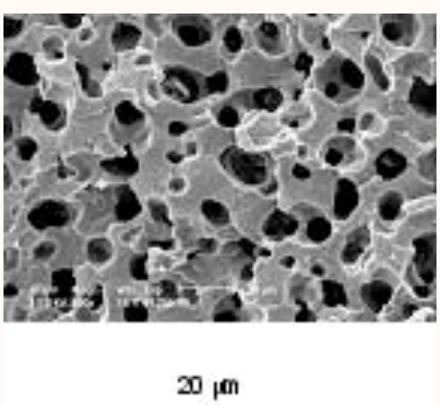
OPPORTUNITIES

> *"There is a theory that creativity arises when individuals are out of sync with their environment. To put it simply, people who fit in with their communities have insufficient motivation to risk their psyches in creating something truly new, while those who are out of sync are driven by the constant need to prove their worth. They have less to lose and more to gain."*
> *Gary Taubes*

Research areas funded by CMMI are experiencing rapid development and breakthroughs are imminent. One goal of CMMI is to find and promote such breakthroughs, thereby enabling and encouraging intellectual growth of the CMMI academic community and benefiting the nation. The following bullets identify a number of areas where breakthrough research is expected.

- Manufacturing: Manufacturing processes are inherently complex, and they involve decision making and optimization under uncertainty and risk. Furthermore, many manufacturing processes involve multiple physical phenomena acting together in complex and difficult-to-measure ways. Metal cutting is one such example. An understanding of metal-cutting processes can be obtained only through modeling. Chatter is a limiting factor in metal cutting, and it can be predicted only approximately. There exists a potential for improved understanding of many manufacturing processes through better modeling on large scales. Processes can also be improved, through the rigorous application of decision theory and through improved active control of these processes.

- Engineering Design: Engineering design has long been practiced in an *ad hoc* manner, using modeling and decision-making approaches that are not mathematically rigorous. The integration of sound mathematical practices and theories holds the promise to greatly improve engineering design decision making as well as to provide a basis for determining whether a new theory is valid or not. Key opportunities are to integrate into engineering design a rigorous theory of predictive modeling, social choice theory and modern normative decision theory.



Researchers at The Ohio State University have investigated the production of nanocomposite foams based on a combination of nanoparticle technology and supercritical fluids technology. The solubility of carbon dioxide in a polymer matrix and the rheological properties of nanoparticle-containing polymer with and without carbon dioxide were studied. Based on the results, the researchers designed a batch extrusion foaming process. Using this process, they have fabricated a variety of nanocomposite foams. Such foams may be used as fire-retardant insulation, electric shielding and tissue scaffolds in biomedical applications.

- Innovative Product and Complex System Design: Design methodologies are being explored to support application domains from bio-nano robotics to complex sensor networks to energy-efficient vehicles and buildings. Methods to support innovative ideation at the crucial stage of initial design will form the foundation for new, competitive products. New optimization and visualization techniques, which seek to capture the depth and breadth of many aspects of the overall design problem, promise to bring advances in information technology to benefit engineering design.

- Macro-Manufacturing via Nanotechnology: Large structures (10m–10^3km) include towers, bridges, aircraft, ships, submarines, and desalination plants. They are manufactured in-place and are significant contributors to the national infrastructure, wealth generation and employment. Research in nanostructured materials, nanoscale processes and nanosystems could greatly transform large infrastructures by replacing defect-prone and resource-demanding assembly with continuous processes and robotic rapid manufacturing based on nanotechnology.

- Bio-Manufacturing—the Cell as a Manufacturing Plant: Beyond chemicals produced via biotechnology, live cells and microbes can be engineered genetically. Enzymantic and viral reproduction can be engineered to create nanostructures, nanodevices and nanosystems having geometrical and material complexity. This manufacturing technique capitalizes on bioinformatics research in genomics and proteomics, as well as cancer research on uncontrolled cell multiplication, just-in-time reproduction and scale-up.

