the design phase of a product.



4.5.5. Far from equilibrium thermal and material systems

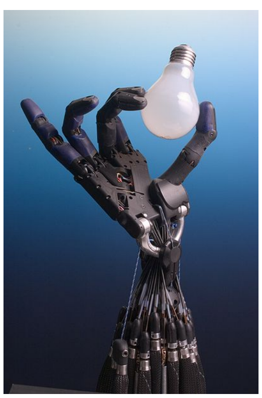
Thermal/fluids engineering, particularly at the micro- and nano- scales, could better exploit methodologies and technologies based on far-from-equilibrium systems. For example, systems designed to be supercooled or supersaturated could be triggered to undergo a "flash" phase change for desired performance. In general, systems could be designed to manipulate energy leading to a discharge in a narrow wavelength or frequency. Such systems are already exploited in microelectronics and photonics, but could be designed for thermal/fluids applications, opening new pathways for rapid response and control. In solid materials, phase changing materials under high rate loading and even polymers in the glassy regime present important systems where non-equilibrium processes call for additional study to enable new understanding and applications.

4.5.5.1. Understanding and controlling evolution of material behavior

Another application for both geological and engineered materials is the continuous, history-dependent evolution of microstructure throughout time scales of practical interest. For the most part, conventional modeling and experimental techniques do not take account of such far-from-equilibrium phenomena, although emerging methodologies that incorporate configurational (or “informational”) entropy look promising. Materials of interest include granular, soil, geological, amorphous, crystalline, and glassy systems, as well as morphing and meta- materials. Understanding and controlling irreversible material phenomena under extreme environments (e.g., high temperature, high strain rates, radioactive, corrosive, etc.) would lead to more robust and safer designs and advances in manufacturing.

4.6. Robot mobility and situation awareness

Successes in Simultaneous Localization and Mapping (SLAM) in robotics have led to sophisticated algorithms for fusing multimodal sensor information into maps of unknown environments, allowing robots to use those maps to localize themselves within the environment. This has led to robots that can map unknown environments in a laboratory setting, and adaptations (combined with motion planning algorithms) are leading to applications such as the Google self-driving car. However, these robots are typically wheeled, allowing reasonable odometry over small distances, and operate in highly structured environments.



To deploy sensors in disaster areas or other harsh or unknown environments, dramatic advances are required in (a) robot mobility and (b) map-building/situation awareness. (a) Robots operating in disaster areas may need to switch between different locomotion modes, depending on the stability of support surfaces, the availability of continuous support patches, the variation in their slope, and the amount of free space. Examples of locomotion modes include flying (fixed-wing and rotorcraft), rolling, walking, leaping, deformable soft-body slithering and inchworm motions, crawling, spider climbing, etc. Creating robots capable of multiple locomotion modes requires advances in mechanism design, energy density, locomotion planning, and feedback control. Some of these challenges may be met through the study of biological counterparts. (b) Map-building and localization are particularly challenging when the data are collected by sensors mounted to robots moving with these locomotion modes, for which even approximate odometry is not available. Map-building and localization are crucial for fusing the data from multiple sensors on a single robot, for fusing the data from multiple robot platforms, for autonomous robot navigation, and for creating virtual environments for the robot's human operators in teleoperation scenarios. Future teleoperated robots will not simply carry cameras to provide feedback to human operators; they will fuse multimodal sensor data to build full 3D models which give their operators the capability to virtually look in any direction. These 3D models may also include other visual, chemical, structural, radiation, or temperature information, depending on the application. Achieving situational awareness and map-building/localization capabilities will require new sensor technologies (e.g., ultrawideband for spatial localization) combined with new multimodal sensor fusion algorithms.

Finally, a new generation of robots will be required to operate in human environments, for which much infrastructure is already developed. Such robots must minimally have the ability to perform simple human functions (e.g., open locked doors with keys, navigate stairs, etc.).

