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Industry-Nominated Technology Breakthroughs of NSF Industry/University Cooperative Research Centers

Industry-Nominated Technology Breakthroughs of NSF Industry/University Cooperative Research Centers 2014

I/UCRC Program Leadership

(2012-2014)

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The NSF Statutory Mission

To promote the progress of science; to advance the national health, prosperity, and welfare;
and to secure the national defense; and for other purposes.

—From the National Science Foundation Act of 1950 (P.L. 81-507)

The NSF Vision

NSF envisions a nation that capitalizes on new concepts in science and engineering and provides global
leadership in advancing research and education.

*—From "Empowering the National Through Discovery and Innovation, NSF Strategic Plan for
Fiscal Years 2011-2016"*

Preface

This 5th edition compendium is intended to acquaint readers with how center knowledge and technology
are being translated into commercial and industrial advances and applications. It catalogues technological
breakthroughs and advances that industry representatives believe are attributable to specific Industry/
University Cooperative Research Centers (I/UCRCs).

The National Science Foundation's Industry/University Cooperative Research Center (I/UCRC) Program is
housed in the NSF's Directorate for Engineering's Division of Industrial Innovation and Partnerships (IIP). A
primary IIP Division strategic goal is to foster the development of sustained university/industry partner-
ships based upon common research interests, trusted networks, and dynamic technical interrelationships.
Many I/UCRCs have become recognized for innovative, cutting edge research. They have amassed an
impressive track record of exploring great ideas through leveraged collaboration and team science.

For almost four decades the I/UCRC Program has catalyzed such partnerships among industry sectors, aca-
deme and government. As of December of 2013, there were over 60 active individual centers involving
over 175 university sites and 760 industry partners (with over 500 distinct organizations holding 1,080
memberships). Over 40 I/UCRC have graduated from the program and are now self-sustaining.

The NSF provides I/UCRCs with a modest amount of funding as base support. The I/UCRC partnership model, which is at the heart of the program, requires that the majority of center funds be contributed by corporate sponsors. In 2012, the NSF invested approximately $16.4 million in the program while industry invested approximately $130 million - primarily in the form of center memberships. The majority of these funds were used for direct research support - a multiplier effect of over 8 to 1.

Each Industry/University Cooperative Research Center (I/UCRC) conducts pre-competitive research that is of interest to its industry sponsors and to the university(s) with which they are involved.

A unique feature of I/UCRCs is that they do not conduct industry's research. On the contrary, in these centers industry joins and supports centers that have research areas and missions in which they are interested. Faculty present proposals annually. After listening to proposals, industry representatives offer their industrial perspectives. This feedback from sponsors is intended to improve the quality of the proposed work.

Each center's industrial advisory board (IAB) advises the center leadership regarding which projects they would most like to see supported by industry's pooled membership funds. Final funding decisions are made by the university-based center director(s). The vast majority of center research is conducted by graduate students under the supervision and guidance of university faculty.

This editor asked each center director to identify industrial advisory board (IAB) member/scientists that they view as particularly knowledgeable about the nature of their center's research program and its impacts on science and technology. These IAB members/industry scientists were then approached by the editor to determine whether any of the center's research endeavors met the following definition of a technological advance or breakthrough.

> TECHNOLOGY BREAKTHROUGH DEFINITION: A technological breakthrough or advance may include: significant process improvements, new processes or techniques, and new or improved products or services that resulted either directly from, or was indirectly stimulated by the center's research program.

When an IAB member viewed any center work as meeting this definition, then they were asked to nominate the work for possible inclusion in the compendium.

All entries were nominated by industry scientists. The editor then worked with them and with the involved university scientists to write the individual entries contained herein. The entries exemplify the countless collaborative efforts of university and industry scientists and the economic impacts of the resulting research.

Each entry's statements of economic impact are designed to help convey how the research is contributing to industry's bottom lines and to the nation's research infrastructure, and to the national economy.

List of Nominated Engineering-Funded Centers

There are both Engineering and CISE-funded centers. The following is a list of Engineering centers that have been nominated for inclusion.

Berkeley Sensor and Actuator Center (BSAC)

Biomolecular Interaction Technologies Center (BITC)

Center for Advanced Forestry Systems (CAFS)

Center for Advanced Processing and Packaging Studies (CAPPS)

Center for Advanced Studies in Novel Surfactants (CASNS)

Center for Advanced Vehicle Electronics (CAVE3)

Center for Building Performance and Diagnostics (CBPD)

Center for Child Injury Prevention Studies (CChIPS)

Center for the Design of Analog-Digital Integrated Circuits (CDADIC)

Center for Dielectric Studies (CDS)

Center for Electromagnetic Compatibility (CEMC)

Center for Excellence in Engineering Logistics and Distribution (CELDi)

Center for Experimental Research in Computer Systems (CERCS)

Center for Friction Stir Processing (CFSP)

Center for Fuel Cells (CFC)

Center for Glass Research (CGR)

Center for Health Organization & Transformation (CHOT)

Center for Integration of Composites into Infrastructure (CICI)

Center for Integrative Materials Joining Science for Energy Applications (CIMJSEA)

Center for Laser and Plasma for Advanced Manufacturing (CLPAM)

List of Nominated Engineering-Funded Centers

Center for Metamaterials (CfM)

Center for Nondestructive Evaluation (CNDE)

Center for Particulate and Surfactant Systems (CPaSS)

Center for Pharmaceutical Development (CPD)

Center for Precision Forming (CPF)

Center for Process Analytical Chemistry (CPAC)

Center for Research on Information Technology & Organizations (CRITO)

Center for Resource Recovery and Recycling (CR3)

Center for Virtual Proving Ground Simulation (CVPGS)

Ceramics Composites and Optical Materials Center (CCOMC)

Cooling Technologies Research Center (CTRC)

Connection One - Integrated Circuits, Systems, and Sensors Research Center

Energy-Smart Electronic Systems (ES2)

GRid-Connected Advanced Power Electronic Systems (GRAPES)

Industry/University Center for Biosurfaces (IUCB)

Institute for Next Generation IT Systems (ITng)

Membrane Science, Engineering and Technology Center (MAST)

Photopolymerizations Center (PC)

Power Systems Engineering Research Center (PSERC)

Silicon Solar Consortium (SiSoC)

Smart Vehicle Concepts (SVC) Center

Water and Environmental Technology (WET) Center

Wood-Based Composites (WBC)

List of Nominated CISE-Funded Centers

The National Science Foundation's Directorate for Computer and Information Science and Engineering (CISE) supports research that helps the nation uphold a position of world leadership in computing, communications, and information science and engineering. CISE also promotes understandings of the principles of advanced computing in service to society. The directorate provides support for number of I/UCRCs in computer and information science and engineering. By doing so it helps develop and maintain cutting-edge national computing and information infrastructure for research and education generally, and contributes to the education and training of the next generation of computer scientists and engineers.