- Information Technology and Information Systems: Advanced information technologies will play a key role in and be necessary for standardizing and integrating various sensors and computer systems for better interoperability. Key information technology research areas involve: computer vision, reasoning, and pattern recognition for rapidly assessing a condition; distributed sensor networks for monitoring critical infrastructure; visual modeling and simulation to better manage resources and constraints; and algorithms for more efficient data mining and analysis.

- Decision Making Under Uncertainty: A central focus of the CMMI Operations Research program is research on quantitative tools to support decision-making. All real decisions involve uncertainty in some form, either uncertainty about the future or uncertainty about the appropriateness or accuracy of a model. Although the need to make decisions under uncertainty long has been known to be "the real problem", incorporating uncertainty into the decision-making process has been immensely challenging both theoretically and computationally. In recent years, however, solutions to this broad problem are coming within reach, and helping to find those solutions promises to be an important strategic goal for the Operations Research program.

- Mechanics and Structure of Materials: Meso-mechanics, which is not well

Since 2003, more than 370 professors, post doctorate researchers and others have participated in the NSF Summer Institute on Nano Mechanics and Materials. In 2005 there were 92 participants. This effort, funded by CMMI, plays a key role in workforce development in an important emerging area. It provides access to specialized courses in nanotechnology not available at many universities and stimulates the development of new course materials. Designed to be accessible to students with a BS degree in engineering, the courses provide an opportunity for students and researchers at many levels to enhance their understanding of frontier areas in nanotechnology.

understood, serves as the bridge between different size scales. According to the late Rick Smalley, the most challenging problems are at the interfaces between wet and dry materials. The mechanics of such interfaces, electronic materials, thin-films, smart materials and bio-inspired materials; multi-scale [spatial and especially temporal scales], multi-physics and multi-phenomena mechanics; and the mechanics involved in the integration of microelectromechanical systems (MEMS) and nanoelectromechanical systems (NEMS) are some of the research frontiers.

- Bio-Geo Engineering: The area of bio-geo engineering offers the possibility of changing soil behavior through biological activity so that, for example, weak, compressible soils might be strengthened, thereby reducing or eliminating the need for costly deep foundations to support structures. Advances in non-intrusive site characterization techniques, based mainly on geophysical techniques, offer the possibility to “see” beneath the earth’s surface in great detail to locate pipelines or other infrastructure; to predict tunneling conditions; and to obtain an accurate measure of spatial variation in soil properties. Integration of site characterization methods, preconstruction numerical modeling, real-time monitoring of excavation behavior and real-time updating of design can lead to significant improvements in urban underground construction safety and cost while speeding up construction and minimizing damage to neighboring structures and litigation.

- GeoEnvironmental Engineering and GeoHazards Mitigation: Research is focused on using biological, chemical and physical means to enable *in-situ* methods of mitigating soil liquefaction, such as occurs during earthquakes. These techniques will result in new technologies to reduce the effects of earthquake ground motion on existing structures. Research on municipal solid waste landfills will lead to decreased danger of groundwater contamination, increased methane collection for power generation and safer ways of sealing landfills after they reach their capacity. These landfill sites can then be safely reused. Research on drilling, tunneling and excavation in rock may lead to further development of geothermal energy resources, as well as methods for sequestering carbon dioxide and nuclear and hazardous wastes; and may facilitate increased use of underground space for environmental and national security needs.

- Hazard Mitigation for Civil Infrastructure: A healthy and functioning civil infrastructure is vital for the continuing operation of our society. This infrastructure, however, is vulnerable to natural and manmade hazards. Currently, infrastructure design codes account for one type of hazard but not others. In addition, most codes are aimed toward preventing collapse during the largest hazard level considered, leaving buildings vulnerable to relatively less extreme (and sometimes more frequent) hazards. As a result, protection of human life is not considered uniformly across all hazards, and protection against the many types of damage possible is not considered explicitly. Developing a process to ensure that performance-based design accounts for many hazards would be a large step toward building a resilient and sustainable civil infrastructure. This approach would consider all potential costs of hazards to society, not just the costs to a specific structure or facility. Realizing this change will require a systems approach to hazard mitigation. Risk measures would be uniform across all hazards, and performance objectives would be defined by hazard level.