4.7. Adaptive and scalable manufacturing processes

Manufacturing techniques for the fabrication of materials and systems must be developed with the following capabilities:

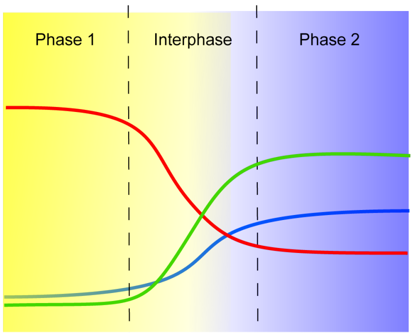
- High precision at multiple length scales
- Rapid implementation from laboratory development to mass production
- Adaptive capabilities for customization and rapid deployment of new processes
- Predictive tools for characterizing process behavior and fabricated product properties using both hard and soft materials

New scalable manufacturing methods are needed for generating precise, highly engineered, high surface-to-volume ratio structures over large scales. To make new fluids/thermal applications practical, implementation at length scales up to meters or above is required. In some instances, manufacturing processes must yield performance at the full system level that is relatively insensitive to imprecisions at the microscale. Some relevant technologies for manufacturing such systems include new surface texturing methods and advanced 3D nanostructuring methods made possible by hydrophilic/hydrophobic surface chemistries, roll-to-roll imprinting and nanoimprinting methods, interferometric lithograph methods, etc., some of which may be combined, or "cascaded". Three-dimensional printing technologies, if pushed to smaller length scales, will enable myriad new possible applications. Optimal manufacturing techniques may include a combination of both top-down and bottom-up methods, both of which should include the capability of guided self-assembly for fabrication. As these systems progress to larger field units, manufacturing techniques used for their fabrication should have low unit cost to facilitate adoption for mass production.

The U.S. has an excellent track record of laboratory scale innovation but is not as successful in scaling these innovations to optimal execution in the marketplace. Thus, there is significant need for the development of scalable manufacturing processes and products that enable seamless transition from the laboratory to mass production. This capability will be driven by global competition and rapidly changing technologies. To bring about this scalability, manufacturing lines must be capable of rapid ramp-up for product launch, which also requires better coupling of design and manufacturing. These lines must also have the flexibility to manufacture a wide variety of products that are highly customizable through adaptive manufacturing processes. Furthermore, these lines will also permit the rapid deployment of new and improved processes, enabling cost-effective and competitive manufacturing enterprises. In addition, such adaptive manufacturing systems can be controlled through cloud computing so that the latest and most advanced manufacturing strategy can be easily deployed to many workstations.

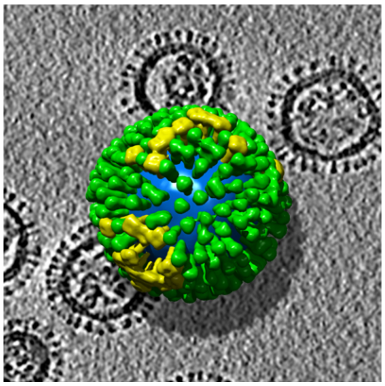
4.7.1. Interface engineering

Heterogeneous materials represent an important class of practical feedstocks in a variety of emerging technological applications such as nanoelectronics, photovoltaics, thermoelectrics, electrochemical energy storage, and fuel storage with solid-state materials. Nanostructuring and surface functionalization, in particular, are expected to enable rapid advances in the performance of materials for such applications. Transport of charge, mass, and/or energy is often essential to the successful performance of these materials in addition to their mechanical behavior, but a theoretical foundation for understanding the influence of microscopic constituent attributes and processing conditions on transport and mechanics is lacking.



The theoretical study of heterogeneous material properties was pioneered more than a century ago, by considering systems of inclusions of simple shapes embedded in a host. Most notably, effective medium approximations of various types have been developed to model material properties based on simplified micromechanical contact models between particles. Despite these advances, only partial understanding has been gained regarding the effects of realistic inclusion shape, microstructure, and particularly subcontinuum processes on the overall properties of heterogeneous media. Additionally, the change of properties of materials near interfaces remains difficult to quantify, yet essential to understanding and designing new materials. New methods that capture the geometric complexity of such composites while also rigorously incorporating the interfacial physics of heterogeneous interactions are needed to exploit the full potential of this emerging field. Such advances will require the combination of large-scale computing, predictive process simulation, and hierarchical stochastic modeling, along with experimental characterization for insight into mechanisms and rigorous experimental validation.