Center for Advanced Knowledge Enablement (CAKE)

Center for Autonomic Computing (CAC)

Center for e-Design

Center for Embedded Systems (CES)

Center for Experimental Research in Computer Systems (CERCS)

Center for High-Performance & Reconfigurable Computing (CHREC)

Center for Hybrid Multicore Productivity Research (CHMPR)

Center for Identification Technology Research (CITeR)

Center for Information Protection (CIP)

Intelligent Maintenance Systems (IMS)

Safety, Security, and Rescue Research Center (SSR-RC)

Security & Software Engineering Research Center (S^{2}ERC)

Wireless Internet Center for Advanced Technologies (WICAT)

Berkeley Sensor and Actuator Center (BSAC)

University of California, Berkeley, John Huggins, Executive Director, 510.643.5663, jhuggins@berkeley.edu

University of California, Berkeley, Richard Muller, Director, 510.642.0614, muller@eecs.berkeley.edu

University of California, Davis, David Horsley, 530.341.3236, dahorsley@ucdavis.edu

Center website: http://www-bsac.eecs.berkeley.edu/

Disposable Blood Analyzer
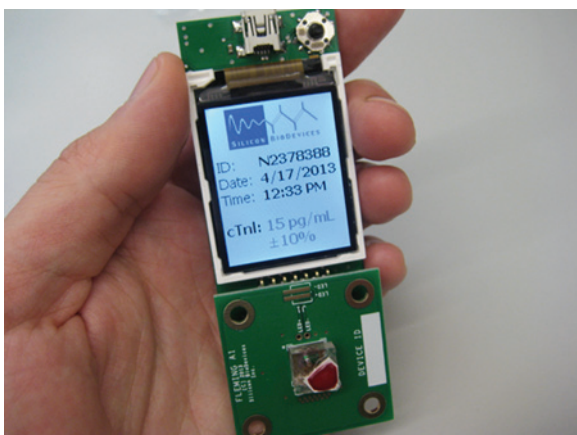
Silicon BioDevices (SBD) has solved a key problem of point-of-care diagnostics - the trade-off of speed versus quality. Now clinicians can get rapid test results without sacrificing quality to make critical-care decisions for improved patient outcomes. SBD's state-of-the-art blood analyzer is as fast and easy to use as an over-the-counter pregnancy test, but with the sensitivity and accuracy of a central lab. In one self-contained system, the handheld device seamlessly integrates all of the assay functions of a point-of-care test directly onto the surface of a Complementary Metal Oxide Semiconductor (CMOS) chip.

Over 6 million people arrive at US hospital emergency departments annually with chest pain and nearly a third of them are admitted for a suspected heart attack. A diagnosis is made using a patient's symptoms, Electrocardiogram (ECG) readings, and biomarker blood tests. Symptoms and ECGs have long been the standard; however, around a 1/3 of patients having heart attacks have non-diagnostic ECGs, and 1/4 have atypical symptoms. Biomarker tests are the most reliable method of detecting heart attacks, with new high-sensitivity tests having diagnostic accuracy of roughly 95%. In 2000, the clinical definition of a heart attack was changed to reflect this. Unfortunately only about 50% of patients presenting with chest pain have biomarkers tested before being sent away or admitted. Currently, performing these tests can be disruptive and results typically take over an hour to return. Because of these difficulties in diagnosing chest pain physicians are caught in a balancing act between inaccurate Point-of-Care (POC) tests and slow laboratory tests.

Using magnetic biosensor technology spun out from BSAC, Silicon BioDevices (SBD) has developed the first single-use, handheld blood analyzer that can measure one or more biomarkers from a drop of whole blood with precision and accuracy equal to a clinical laboratory. Results can appear either on the device's integrated digital display or wirelessly on a secure smart phone or other remote display in less than 10 minutes.

The heart of the product is a microchip that contains a sensor array capable of detecting up to 100,000 single molecules directly from unprocessed samples - without the need for an external reader. In addition to overcoming the challenge of speed versus accuracy in point-of-care testing (POCT), the device's stand-alone design allows caregivers and patients to test anytime, anywhere.

With the potential to house up to 100,000 sensors, each about 100th the cross-sectional area of a human hair, the microchip-based device has the unrivaled ability to count single molecules one at a time. The microchip is mated to a passive sample-filtration system that takes a drop of human whole blood and delivers plasma onto the chip for analysis. Due to the advantages of CMOS digital technology, SBD can offer immunoassays, small molecules and DNA tests all in one handheld, single-use device.

An industry first, its on-chip integration of all analytical functions eliminates the need for an external reader, thus greatly simplifying the use of the device in any workflow environment and reducing its manufacturing cost. Exploiting microchip manufacturing, Silicon BioDevices estimates the devices can be produced at a cost of under $2 for production volumes in excess of 10 million a year.

Encryption and wireless transmission can be integrated so digitized data can be sent wirelessly to any remote display such as a smart phone, tablet, or computer-based electronic medical record. Since the device requires only one microchip, a battery and a digital display, it can be designed to conform to any form factor such as a thumb-drive or smart phone. Moreover, the single-use design is a key advantage that addresses the growing concern for infection control in hospital settings.

Silicon BioDevices' blood analyzer can be engineered to rapidly measure a wide range of single- or multi-target biomarkers that require highly sensitive quantitative detection in any setting - including ambulances and the home. These include biomarkers for heart failure, liver enzymes, inflammation, sepsis and a wide range of other infectious disease agents.

> **Economic Impact**: On the one hand, 2% or more of patients having heart attacks are sent home, representing the single largest source of medical malpractice costs. On the other hand, billions of dollars are wasted each year caring for patients unnecessarily admitted with benign chest pain. Accurate POC testing, which gives results in under 15 minutes, can substantially reduce both types of errors by providing results sooner, and for those patients admitted it can reduce the average total admission time by 30% and total charges per admission by 25%, resulting in millions of dollars of savings per emergency department per year.