- Supply Chain Management and the Management of Disaster Relief: Moving goods in a timely way is crucial for disaster relief. Industrial engineers have refined "just in time" and other supply chain concepts that improve efficiency and resist disruption. These concepts are fueling breakthrough applications in disaster relief. In applying these ideas, emergency managers will learn more about useful supply chain concepts, and researchers will learn about how supply chains perform under stress.

- Coupled Oscillator Theory (resonant and/or networked): The advances in this area will lead to breakthroughs in understanding and/or synthesizing oscillators in a multitude of applications. For example, carbon nanotube resonators are examples of ultra-high frequency devices that can function as RF filters, transistors, mixes, modulators, demodulators, zeptogram-level mass sensors and memory elements; micro- and nanomechanical resonators can also be used as sensors with unprecedented resolution for application in biomechanics and biophysics of cellular and subcelllular structures. Many discoveries will be enabled in biology, from macro scale (such as in human biomechanics) to nanoscale (such as the "repressilator" involved in gene transcriptions), and including understanding the functioning of the brain and neural systems.

- Advances in Analysis and Design of Large-Scale Complex Dynamic Systems: New theories will lead to innovative architectures and understanding of a system's inherent abilities and limitations resulting from properties of the system's components and properties of the whole system. Breakthroughs in this area will enable new integration methods that account for complex dynamic interaction between components. A prominent area that will benefit from these developments will be in mechatronics with smart components and self diagnosing, self-healing systems and materials.

- Human Behavioral Modeling in Service Enterprise Modeling: Integration of human behavioral modeling into service enterprise modeling is a key driver for engineering more effective service systems. Increasingly sophisticated brain imaging data allow us to understand the components of the brain that are engaged during decision making, and why our decisions may not conform to a formal reconstruction of the decision problem. Building this understanding into our service system design is an emerging frontier.

CMMI Priority: Modeling and Simulation in Engineering

With the high capital and labor costs associated with conducting experiments and the difficulties associated with the intelligent design of experiments and the control of important experimental parameters, the development and pervasive application of modeling and simulation in essentially all disciplines of engineering and science are of critical and growing importance. Effective use of modeling and simulation can reduce the number and complexity of experiments required and the time required to gain insight into important physical phenomena and systems.

Modeling and simulation in engineering is a field that cuts across engineering disciplines. Researchers, supported by CMMI, are laying the groundwork for initiatives in predictive modeling and in simulation-based engineering and science. Predictive modeling underlies all of engineering practice and relies on the application of probability theory, in which engineering has seriously lagged behind corresponding mathematical developments. Serious challenges exist in bridging the multiple spatial and temporal scales from nano to micro to meso and macro, as well as simulating multi-physics, multi-phenomena problems. New approaches both to these subject areas and to the conduct of research in them must be sought.

In many cases, such as predictive modeling, the knowledgeable research community is quite small, and experts are not located near each other. Therefore, the need is to enlist and encourage geographically dispersed investigators to collaborate. Virtual groups are one possible approach. Such groups would start small and grow as new investigators become experts in the emerging area. They would mature as the new technology permeates engineering research and engineering curricula across the nation. Establishing the virtual center would require about $1 million annually in funding. This amount would grow to several million annually as the activity matures. In the fully mature stage, multiple investigators would coalesce at leading institutions, and the virtual center would fragment into real clusters of investigators doing group research.

In other cases, such as simulation-based science and engineering, there is a strong need for collaboration across many disciplines. Again, the virtual center model might be a good approach, but require modification to enable the types of close collaborations that require physical presence as a part of the overall plan. As a result, the start-up budgets would be a bit higher, perhaps $2 million annually, and may grow to higher levels, especially given the potential need for experimentation.