4.7.2. Three-dimensional characterization techniques



There have been spectacular advances in experimental techniques for characterization of material structures, surfaces, interfaces, and internal deformation and failure mechanisms. Such advances have been facilitated by improvements in (i) probing sources such as electron beams, x-rays, lasers, etc., (ii) diagnostic methods using detectors at high spatial and temporal resolutions, (iii) precision control in experiments aided by computer automation in these devices, (iv) surface probes such as atomic force and other scanning probe microscopes, (v) data interpretation and representation through computer aided tomography and other techniques and (vi) analysis that combines the multi-diagnostic information from experiments with quantitative models using computational inverse modeling approaches to provide unprecedented resolution in experimental diagnostics. While each of the methods is accompanied by limitations and uncertainties, together the suite of techniques is fundamentally changing our understanding of hierarchical material structure and mechanisms. For example, electron back scattered diffraction (EBSD) methods have advanced to an extent where they now provide detailed grain information in polycrystalline materials; x-ray computed tomography is able to provide three-dimensional characterization of the in situ conditions in a material during deformation, although currently the resolution in space and time is somewhat limited. Advances in these techniques as well as development of new techniques with increased spatial and temporal resolution are needed in order to provide three-dimensional representations of the material microstructure and its evolution during deformation. Research focusing on the use of these techniques in order to improve our understanding and modeling of material behavior can steer the development of new materials with dramatically superior properties.

4.7.3. Three-dimensional fabrication methods – Additive Manufacturing

Additive manufacturing is a good example that illustrates the four key capabilities

described by the bullet list in Section 4.7 above for adaptive and scalable manufacturing processes. Additive manufacturing is often defined as the process of joining materials to make objects from powders, droplets, or liquid baths, usually in a layer-by-layer manner. The figure shows the Airbus A320 Nacelle Hinge Bracket using conventional manufacturing processes (top) and the optimized design for light weight structure produced by additive manufacturing from metal powders with particle sizes of 20-50 microns (bottom), which attains high precision at multiple length scales, including surface roughness under 5 microns. Rapid implementation of additive manufacturing technologies requires a coherent and collaborative effort among university researchers and industrial practitioners across the fields of material scientists, computational mechanics, design, control, machine architecture, in-situ metrology, computer-aided design, etc. Additive manufacturing has the potential to revolutionize optimal structures in conjunction with systems level analyses (Section 4.3.1).

4.7.4. Parts with integrated multi-functions and self-description

The integration of material, energy source and data into parts is an area of great potential. Such parts may have their own power (e.g., batteries) and product-specific information (e.g., build date, material type, processing methods, etc. via RFID tags) embedded in each part that can be transmitted through onboard communications (e.g., wireless data transfer). In order to produce parts with these capabilities, multifunctional, “smart” materials (Section 4.4) must be incorporated in their design and fabrication.

5. International Context

The previous two sections of this report describe five application domains (i.e., energy, water, engineering for human health and safety, infrastructure, and manufacturing) with emerging long-term challenges, as well as the technological needs that will be critical for meeting these challenges. As an additional consideration, it is important to outline these challenges within the scope of an international context in order to ensure that the United States be a world leader in a range of technologies heading into the future.

A report by the National Academies published in October 2007 titled "Benchmarking the Competitiveness of the United States in Mechanical Engineering Basic Research" indicated that the U.S. was a strong leader and would continue to be a major player in basic ME research. Particular strength in areas of an interdisciplinary nature was found, and it was further predicted that significant US leadership in these areas would remain. The report predicted that mechanical engineers in the United States would continue to contribute significantly to ME journal articles, as would growing world economies such as China and India. Moreover, the National Academies reported a decline in the number of U.S. citizens obtaining advanced degrees, leading to a potential shortage of U.S. Mechanical Engineers. Finally, it was reported that funding of ME basic research and infrastructure was likely to remain steady in the U.S., with solid leadership in emerging areas.

Each subsection below describes the considerations of the United States as a world player with respect to the application domains outlined in section 3, including the emerging technologies presented in Section 4 of this report.

5.1. Energy

The United States faces several challenges in maintaining leadership in energy research. For example, Japanese investment in fuel cells is on the rise, while that of the United States may be declining. Battery and wind power manufacturing is increasingly dominated by Europe and China, and research there is following. There is a challenge in managing the supply chain for raw materials used in alternative energy sources, especially as new materials are developed for use in batteries, magnets, fuel cells, etc.