For more information, contact Octavian Florescu, 510.292.6260, octavian@siliconbiodevices.com

Wireless HART: Open Source Protocols for Wireless Sensor Networks

One of the first international wireless sensor standards to emerge, one that UC Berkeley professor Kris Pister helped draft, is known as Wireless Highway Addressable Remote Transducer or "Wireless HART." His previous work with "SmartDust" (see "Radio-Equipped Wireless Sensors called "Smart Dust"" on page 9) offered an advantage with an up to a 100:1 reduction in installation costs of new sensors. This is because installations do not require wiring to connect to the sensor networks. Quite simply, the "Wireless HART" protocol untethers a multitude of pre-existing industrial sensors previously connected and communicating locally over physical wires and globally via modems over the switched telephone network. It enables a pending swarm of up to a trillion connected sensors.
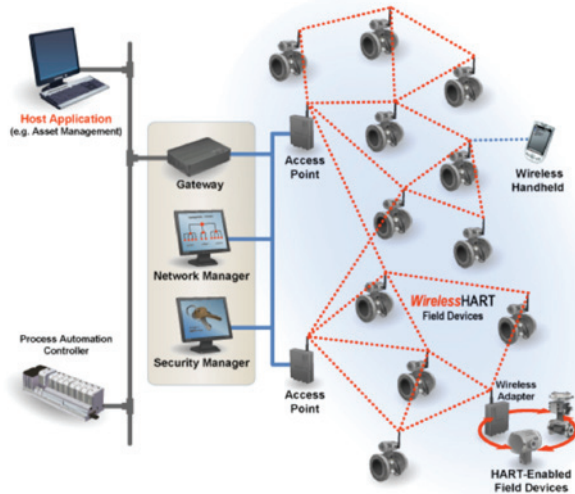
Wireless HART: Expands or Replaces Wired HART Networks with Economic & Reliable Wireless Devices in a MESH Network with no Change to Host Applications

Illustration courtesy Hart Communications Foundation

The work started as a modest effort involving an "Open Wireless Sensor Network" or OpenWSN by BSAC scientists at the University of California. This work helped foster and support industry standardizations by the International Institute of Electrical and Electronics Engineers (IEEE), the world's largest association for the advancement of technology, by the International Society of Automation, and soon by the Internet Engineering Task Force. BSAC Professor Kris Pister helped initiate efforts to fill this need with issuance of a series of software communications protocols "out in the open" (publicly available to all parties, without charge).

Cell phones are arguably one of the most important and impactful consumer product ever. These devices will soon be speaking wirelessly to local sensor networks using WSN radios and protocols. The smartphone, by accessing these emerging arrays of external sensor networks, will enhance healthcare and fitness as well as enable context awareness and control and a multitude of information-enabled applications that have not yet been conceived or invented. The synergies of the wireless sensory swarm and the smartphone are becoming truly transformative to the communications industry and to the personal lives of hundreds of millions. Smartphones already speak to a very small number of other electronic devices using wireless standards such as Bluetooth.

> **Economic Impact**: More than a billion smartphones were shipped in 2012; many were so called "smartphones" with touch screens, cameras, compasses, navigation aids, even built-in projectors and significant computational capabilities. "Wireless HART" makes the previously wired networks wireless. This is accomplished with virtually no change to the (HART) language spoken by the sensors or to the massive hundred-billion dollar industrial control infrastructure of which these sensors are a part. Qualcomm has funded a new research laboratory at UC Berkeley called the "SWARM Lab" to stimulate amazing new WSN applications, testbeds and industry collaboration. Several BSAC faculty co-Directors are important contributors to the work underway in this laboratory, much of which might not exist without some of the pioneering work of Pister and other UC Berkeley researchers who with their technical leadership as well as scholarship, inspired new

generations of engineers. Qualcomm continues to invest in wireless health and other connected applications.

For more information, contact Kris Pister at the University of California, Berkeley, 510.643.6690, reception@bsac.eecs.berkeley.edu, pister@eecs.berkeley.edu.

MEMS-Based Timing Components

Today (and for most of the past century), electronic systems depend upon or have depended upon quartz crystals for generation of basic timing signals. That is about to change. Microelectromechanical systems (MEMS) include an important class of devices that "resonate" at high frequencies and that can be used to create precise electronic timing and frequency-selective systems. These promise to change the way electronic systems derive their timing.

Several BSAC-inspired startup companies including SiTime (co-founder BSAC and co-Director Bernhard Boser), Harmonic Devices (acquired by Qualcomm), and Silicon Clocks founded by former BSAC co-Director Roger Howe and BSAC post-doctoral researcher Emmanuel Quevy (acquired by Silicon Labs), and current and former BSAC industrial member companies including Japanese NDK, and University of Michigan startup Discera Corporation (founder BSAC and co-Director Clark Nguyen) have been introducing quartz replacement technology based on these MEMS resonators.

MEMS resonator-based timing components (left) will likely be embedded in most computing and mobile devices (above).

Image courtesy of SiTime Corporation.

Before end of this decade, it is nearly certain that high frequency filtering required for all mobile devices including cellular telephones and mobile computers as well as communications systems for wireless sensor networks, will depend upon integrated components with thousands of interconnected MEMS resonators. These will perform most of the radio frequency filtering functions currently done with external discrete surface acoustic wave (SAW) and discrete Film Bulk Acoustic Resonators (FBAR) devices. At that time, more than 2 billion portable computers and mobile (cellular) telephones will make use of this technology pioneered in large part at BSAC.

> **Economic Impact**: The current US timing devices market of nearly $2B/year represents only the initial target market for MEMS timing components (source: BCC Research Inc). In 2006, this market was 99% served by quartz crystal devices. Private estimates by both crystal and MEMS technology companies suggest a MEMS resonator penetration of approximately 5% in 2012 and 10% to 50% of a $5B/year worldwide market by 2020.

For more information, contact Bernhard Boser, 510. 643.8350, boser@eecs.berkeley.edu.

Radio-Equipped Wireless Sensors called "Smart Dust"

Kris Pister of the Berkeley Sensor and Actuator Center popularized the term "Smart Dust" to help visualize his goal of an autonomous network of highly miniaturized "motes" containing microradios and microsensors that can be deployed at random; that wake up; identify who and where their neighbor motes are; and form a dynamic ad hoc self-organized mesh data network over which sensor data such as location, motion, light, pressure, temperature, etc, is communicated wirelessly, reliably and without human intervention. In 2006, Professor Pister, professor of electrical engineering and computer science at UC Berkeley, was awarded the Alexander Schwarzkopf Prize for Technological Innovation from the I/UCRC Association.

