OneNSF INVESTMENTS
CYBER-ENABLED MATERIALS, MANUFACTURING, AND SMART SYSTEMS (CEMMSS)

OVERVIEW

In the spirit of OneNSF and in response to the President's Materials Genome Initiative and Advanced Manufacturing Partnership, the Cyber-enabled Materials, Manufacturing, and Smart Systems (CEMMSS) framework includes a number of related science and engineering activities – breakthrough materials, advanced manufacturing, and smart systems – across the Foundation. NSF recognizes that substantive advances in the next generation of discoveries in any single CEMMSS domain are entirely dependent upon complementary advances in the other two domains. CEMMSS is a new investment framework that will pursue solutions to three major questions:

1) What is the scientific basis for designing, manufacturing, and deploying cyber-enabled smart systems and the new materials from which they will need to be composed?
2) Who will have the multidisciplinary skills to design, build, and implement these materials and systems? and
3) What gives us confidence that these materials and future systems will predictably perform as designed once transitioned into practice?

Materials science, advanced manufacturing, robotics, cyber-physical systems, and innovation are not new research topics for NSF. Over the years, elements of these areas of research have been included in core and cross-cutting programs in the Directorates for Computer and Information Science and Engineering (CISE), Engineering (ENG), Mathematical and Physical Sciences (MPS), Biological Sciences (BIO), and the Office of Cyberinfrastructure (OCI). Bringing these investments together under one umbrella emphasizes the important interdisciplinary research to be undertaken and the potential for interaction among various research ideas, boosting scientific discovery and the economic future of the Nation. The research needed to make progress includes the following three areas:

1. Breakthrough materials. New integrated computational, experimental, and data informatics tools are needed to create advanced materials; seamlessly integrate improved predictive modeling algorithms of materials behavior into product design tools; and design frameworks that enable rapid and holistic design engineering. Research areas include:

- Discovery and development of materials with multi-functional capabilities;
- Predictive algorithms that have the ability to model behavior and properties across multiple spatial and temporal scales;
- Computational mining of the genomic data from diverse biological systems to identify inspirations for the design and synthesis of new materials with defined properties and capabilities;
- Predictive synthetic biology to design new nanomaterials, particularly based on photosynthesis and other biological processes;
- Improved physics-based models that can be used in advanced techniques, such as high-throughput combinatorial processing;
- New synergies between experimental and computational methods; and
- Cyberinfrastructure for materials to facilitate multi-disciplinary communication, to accelerate the rate of innovation by sharing materials properties data, and to develop modeling and simulation tools that enable the creation of advanced materials with specific parameters.

2. Advanced manufacturing. This area focuses on product and process design, including novel features, functions and desirable attributes, increased quality and reliability, greater customization, production speed, productivity, reconfigurability, resource optimization, and sustainability. Research areas include:

- Robotics, autonomous systems, the role of simulation and modeling, and the role of big data from multiple sources to assist in computer-integrated and cyber-based manufacturing;
- Dynamic behavior of manufacturing and supply chain operations for more efficient and responsive production and distribution;
- Improved flexibility in interface protocols, interoperable applications and service architectures for advanced manufacturing;
- Novel paradigms for reconfigurable, evolvable, adaptive nano-hardware architectures, and the use of heterogeneous systems that can dynamically change via software mechanisms capable of combating error-prone devices at the nano-scale;
- More adaptive, responsive applications that are made possible by intelligent computation and communications; and
- Optimizations of low-power, self-calibrating, and inexpensive cyber systems.