Justification and support for energy research is particularly sensitive to the U.S. political climate prevailing at any given time, and in a sense also to the prevailing price of oil. These considerations affect our ability and will for basic research planning in both the government and private sectors. Military needs, however, remain relatively stable and predictable, where the high effective cost of fuel at operational theaters is well known. The DoD can play a particular role in keeping US energy research competitive internationally. For example, besides the basic research areas mentioned in Section 3.1, energy systems research in microgrids would be valuable for military needs and would also advance civilian interests. Integrating alternative energy sources and storage abilities in such microgrids, and optimizing the systems for increased reliability and independence would provide significant value to both planners and service members. Such research will be also valuable to scale-up efforts for civilian implementations.

Europe, Japan and China have made major commitments to new transportation and automotive technologies, and indeed have made national goals out of their leadership in these areas, particularly in the development of electric vehicles. Recent market experiences in the U.S. demonstrate the difficulty of relying on market forces alone to provide the basic research support needed in this emerging area. The DoD has an excellent record in early support of hybrid vehicle technology research but this support has lagged as the automakers have moved into commercial production. However, basic research is still needed to improve reliability and cost of electrified vehicles beyond the gains of mass production. Less conventional forms of vehicles enabled by electrification that are of specific value to the military – for example, vehicles that can multitask and cooperate with each other in real-time in response to operation needs – are also of importance.

5.2. Water

Israel and Singapore are leaders in desalination via membrane technology, whereas China is an emerging leader in phase-change desalination technology. China and Europe are both on-par or even leading the United States in functionalized surfaces for use in separation processes for the derivation of potable water from municipal waste water, industrial waste water, and ocean salt water.

The United States is competitive in the conceptualization of technology for monitoring and control systems, whereas England and Singapore are seeing field deployments. Holland is leading in the development of technology for health monitoring of critical flood-protection infrastructure systems. It is not clear what the international context is regarding the water-energy nexus. India is on-par or leading the United States in computational fluid dynamics (CFD) technology for the simulation and modeling of fluid systems.

With the above in mind, it is still the belief of the participants in this workshop that the United States is a clear leader in water-related technologies. While the U.S. may find itself on par with some of its peers, it is often the case that the U.S. is a key conceptualizer of water technologies. However, the U.S. is clearly lagging in the implementation and manufacturing of these critical technologies, which results in fewer opportunities for innovation derived from extensive expertise in both deployment and manufacturing, thereby breaking the historical feedback loop in improving technologies.

5.3. Engineering for Human Health and Safety

5.3.1. Bio-marker sensor development

Significant government funding toward developing bio-marker sensors are available both in European countries such as Germany and Switzerland, as well as in Asian countries such as China, Japan, Korea, and Singapore. In many of these countries, up to 50-75% of proposals receive government funding, which amounts to a proposal success rate approximately an order of magnitude higher than that of the U.S. As evidence for the high level of government funding in Asia and Europe, there is a large amount of high quality papers from those countries published in international journals on micro/nano bio-sensors. However, strict regulatory rules have limited the prevalence of commercial bio-sensor products both overseas and domestically, which highlights an opportunity for the U.S. in bio-sensing technology, even with the relatively small amount of domestic government grants in the area.

5.3.2. Pharmaceutical industries

In Switzerland, the development of new drugs has been ongoing for many decades and is still strong. China, Japan and Korea all have well-established research and industrial efforts to convert traditional Chinese medicine into scientifically based drugs for Asian markets, rather than devoting efforts toward new drug-screening. India, Japan and China also have sizable industries in the manufacturing of generic (i.e., patent-expired) drugs. The United States still dominates in new drug developments.

5.3.3 Robotics research

Korea and Japan have made heavy investments in the development of humanoid biped robots through focused national projects. They are currently the world leaders in biped humanoids that can operate in human environments, with integrated arms, legs, and full head-mounted sensor suites. Private sector-led progress in the US includes Boston Dynamics' Petman, funded by DoD. Petman is perhaps the most advanced biped walker today, though it is not a fully integrated humanoid like those found in Japan and Korea. Other significant developments in the US include the Willow Garage PR2 two-armed wheeled mobile manipulator, which has become a de facto standard platform for AI and robotics research, allowing a blossoming of shareable software for the standard platform. The PR2 is not as sophisticated as mobile manipulators available in Europe, such as DLR's Justin, but is considerably less costly and more widely used.