This Smart Dust story is really a story of collaborative "stone soup" in which Pister contributed the stone from a $25,000 industrial award from I/UCRC member company Hughes and a $10,000 California (state) MICRO industrial matching grant that eventually led to a $1.7M DARPA Smart Dust program.
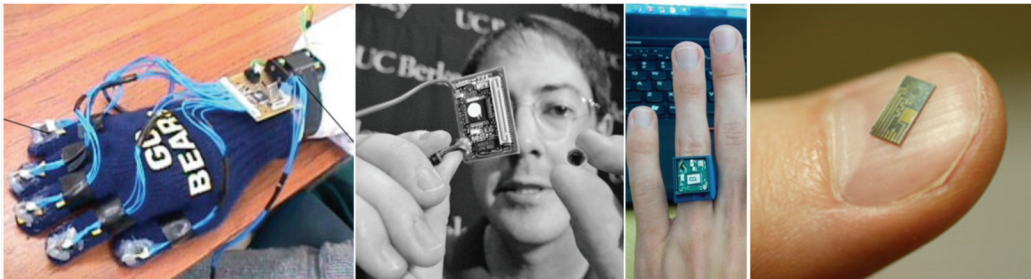
Smart Dust Evolution: inertial sensors + wireless communications
From Left: 1999 sensors & radio GLOVE..2004 BOARD…2013 RING …2016 GOAL

This work resulted in a groundswell of industrial and new venture capital investments in wireless sensor networks (WSN). UC Berkeley computer science collaborators developed an open source small footprint (4KROM, 256 bytes RAM) network operating system called Tiny OS for the little micromotes that were built from off-the-shelf components and later miniaturized. The micromotes were dropped from UC Berkeley unmanned aerial vehicles and installed at 1/100th the installation cost of wired sensors in a structure of a

sister I/UCRC: "Center for the Built Environment (CBE)" on page 41. This inspired academic and industrial collaborations that haven't subsided today. This technology was awarded the Alexander Schwarzkopf Prize for Technological Innovation by the I/UCRC Association in 2006.

> **Economic Impact:** Market forecasts of more than $8B/year made some 8 years ago by market analyst InStat* of overall wireless sensors and network components enabled in large part by the "Smart Dust revolution", were about 8 years too early; but these technology-enabled promises to revolutionize homeland security, environmental control, power management, and infrastructure monitoring are now materializing into the multi-billion dollar market envisioned. The global market for wireless sensor devices used in end vertical applications totaled $532 million in 2010 and $790 million in 2011. This market is expected to increase at a 43.1% compound annual growth rate and reach an estimated $4.7 billion by 2016.
> *Source: InStat/MDR 11/2003 (Wireless); Wireless Data Research Group 2003; InStat/MDR 7/2004 (Handsets); www.MarketResearch.com. 2012.

For more information, contact Kris Pister 510.643.6690, pister@eecs.berkeley.edu.

Biomolecular Interaction Technologies Center (BITC)

University of New Hampshire, Thomas M. Laue, Director, 603.862.2459, tom.laue@unh.edu

Center website: http://www.bitc.unh.edu/

Making Biopharmaceuticals Safer

By preventing aggregation in serum, drugs will be safer and more effective.

Protein drugs, also called biopharmaceuticals, are at the forefront of modern medicine. Of particular use are antibodies, proteins that are part of the body's immune system. Therapeutic monoclonal antibodies are used in the treatment of cancers, multiple sclerosis, asthma, and other life-threatening diseases. Delivery of these drugs is currently achieved by intravenous injection.

Pharmaceutical companies wish to develop high-concentration versions of the drugs that can be administered by patients subcutaneously at home, similar to how insulin is administered now, thus substantially reducing costs and making treatment easier.

The analytical ultracentrifuge (AUC) is widely used in academic and industrial laboratories to characterize molecular interactions, including aggregate formation. BITC funding helped develop a fluorescence detection optical system (FDS) with unparalleled sensitivity and selectivity, which is now produced commercially by Aviv Biomedical, Inc (the AU-FDS). Using the AU-FDS, it is now possible for the first time to detect antibodies and their aggregates in serum. BITC member companies are using this instrument to determine whether their therapeutic antibodies form aggregate serum after injection: the drug development and formulation divisions in Genentech, Roche, Amgen, Abbott, Boehringer-Ingleheim, Pfizer, and Johnson & Johnson either have purchased an AU-FDS to conduct these studies, or are contracting with laboratories that have an AU-FDS to make the measurements. By developing formulations that prevent aggregation in serum, drugs will be safer and more effective.

Economic Impact: Costs associated with chronic monitoring of drug effectiveness exceed billions of dollars annually. By detecting aggregate formation early in the drug development process, companies can modify or reformulate their drugs before beginning drug trials. This saves hundreds of millions of dollars annually. Lower drug development costs reduce medical costs. For example, one BITC member pharmaceutical company switched to another molecule when its original candidate molecule was discovered to aggregate in human serum. Since no clinical trials of the drug had begun, the switch to the new, non-aggregating molecule cost almost nothing

and saved the company upwards of $100,000,000 in fruitless clinical trials. There are considerable cost savings to society by making non-aggregating drugs. First, by not aggregating, these molecules are far more likely to be tolerated by patients over a longer period of time. This means that patients require less medical supervision and do not need to be switched so frequently to new drugs. It is estimated that 30 to 60% of patients must switch drugs, often several times during treatment, to circumvent aggregate-related immune responses. Reduced aggregation results in lower incidence of anaphylactic shock, a life-threatening condition. The rate of severe anaphylaxis is 1 to 3 per 10,000 patients, costing an average treatment of $10,000 per incident.

For more information, contact Thomas M. Laue, 603.862.2459, tom.laue@unh.edu.

Making Biopharmaceuticals Less Expensive
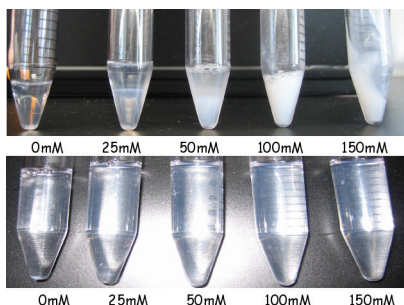
The top photo shows a protein that forms a white precipitate as the salt concentration increases. Protein drugs with precipitates cannot be injected because doing so can lead to patient death. The bottom photo shows a second protein drug that does not precipitate as the salt concentration increases. This protein was therefore a suitable candidate for injection. The first protein had to be abandoned from further development, even though $100M already had been spent in its development.

In order for proteins to remain soluble they must carry a net charge that blocks aggregation. Only those antibodies with a high net charge are good candidates for formulation. This BITC research demonstrated that: charge must be measured with protein drugs; charge can and should be measured early; and a prototype device in an academic lab could make accurate measurements. Researchers developed methods for accurately determining protein charge. The charge measurement can be made non-destructively on tiny quantities of the protein (significant since only small quantities of candidate molecules may be available).

Just as NaCl dissolves in water to form Na^+ and Cl^- ions, proteins also may be charged. The difference between the two proteins in the photos was their net charge. More charged proteins remain in solution, while the low-charged proteins aggregate and form precipitates. BITC-sponsored research has shown that only proteins that have a high net charge remain soluble. This research demonstrated that the previous methods for calculating the net charge could be exceedingly inaccurate. The methods often mislead researchers about protein's solubility. That was the case for the proteins shown in the photos.

Prior to the work by BITC, pharmaceutical companies did not have a way to measure protein charge. Instead, they calculated charge estimates based on indirect measurements. The companies were repeatedly and unpleasantly surprised to find that their therapeutic proteins were not soluble at high concentrations. Because the proteins had to be diluted, patients had to undergo long and expensive infusions in the clinic. By developing ways to determine protein charge, BITC has reduced the cost of drug development substantially. For example, companies now know that their charge estimates were too often incorrect, which is why the drugs were aggregating.