3. Smart systems. New algorithms, materials, control schemes, user interfaces, communication protocols, and devices will be required to produce the physical world transducers and autonomous actuation devices needed for engineered systems to perform smartly in dynamic environments. Research areas include:

- Systems technology frameworks to support networked cyber-physical systems with built-in assurance of their critical properties, including safety and security, and correct, timely performance of their intended functions;
- Rigorous, systematic, scalable, and repeatable design, development, verification, and validation methods, particularly to integrate design, evolution, and certification and reduce the cost of including (or modifying) new Information Technology (IT)-based capabilities in products for public use;
- Development of the next generation of robotics to advance the capability and usability of such systems and artifacts and to encourage existing and new communities to focus on innovative application areas;
- Advances in extracting information from diverse inputs, including the continuous streams of data generated by embedded physical and chemical sensors, to provide timely and critical input into control loops that must make decisions and take actions in real time; and
- Fundamental cognitive and behavioral science needed to make devices that are trustworthy and will be effectively used by people in the U.S. and in markets around the world, as well as the economic, social, and decision science needed to understand adoption and deployment.

Why NSF? NSF is unique among federal agencies because it supports foundational academic research in computer science, engineering, the physical and biological sciences, and education; has long experience in developing and implementing interdisciplinary programs across these fields; and invests in innovation and transition of discoveries into practice. To accomplish the vision of cyber-enabled smart systems and the new materials from which they are composed, increasingly complementary and interdisciplinary research challenges need to be addressed. Each system conceived and developed at the intersection of these domains must evolve under both the constraints and degrees of freedom that each one contributes. Interdisciplinary advances are necessary to make progress in scientific and engineering foundations and for the emergence of novel smart systems application solutions.

Goals

The CEMMSS framework will focus on activities in three tracks – science and engineering, education and workforce, and cyberinfrastructure. The goals of the three tracks include:

1. *Science and engineering*: Establish a scientific basis, a codified knowledge base, and shared principles for designing, manufacturing, and deploying cyber-enabled, smart engineered systems.
2. *Education and workforce*: Educate a cadre of high caliber disciplinary and interdisciplinary researchers and develop a vibrant workforce so as to ensure a pipeline of talent and a growing community in this critical area.
3. *Cyberinfrastructure:* Develop the infrastructure that can be used to discover, test, refine, validate, and approve materials, designs, and manufacturing and development methods for smart engineered systems.

Approach

The interaction of research ideas that is promoted by CEMMSS multiplies their impact across multiple research communities. Bringing together researchers focused on breakthrough materials, advanced manufacturing, and smart systems will increase collaboration and communication among these research communities leading to enhanced disciplinary research, as well as more interdisciplinary research. These efforts will transform static systems, processes, and edifices into adaptive, pervasive "smart" systems with embedded computational intelligence that can sense, adapt, and react. While hints of what is possible are already apparent, the smart systems of tomorrow and the materials from which they will be composed will vastly exceed those of today in terms of adaptability, autonomy, functionality, efficiency, reliability, safety, usability, recoverability, and recyclability.

Programmatic. To generate new capabilities with meaningful impact, NSF must develop a portfolio that coordinates and synchronizes activities across the three main areas – breakthrough materials, advanced manufacturing, and smart systems – and allows interdependencies and common research elements to surface and be exploited in each subsequent stage of the evolution of the program.

Organizational. An internal working group (WG) will be charged in FY 2012 to develop CEMMSS activities and implement the suite of activities over the next four years. The WG will also be asked to develop a set of metrics by which program progress can be evaluated over time.

Scope. Pair-wise connections already exist at NSF, e.g., between robotics and manufacturing; materials and manufacturing; cyber-physical systems and robotics; and robotics and the biological sciences. Activities that aim to bring together all of these research areas will be critical if this ambitious program is to succeed. NSF will hold workshops and request white papers for the associated research areas to contribute to the development and evolution of CEMMSS program solicitations and dear colleague letters. In addition, NSF will develop partnerships with other agencies and with industry to leverage CEMMSS investments.