Under Europe's FP7 program, large multinational projects are being funded to study various topics in robotics, while non-military US efforts have been smaller scale and less focused, at least until the recent National Robotics Initiative. The US and Europe have been the leading developers of SLAM technology, and DoD investments in advanced robot locomotion have kept the US in a leadership position with respect to new technologies for agile locomotion. Robotics efforts in China are rapidly growing, but China is currently a relatively small player in robotics compared to the US, Europe, Japan, and Korea.

5.4. Infrastructure

In the post-WWII years, the US built the greatest infrastructure of the modern world. It was the construction and utilization of this modern infrastructure that created jobs and transformed the US into a superpower of the world in record time. Today, infrastructure continues to be the key engine for economic growth, national security and quality of life.

Like everything else, infrastructure has a lifespan. Years of neglect have left the US infrastructure in dire conditions. According to the 2009 Report Card for America's Infrastructure by the ASCE, trillions of dollars in repairs and upgrades will be needed in the next few years to restore our infrastructure to an acceptable condition. It is clear that, if not addressed, the deterioration of the US infrastructure will continue to threaten our way of life. Failure to act now will have enormous economic, social and political impact.

The United States is currently a leader or competitive with the most important international players, as far as fundamental research is concerned. However, it is recognized that there are several fast developing scientific communities (e.g. China) that can potentially overcome American current leadership status if appropriate resources are not directed towards infrastructure research in the United States.

In addition, substantial efforts are needed by federal and state agencies to foster deployment and timely implementation of the identified emerging technologies for infrastructure. In this area, current US investments are minimal compared to investments by other countries. The United States now ranks *twenty-third* overall for infrastructure quality, between Spain and Chile; government expenditures on infrastructure have fallen to just 2.4% of GDP in the United States; in contrast, Europe and China invest 5% and 9% of GDP on infrastructure, respectively.

5.5. Manufacturing

Manufacturing has been at the center of globalization for centuries. A series of publications and studies in the last five years has emphasized or re-emphasized the role of manufacturing on our society. In the 2007 National Academy of Engineering report "Rising Above the Gathering Storm," the opening line of the preface makes this crystal clear: "*The United States takes deserved pride in the vitality of its economy, which forms the foundation of our high quality of life, our national security, and our hope that our children and grandchildren will inherit ever-greater opportunities*." Common findings in about 10 *World Technology Evaluation Center* studies on manufacturing-related topics revealed:

1) The U.S. lags behind Asia and Europe in the development of advanced manufacturing equipment
2) The U.S. is particularly behind in transitioning R&D results to commercialization
3) The U.S. gets low marks for its ability to leverage university research through strong industry partnerships
4) U.S. IP regulations have a much larger detrimental impact on technology transfer than similar regulations elsewhere.

So where do we compete favorably? There is a positive answer to this question and it suggests the strategies we need to adopt and the directions we need to move in most vigorously. We tend to compete well in situations where:
1) Product development/capability enhancement times are short and are driven by innovation and high-tech resources, even if the industry is considered mature, e.g., computer chips;
2) Innovation-based new product development, with examples in virtually all sectors, e.g., electronic entertainment-based consumer items, minivans, SUVs, cell phones/smartphones;

3) Products associated with national defense, particularly those that are oriented for dual-use or have near-term spill-over into commodity markets, e.g., aircraft, missile-systems, space exploration;

4) Products associated with personal needs and tastes, particularly those associated with the entertainment business.

The good news may be that all of these products have a heavy reliance on innovation and the application of high-tech resources including brainpower. The adaptive and scalable manufacturing platform can steer us back to a sustainable “making products” economy from an unsustainable “selling products” economy.

6. Concluding Remarks

Over the course of this workshop, five application domains with significant challenges to long-term growth, as well as a number of cross-cutting discipline-based technologies that will prove key for realizing those challenges, were identified. US competitiveness in these key areas of mechanical and civil engineering was assessed. Future investment in research and application along the critical areas identified herein will help ensure long-standing US leadership and will contribute to global needs for key advances in our societies. Both DOD and civil interests will be well served by these investments. History has shown that federal support of long-range, high-risk fundamental research develops US innovation and trains new creative thinkers, providing a key differentiator to keep US research at the leading edge of critical technologies.