The biochemistry of cells and tissues takes place at very high protein concentrations. It is clear that charge measurements must be made a routine part of all of biochemistry and cell biology if we are to have an accurate view of how cells function. This new knowledge will be at the heart of biological medicine and will open up new horizons for how medicines are developed and used.

BITC put up the funds to help develop a commercial version of this prototype. A small company was founded to make the instrument. Workshops were held to teach researchers how to make the measurements.

> **Economic Impact:** It is estimated that the development of a protein drug costs over $1 million a day. By instituting charge determinations as part of the drug development process, pharmaceutical companies are now able to prevent drug aggregation prior to expensive clinical testing. By making the charge measurements early in the development cycle, it is now possible to weed out bad candidate molecules earlier, thus saving a tremendous amount of time, effort, and money. Because drugs will remain aggregate free up to very high concentrations, it is more feasible for patients to administer them at home, thus saving clinic costs. All BITC member companies (Genentech, Roche, Johnson & Johnson, Pfizer, Amgen, Abbott, Boehringer-Ingelheim) have instituted routine screening of candidate drug proteins early in the drug development process to determine which candidates carry sufficient charge to remain soluble at high concentrations. They now measure the charge on candidate therapeutic monoclonal antibodies before embarking on multi-million dollar drug development projects.

For more information, contact Thomas M. Laue, 603.862.2459, tom.laue@unh.edu.

Broadband Wireless Access & Applications Center (BWAC)

BWAC is a proposed center. Its predecessor was the Wireless Internet Center for Advanced Technologies (WICAT); see the WICAT entries below.

University of Arizona, Tamal Bose, Director, 520.621.6193, tbose@arizona.edu

Auburn University, Prathima Arguwal, 334.844.8208, agrawpr@auburn.edu

University of Virginia, Barry Horowitz, 434.92.0306, bh8e@virginia.edu

Virginia Tech, Jung-Min (Jerry) Park, 540.231.8392, jungmin@vt.edu

Center website: https://bwac.arizona.edu

Millimeter-Wave Propagation: Enhancing Wireless Technology

Testing wireless signals in outdoor environments.

Wireless service providers today face a bandwidth crisis that will soon impede their growth, unless solutions that provide more bandwidth, such as millimeter-wave technologies, are perfected and adopted within the next few years. As mobile data traffic continues to increase at an exponential rate, wireless services are now faced with a bandwidth crisis, as there is not enough bandwidth at lower carrier frequencies to accommodate global data traffic. While current wireless technologies provide data rates on the order of Megabits per second, millimeter-wave devices will offer users Gigabits per second, a 1000-fold increase. These millimeter-wave technologies offer a solution to the bandwidth-crisis, as there are 10's to 100's of Gigahertz of bandwidth available at millimeter-wave frequencies. Successful development of millimeter-wave systems, however, requires accurate knowledge of how millimeter-wave signals propagate and are affected by their environment. Wireless Internet Center for Advanced Tech (WICAT) researchers at the University of Texas at Austin are developing fundamental millimeter-wave propagation models that should lead to wider propagation of wireless signals in outdoor environments. The understandings gained through this research are enabling development of improved millimeter-wave mobile broadband communication technologies and systems. This research is a breakthrough in the sense that this is the first time that millimeter wave channels are studied in an outdoor mobility environment.

Improved applications of millimeter-wave wireless technologies are everywhere because the application space is broad and growing quickly. These include cellular-phones that will provide data rates of 10's to 100's of Gigabits per second. Data rates in these ranges will enable mobile users to download entire libraries worth of information in fractions of a second. Shorter-range applications, such as wireless home media-

centers, are already available, and provide consumers a hint of what is possible with data rates several orders of magnitude greater than what is currently achievable with most wireless technologies, including streaming of high-definition media content. Data centers, which are an increasingly large consumer of electricity throughout the globe due largely to the energy required to cool larger servers, will benefit from millimeter-wave wireless technologies. These data center designs will be more space and power efficient because cables will no longer prevent servers from being arranged for optimal cooling. Millimeter-wave technologies also have applications outside of traditional communications. Homeland security will likely benefit because the nature of millimeter-wave signals are more applicable for detecting motion and for identifying objects hidden under thin layers of clothing or tissue. In the near future, security personnel will likely have mobile hand-held millimeter-wave scanning devices that can detect hidden weapons. Doctors may soon have portable scanning devices that can detect tumors without the need for more expensive technologies.

> **Economic Impact:** It is clear that millimeter-wave systems will enable continued development of wireless technological and market growth. This WICAT research provides the fundamental knowledge to support the continued growth of the communications industry - which accounts for ~8% of the GDP of the United States, or more than $1 trillion of annual revenue. This leadership in the development of millimeter-wave technologies will help ensure the global competitiveness of the communication industry of our nation. By enabling orders-of-magnitude higher data rates the nation's wireless capacity, productivity and competitiveness will be enhanced.

For more information, contact Tamal Bose, 520.621.6193, tbose@arizonat.edu.

Alleviating the Mobile Bandwidth Crunch

The rapid growth in cellular wireless traffic as a result of the popularity of smart phones has assumed crisis proportions as cellular carriers have scrambled to keep up. A widely quoted study from Cisco estimates that traffic will double every year or so for the next several years. This traffic will increasingly consist of popular video applications such as video streaming, which consumes about two orders more bandwidth than a voice call. Researchers at the WICAT are working on a variety of low cost technologies to provide the required additional bandwidth. These include cognitive radio, which makes use of unused wireless spectrum in a smart way. Other avenues include the use of 60 GHz radio technology, a part of the radio spectrum
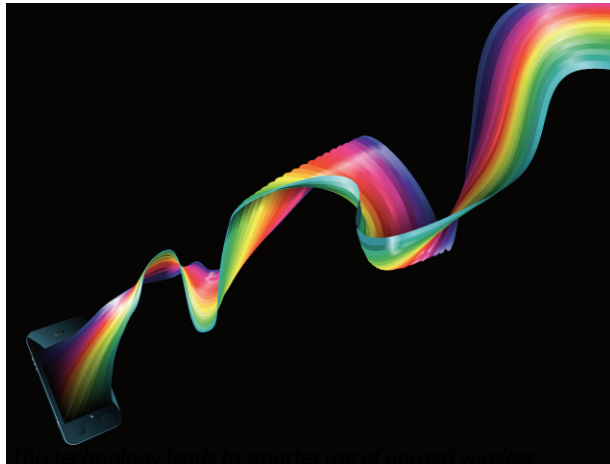
This technology leads to smarter use of unused wireless bandwidth.

which has been shown to have much higher range, and is therefore more usable, than previously reported. Advanced wireless channel aware video compression and transmission technologies will also play a part.