INVESTMENT FRAMEWORK

FY 2012

This initiative aligns well with the President's commitment "to winning the future through investments in innovation, education, and infrastructure," which he launched in June 2011 through the Advanced Manufacturing Partnership[1], National Robotics Initiative[2], and Materials Genome Initiative[3], all activities in which NSF participates. The President's Council of Advisors on Science and Technology (PCAST)

[1] http://www1.eere.energy.gov/industry/amp/
[2] http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503641&org=CISE
[3] http://www.whitehouse.gov/sites/default/files/microsites/ostp/materials_genome_initiative-final.pdf

recently focused on these national priorities in the "Designing a Digital Future: Federally Funded Research and Development in Networking and Information Technology"[4] report.

To make progress across the three tracks, in FY 2012, the CEMMSS WG will leverage existing research and education programs, as well as initiate community development activities, as described in more detail below.

Science and engineering track. In the first year, the CEMMSS WG will start by developing a baseline derived from portfolio and gap analysis. The analysis will provide a better understanding of the state of the research and will identify the areas that need increased emphasis. The CEMMSS WG will also summarize the recommendations made in recent reports from the PCAST and National Academy of Sciences (NAS) on materials, advanced manufacturing, cyber-physical systems, and robotics. Based on the recommendations in these reports and the portfolio analysis carried out by the WG, it will develop a multi-year plan for CEMMSS with associated milestones and performance measures.

In FY 2012, CEMMSS support includes the NSF investments in Cyber-Physical Systems (CPS) ($31.5 million), the National Robotics Initiative (NRI) ($20.83 million), as well as activities in core research related to advanced manufacturing, robotics, and materials. NRI will provide U.S. leadership in science and engineering research and education aimed at the development of next generation robotics, conceived as co-robots that work beside, or cooperatively with people, increasing their productivity, performance, and safety, especially in manufacturing, while support for basic research in robotics will enable new functionalities and provide the next-generation of products and services for various industries. A number of pilot programs in materials and engineering will also start in FY 2012, including Designing Materials to Revolutionize and Engineer the Future (DMREF), involving MPS and ENG ($10.0 million).

To jumpstart the CEMMSS activity within the research communities, white papers will be requested, webinars and workshops will be held, and Early-Concept Grants for Exploratory Research (EAGER) awards will be made. A communications plan will also be developed and will include a website with links to relevant programs, information, and activities. During the year, the CEMMSS WG will present their recommendations for the plan to relevant NSF senior management as well as to directorate advisory committees to solicit their input.

Education and workforce track. Science and engineering education needs to be transformed to embrace the data- and computationally- intensive components of smart systems. In particular, changes in undergraduate and graduate education will be necessary to ensure a pipeline of a talented and vibrant workforce. In FY 2012, the CEMMSS WG will engage in portfolio and gap analysis; develop a logic model and an appropriately rigorous evaluation methodology; and begin to collect baseline data. NSF will support community workshops specifically focused on the educational aspects of materials, manufacturing, and smart systems. The CEMMSS WG will also partner with existing NSF education working groups, for example, CAREER, Integrative Graduate Education and Research Traineeships (IGERT), Computing Education for the 21st Century (CE21), and Cyberlearning Transforming Education (CTE), to further emphasize smart systems research and education throughout the Foundation.

Cyberinfrastructure track. Many reports on cyber-enabled materials, manufacturing, and smart systems establish the need for cyberinfrastructure to accelerate discovery and innovation. The CEMMSS WG will focus on developing partnerships with other NSF working groups, including Cyberinfrastructure Framework for 21st Century Science and Engineering (CIF21), to better align with their activities and to better understand how CEMMSS discoveries, materials, and systems might be transitioned into practice.

[4] http://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nitrd-report-2010.pdf

FY 2013 Request

Focusing on the knowledge base developed in FY 2012, the CEMMSS WG will create a coordinated set of solicitations and dear colleague letters that cross over two or more areas, expanding on what has been accomplished to date. For example, one new activity will include a focus on the science and engineering foundations of 21st century smart systems and materials. This new program will emphasize, mid-scale team-based interdisciplinary research, building the knowledge base needed to make progress in cyber-enabled materials, manufacturing, and smart systems, with opportunities for transitioning discoveries into practice. In addition, the DMREF program piloted in FY 2012 will evolve to new interdisciplinary areas of cyber-enabled materials ($32.0 million). In FY 2013, CEMMSS will continue to support investments in NRI ($27.50 million) and CPS ($43.0 million).