Appendix 1: List of attendees at the Workshop for Future Directions in Mechanical and Civil Engineering

Name	Affiliation	E-mail Address
Jan Achenbach	Northwestern University	achenbach@northwestern.edu
John Bassani	University of Pennsylvania	bassani@seas.upenn.edu
Zdenek Bazant	Northwestern University	z-bazant@northwestern.edu
David Boyce	University of Illinois at Chicago	d-boyce@northwestern.edu
Mary Boyce	Massachusetts Institute of Technology	mcboyce@mit.edu
Cate Brinson	Northwestern University	cbrinson@northwestern.edu
Jian Cao	Northwestern University	jcao@northwestern.edu
Julie Chen	University of Massachusetts - Lowell	julie_chen@uml.edu
Gianluca Cusatis	Northwestern University	g-cusatis@northwestern.edu
Armen Der Kiureghian	University of California - Berkeley	adk@ce.berkeley.edu
Richard Finno	Northwestern University	r-finno@northwestern.edu
Timothy Fisher	Purdue University	tsfisher@purdue.edu
Srinivas Garimella	Georgia Institute of Technology	srinivas.garimella@me.gatech.edu
Youssef Hashash	University of Illinois - Urbana Champaign	hashash@illinois.edu
Chih-Ming Ho	University of California - Los Angeles	chihming@seas.ucla.edu
Harley Johnson	University of Illinois - Urbana Champaign	htj@illinois.edu
Maria Juenger	University of Texas	mjuenger@mail.utexas.edu
James Kuffner	Google	kuffner@google.com
Vijay Kumar	University of Pennsylvania	kumar@seas.upenn.edu
Tom Kurfess	Office of Science and Technology and Policy	tkurfess@ostp.eop.gov
Jerome Lynch	University of Michigan	Jerome.Lynch@umich.edu
Kevin Lynch	Northwestern University	kmlynch@northwestern.edu
Yu (Marco) Nie	Northwestern University	y-nie@northwestern.edu
Donald Norman	Northwestern University	don@jnd.org
Panos Papalambros	University of Michigan	pyp@umich.edu
Neelesh Patankar	Northwestern University	n-patankar@northwestern.edu
Jianmin Qu	Northwestern University	j-qu@northwestern.edu
Krishnaswamy Ravi-Chandar	University of Texas - Austin	kravi@mail.utexas.edu
Glenn Rix	Georgia Institute of Technology	glenn.rix@ce.gatech.edu
Pol D. Spanos	Rice University	spanos@rice.edu
Kripa Varanasi	Massachusetts Institute of Technology	varanasi@mit.edu
C Michael Walton	University of Texas - Austin	cmwalton@mail.utexas.edu
Ming Wang	Northeastern University	mi.wang@neu.edu
Andrew Whittle	Massachusetts Institute of Technology	ajwhittl@mit.edu
Neil Gupta	Department of Defense	Neil.Gupta.CTR@osd.mil
Robin Staffin	Department of Defense	
Stuart Wolf	Department of Defense	
David Mann	US Army Research Office	david.mann1@us.army.mil

Appendix 2: Chronological breakdown of workshop organization by session

In order to gain an overarching view of the future in mechanical and civil engineering, the participants were divided into groups for a series of breakout sessions. For discipline-based breakout sessions, each group consisted of members with expertise in a combination of the disciplines shown in Figure 1 as follows:

- Geotechnology and Materials & Mechanics of Materials
- Transportation, Structural Health Monitoring, and Structures
- Systems, Design, and Manufacturing
- Thermal and Fluid and Micro/Nano Engineering

In the first of several breakout sessions, each group identified emerging technologies that could create a fundamental paradigm shift and the supporting data, methods, and infrastructure essential for realization. With these potential future paradigms in mind, the second breakout session focused on identifying discipline-based emerging needs (e.g., fundamental breakthroughs, major theoretical/experimental advances, new enabling technologies).

After summaries of each breakout group's findings were presented in a group discussion, a third breakout session was held for each group to identify 4-5 application domains that are expected to yield the largest impact within the context of the discipline-based emerging needs. A subsequent group discussion consolidated the lists of application domains into the five application domains with the largest future impact. Participants were regrouped into the five application domains and each group identified the emerging directions and challenges specific to its specific application domain, crossing across sub-disciplines. A final round-table discussion amongst the full group was devoted to fine-tuning the major technological needs required to meet the emerging challenges within the five application domains.