Finally, the notion of using relays to extend the range, coverage, and capacity of cellular networks has been pioneered by WICAT.

All of these innovations are now at various stages of adoption or consideration by the cellular network vendors, many of which are industry members of WICAT. For example, partner companies like InterDigital and Samsung have incorporated WICAT research in their future plans. WICAT has also participated in standards meeting to influence their trajectory. Once deployed by cellular carriers, these will enable new applications, many video based, that would have been infeasible without the additional bandwidth unlocked by these technologies. The focus of WICAT is to facilitate the growth of low cost, mobile access to the Internet, using innovative technology.

> **Economic Impact:** The cellular business in the United States has annual revenue of approximately $200 billion and employs over 250,000 individuals. Billions are spent annually by the carriers to keep up with demand, most recently with the upgrade to the new 4G technology. We estimate that the technologies WICAT is pioneering will save carriers tens of millions of dollars over the next decade or so by providing innovative, efficiency enhancing solutions to some major problems. This will result in lower cost for consumers and a more internationally competitive industry.

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Using Stable Isotopes to Trace Nitrogen Fertilizers in Forest Plantations

Aerial fertilization of loblolly pine plantation in the southern United States. CAFS researchers have demonstrated that use of enhanced efficiency nitrogen fertilizers can reduce volatilization losses by 15% which could save forest industry at least $15 million annually. Photo courtesy of CAFS member Thrash Aviation.

The growth of many forest plantations is limited by the amount of nitrogen available in forest soils. Researchers at the CAFS have demonstrated that forest productivity can be substantially enhanced by fertilization with enhanced efficiency nitrogen fertilizers. These enhanced efficiency fertilizers reduce losses due to nitrogen volatilization and can thus improve the crop tree uptake efficiency. This breakthrough provides foresters a new tool that can be used to improve growth and sustainability of forest plantations.

This research has increased understandings of the fate of applied nitrogen and the fundamental processes controlling nitrogen transformations in forest ecosystems. Researchers have finally determined how much of the fertilizer nitrogen was taken up by the trees and the understory vegetation,

as well as how much was retained in the forest floor and the soil at each site.

Fertilization with nitrogen can be used to increase the growth and productivity of forest ecosystems that commonly grow on relatively infertile soils. Urea is the most frequently used nitrogen fertilizer. However, recent advances in fertilizer technology have produced enhanced efficiency nitrogen fertilizers that may be more effective and have less environmental impacts than urea. In this research, CAFS scientists compared three different types of enhanced efficiency fertilizers with urea to determine how effective they are when used in forestry. They studied three of the major types of forests in the United States: loblolly pine in the South, Douglas fir in the Pacific Northwest, and walnut in the Midwest.

Results demonstrate that enhanced efficiency fertilizers can be used to reduce volatilization losses following nitrogen fertilization in forest ecosystems and that the majority of the nitrogen added to the ecosystem in the fertilizer remains. This nitrogen may be available to be taken up by the trees through time and may lead to continued growth increases.

These findings will enable foresters and land managers to more efficiently apply nitrogen fertilizers in forests. This will decrease the amount of fertilizer needed to achieve a given level of growth, which will increase financial returns and help increase the competeveness of the US forest industry. It will also reduce negative environmental impacts of forest fertilization because the precise amount of fertilizer needed can be applied to forests.

> **Economic Impact**: This breakthrough will lead to improved forest productivity and more efficient use of high cost nitrogen fertilizer. It will enable forest managers to optimize growth and minimize potential environmental impacts from excessive fertilizer use. Society will benefit from increased productivity of plantation forests (more wood from less land) with less environmental impacts. Over the last 10 years, forest industry in the southern United States has fertilized between 800,000 and 1,500,000 acres of pine plantations annually to ameliorate nutrient deficiencies and increase forest productivity and growth. Based on 2013 fertilizer prices, forest fertilization in the South currently costs around $125/acre. This translates into annual investment by forest industry of between $100 to $187.5 million. This work by CAFS scientists has shown that losses from nitrogen volatilization can be reduced by around 15%. This is allowing forest managers to apply 15% less fertilizer and still obtain the same growth response following fertilization. If enhanced efficiency fertilizers were used on all acres fertilized in the South, this could save the equivalent of $15 to $28 million in fertilizer nitrogen lost through volatilization annually.

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Refinement of Growth and Yield Models for Naturally-Regenerated, Mixed-Species Stands

Forest growth models are widely used by forest managers and researchers to forecast future growth, update forest inventory information, and assess alternative forest management strategies. Growth models are also used to test hypotheses about future tree growth and mortality patterns. Currently used computer simulation models across the Northeastern United States typically show significant biases. Because of these biases, improved growth and yield tools have recently become a top research priority by Maine's industrial forest landowners. This CAFS project has developed a computer simulation tool that better reflects present-day forest conditions and can more accurately represent alternative forest management regimes across the Northeast.
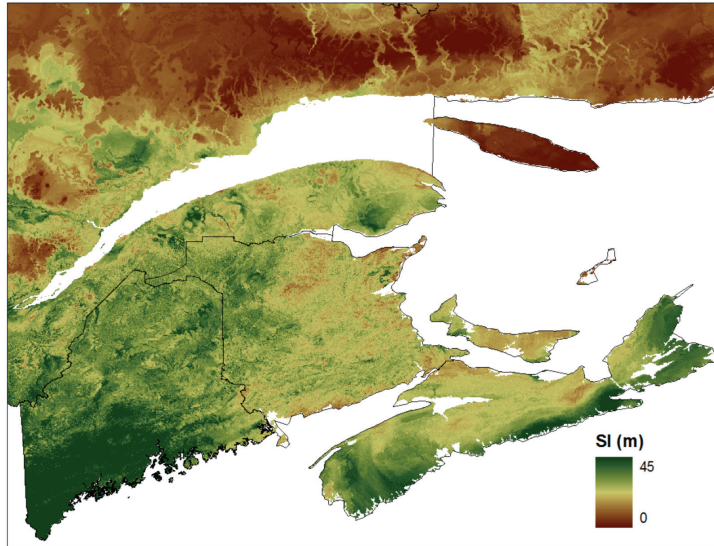
Map of current climate-derived "value of site" index (SI). Higher site indices are generally associated with higher forest productivity. The SI is a driving factor in several forest growth models like the one described here. SI is also used to stratify forestland ownership, develop forest inventory programs, and evaluate forestland values, all of which influence forest management decisions.