To make progress across the three tracks, CEMMSS WG activities in FY 2013 will include:

- Workshops that bring together researchers from the different communities to develop grand challenge research problems in the overarching CEMMSS areas with clear outcome goals and performance measures. In addition, the associated big data and cyberinfrastructure components necessary for making advances in cyber-enabled materials, manufacturing, and smart systems will be identified.
- The first CEMMSS Principal Investigator (PI) meeting will be held to provide opportunities for building new interdisciplinary research communities.
- CEMMSS summer schools and new curricula for undergraduate and graduate students in engineering, computer science, materials, and biological sciences will be developed and deployed. To measure the impact of these efforts, the working group will continue the rigorous evaluation methodology started in FY 2012.
- Industry partnership development, interagency activities, and joint programs will be increasingly emphasized in order to leverage NSF investments.

FY 2014 – FY 2016

As the CEMMSS investment matures, the focus will be on evolving a comprehensive, integrated program across the focus areas to encourage new connections, discoveries, and/or emerging fields of science and engineering. The CEMMSS WG will develop a coordinated set of integrated innovative solicitations that include all three focus areas and that encourage foundational and interdisciplinary research across them. For example, in FY 2014, CISE and ENG, working together with BIO, MPS, and OCI, will replace the Cyber-Physical Systems solicitation with one on CEMMSS to discover commonalities, leverage new knowledge, and transform fields. Starting in FY 2014, NSF plans to invest in center-scale multidisciplinary research across the CEMMSS activities.

NSF has worked with other agencies, such as the National Institute of Standards and Technology (NIST), the National Institutes of Health (NIH), the National Oceanic and Atmospheric Administration (NOAA), U.S. Department of Agriculture (USDA), and the Departments of Transportation and Defense, which are currently building and deploying smart systems of all kinds (e.g., underwater sensor networks; autonomous vehicles that swim, fly, crawl up walls; portable energy efficient storage devices, etc.). Combining mission agency investments with the basic science and engineering funded by NSF could have a significant impact on future U.S. critical infrastructure by embedding computational intelligence in the underlying systems and the materials from which they are composed. By developing partnerships with other agencies, NSF will pave the way to an interagency CEMMSS program starting in FY 2014 or FY 2015.

CEMMSS Funding

(Dollars in Millions)

Directorate/Office	FY 2012 Estimate	FY 2013 Request
BIO	$3.00	$5.00
CISE	50.00	91.00
ENG	56.00	110.42
MPS	32.15	50.00
OCI	0.50	1.00
Total, NSF	**$141.65**	**$257.42**

Totals may not add due to rounding.

EVALUATION FRAMEWORK

Using portfolio analysis tools, a baseline of NSF research and education activities in CEMMSS will be established. Metrics will be identified to measure progress across the three tracks. Possible indicators include:

- For science and engineering – increase in breakthrough discoveries; the emergence of new fields; increasing agency, industry and international partnerships; and increasing transition of discoveries into practice (i.e., patents, start-ups, new products);
- For education – increases in the number of smart systems courses offered, faculty recruited and students graduating from academic programs; and
- For cyberinfrastructure – the development of de facto standards for interoperability, increased use of shared data analytic, simulation and modeling tools and common software platforms, and the growth of computer-integrated and cyber-based manufacturing across the U.S.

Based on the program goals and associated metrics, a plan will be developed by the start of FY 2013 for the following four years (FY 2013 through FY 2016) with milestones, subgoals, and evaluation plans at each stage. Yearly program assessments will be carried out by the CEMMSS WG and presented to NSF senior management.