Compared to plantations, growth and yield models for naturally regenerated, mixed-species stands have received relatively little attention. This project also provides a tool that can be used by forest managers in a variety of settings. First, this model uses data generated from diverse sets of stand conditions and forest management regimes (>3 million observations are typical). Second, it is specific enough to predict individual tree growth in the complex mixed-species stands that comprise much of the Northeast. As a result, outputs are flexible enough to account for varying forest types and stand histories. Third, this project uses model-fitting techniques that are capable of flexibly accounting for dynamic growth patterns. At the same time, alternative measures of site productivity are being tested to find out which measures best correlate to and model forest growth. Finally, similar models are being developed to accurately represent common forest management practices such as thinning, an attribute that existing models lack.
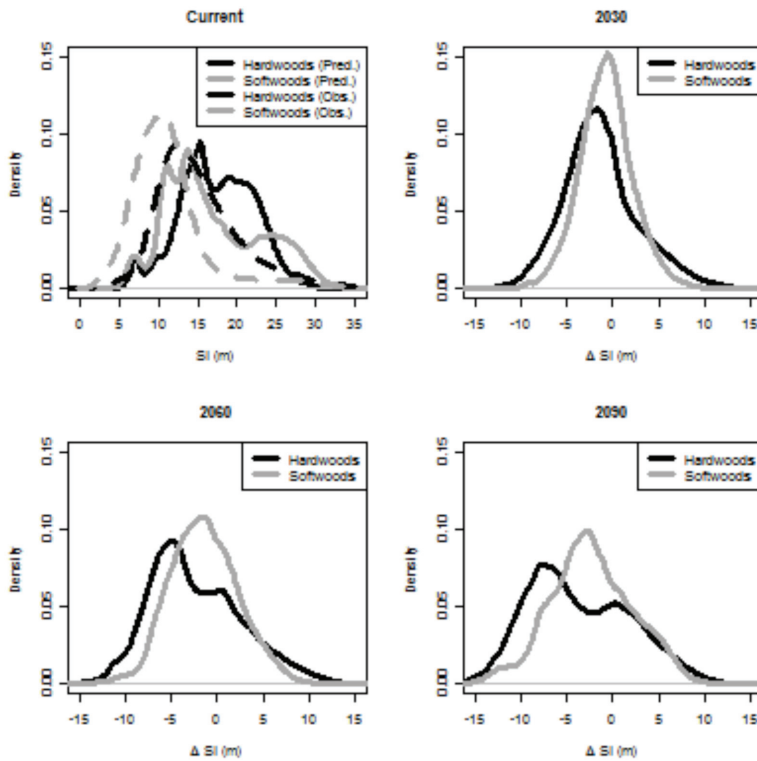
Current observed and predicted, as well as projected future change, in climate site indices (SI; m) for both hardwood and softwood species based on several downscaled global circulation models (GCM). On average, softwood species will limit change in the site index, while hardwood species are projected to decrease over the coming decades.

Economic Impact: Forest growth models allow landowners to forecast future wood supply and evaluate management alternative. As a result of this research, there has been substantial external financial and database support from CAFS member organizations for developing and testing of this new model. The reason for this strong support from the forest industry is that prediction bias for net stand basal area growth with the current Forest Vegetation Simulator Northeast Variant (FVS-NE) model is 10.7% per year of projection. Assuming a conservative board foot volume to basal area ratio of 50, this represents nearly 84 bdft/ac/yr of bias. If we multiply that across the 8.3 million acres represented by our CAFS members and using an average stumpage value ($120/Mbdft) for spruce-fir sawlogs, this represents a $83.6 million prediction error that must be born annually by the Maine forest industry alone. The CAFS modeling efforts have reduced this bias by over 75%. In addition, a useful forest science spin-off in the development of Acadian Variant of FVS was the production of a high-resolution map of current and future potential forest site productivity for the Acadian region (images above). Such maps have a number of ecological and management applications. They are currently being used for forest sampling stratification and forest management planning by several CAFS members.

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Predicting the Quality Value of Fast Grown Wood

CAFS researchers at the University of Georgia have been dissecting trees and analyzing the wood grown throughout the South under the range of forest management intensities and have put their findings into prediction models that can predict wood density, stiffness, and strength. Most importantly, they have integrated these wood quality predictions into the growth and yield models foresters use for evaluating volume gains from advanced genotypes and intensive silvicultural treatments such as weed control, thinning, and fertilization. This allows wood growers, for the first time, to incorporate the quality of wood in their planning along with the quantity of wood. Results are helping sponsors to better understand wood quality impact on forest product mix. Large timberland owner such as Plum Creek need to understand value of wood that is grown as it relates to their customers' needs. This work is a breakthrough because it enables direct predictions of value along with volume, linking the tree grower with the wood buyer and the lumber manufacturer.

A managed planation forest.

Over the last two decades foresters have dramatically increased growth rates and yields of the South's forests through intensive plantation management (advanced forestry systems). What is the quality of this fast grown wood compared to historic wood products? Until now that question has either been avoided or addressed with very limited data and a good bit of speculation. Forest landowners rely on long term forecasting models of forest growth and yield as they plan these intensive management regimes. Traditional forecasting models predict the timber volumes but do not take into account important qualities of the wood produced, such as lumber stiffness and strength. Wood growers currently do not have good understandings of the quality of the wood they are growing. There has been no region-wide consensus among wood growers on how to manage for wood quality, nor is there a broad understanding among wood products manufacturers about the value of trees grown in different ways.

> **Economic Impact:** This outcome of this project will improve how timber is grown and marketed, because it will allow wood quality and value to be factored into the long term forest management decisions. This in turn will help manufacturers better market their products to end-users. It will result in more competitive pricing for timber based on wood quality. It should also dispel myths about plantation grown wood that have negative market impacts and could improve sales of the products. By factoring wood quality into silvicultural decisions, growers may increase the proportion of high quality sawtimber by 25% or more. This could mean gains in value at harvest of $1000 or more per acre; that could easily reach $1 billion in new value annually across the South.

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Exponential Nutrient Loading

A new approach referred to as "exponential nutrient loading" has been developed by researchers at CAFS to pre-condition black walnut grafts in the greenhouse for field planting. The technique increases the morphological and nutritional quality of grafted plants, as well as stores nutrients in roots for later utilization to benefit early plantation establishment success. This protocol, allows for a higher growth rate of the grafts in their first year after planting in the field. Black walnut grafts that have been grown exponentially will be used in intensively cultivated plantings. In intensive cultivation, this is important because the response to fertigation and weed control is higher and rotation age will be decreased, which brings substantial financial benefits. In extensive cultivation, the rapid growth and competitiveness exhibited by exponentially nutrient loaded grafts will accelerate plantation growth to reach free-to-grow status sooner, which increases the chances of crops escaping damage from animal browsing and weed competition. Intensively cultivated clonal black walnut plantings are currently being offered as a financial opportunity for long-term investors.

*Northern red oak (*Quercus rubra*) seedlings that were subjected to a fertilizer dose response trial to maximize nitrogen (N) storage for use in subsequent field planting. While sufficiency was detected at 25 mg N per plant, luxury consumption occurred thereafter and so optimum N uptake occurred at 100 mg N per plant. This trial demonstrated how exponential nutrient loading, which has been previously studied for conifers, can also be applied to hardwood regeneration systems.*

Exponential nursery nutrient loading of forest trees utilizes the concept of luxury consumption whereby with increasing nitrogen (N) fertilization, tissue nutrient concentration increases in a linear manner. However, plant growth (or biomass) increases to Point A (sufficiency), beyond which luxury nutrient consumption occurs and plants continue to accumulate N reserves until Point B (optimum), beyond which toxicity occurs. The optimum fertilization rate allows for maximum storage of N to be used in subsequent field planting. Illustration credit: Thomas D. Landis
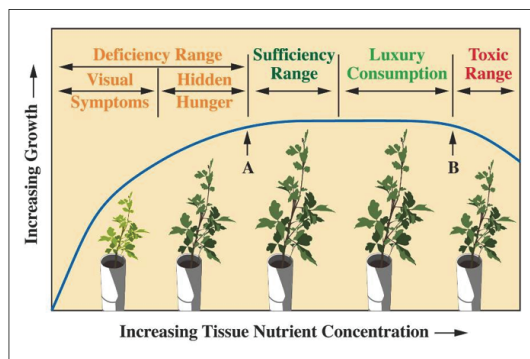
Economic Impact: In the past 10 years, forest cover has increased by 300,000 acres. Many of these acres are populated with trees produced with this new technology. This method makes possible a two-year reduction in the long-term production cycle or a 6% increase in return on investment. Based on today's prices for black walnut timber, this new method of tree production is increasing the profitability of one CAFS corporate partner by an estimated $8 million over the expected production rotation period. This corporate partner employs over 50 staff annually. The increased profitability allows the company to maintain its current level of employment. This technology has been adopted by a number of large public nurseries. It is increasing their competitiveness by allowing them to sell higher quality products and thus stay more competitive in the current recessionary market. Consumers who buy these products from public nurseries experience increased success in plantation establishment and increased return on their investment.

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Precocious Flowering in Populus

Trees have not been domesticated to the same extent as agronomic row-crops because of their extended juvenile periods. Moreover, significant amounts of sugars fixed as a result of photosynthesis are diverted away from vegetative growth (e.g., stems, branches, roots, and leaves) to form reproductive structures (e.g., cones, flowers, seeds, etc.) after trees have undergone the transition to maturity.

Federal regulators have made it clear that a transgene confinement system is likely to be needed before genetically engineered trees can be deployed commercially. CAFS researchers are attempting to genetically engineer flowering control as a way to satisfy this requirement.

In order to test the efficacy of the genetic constructs inserted in the poplar genome for their ability to affect

CAFS scientists now have a variety of effective model systems for testing flower-control constructs, without having to conduct lengthy, expensive field trials.

floral development, researchers must wait for plants to acquire the competence to produce flowers. The long delay before the onset of flowering in poplars (they have a juvenile period of five to seven years) and their resistance to various conventional flower-induction treatments have been serious impediments to engineering sterility. CAFS researchers obtained a genotype of *Populus alba* from the University of Tuscia (Viterbo, Italy) that flowered nine months from when the seed was sown. Vegetative propagules from this line remained true to type (i.e., they flowered in nine months). However, this genotype had to be regenerated in vitro and grown under aseptic conditions before it could be imported into the United States. The regeneration process caused this genotype to lose its ability to flower early. CAFS researchers experimented with a variety of inductive treatments and discovered one that restored the early-flowering phenotype. Center researchers have also obtained a genotype of *Juglans regia* that is capable of producing flowerings on nine-month-old plantlets and have identified conditions required to induce flower formation on *Prunus serotina* grown in vitro.

Economic Impact: It is estimated that annual value of the United States poplar industry is about $300 million. Poplars are grown for fiber to manufacture paper, window and door casings, moldings, pallets, core stock for plywood, and, increasingly, as a feedstock for biofuel production. Through better understandings of the process by which trees control the onset of flowering, it may be possible switch flowering on or off at will, through genetic engineering. This will shorten breeding cycles. This will allow for more rapid selection of trees that produce more biomass and are resistant to various biotic and abiotic stresses, thus minimizing economic losses and increasing profits. Preventing flowering allows for more photosynthate to be used for vegetative growth. Because there are so many tree species grown for a diverse range of products, it is difficult to quantify the benefits associated with this technological advance.

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A CISE-funded Center

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Autonomous Lighter Than Air (ALTA): Sub-centimeter Aerial Photography

Lower than a plane, higher than any street view, Autonomous Lighter Than Air (ALTA) platforms provide a brand new vantage point. ALTA is a smart balloon that transmits images and environmental information from distant locations. ALTA models may be tethered to continuously monitor specific patches of land or sail on air currents along predicted wind-driven paths.

Autonomous Lighter Than Air (ALTA) Platform and its view of Washington DC.

ALTA's remote-controlled, smart balloons transmit to the Internet geo-referenced super-resolution, oblique imagery, as well as air quality data. The US patented, Federal Aviation Administration (FAA) compliant technology operates from otherwise unreachable places, higher than ground cameras and lower than most planes. Its low cost makes frequent updates cost effective. The ALTA balloons' (R series) ability to operate at low altitudes makes possible aerial photography with unprecedented detail. ALTA's image clarity is not hampered by propulsion vibration or cloud cover. Because of these advantages, ALTA photography often yields higher fidelity images than are produced by other geo-referenced imagery.

Atmospheric graphical information can be attached to the images to depict air quality and other atmospheric data. The ALTA imaging technology http://altadrifter.com is being combined with TerraFly at http://TerraFly.com, see Figure , "TerraFly Maps Enable Monitoring of Airborne Cameras," on page 31. As such, it will be provided as a service via http://TerALTA.com. The ALTA team services public safety, news agencies, agriculture, construction, real estate, travel and tourism. A demonstration prototype is at http://cake.fiu.edu/ALTA.

Economic Impact: ALTA opens a new multi-billion market for aerial photography as it produces images that are orders of magnitude higher resolution than the current state of the art. Image collection is currently accomplished from ground-based cameras, aircraft or satellites. Because ALTA is higher than ground-based cameras, it sees more. ALTA is lower than an aircraft and therefore sees better. Additionally, compared to other aerial platforms, ALTA has low cost components. For the capital outlay of one manned aircraft, 300 ALTAs could be purchased; balloons are also dramatically cheaper than drones. It costs $100 to build one ALTA. It costs many thousands dollars to build other aerial platforms. Operations costs also are a fraction of what other aerial collections cost. ALTA missions eliminate cost of pilots, aircraft, and airports.

In addition, ALTA can be deployed in minutes and have information and images returned instantaneously. The ALTA technology is thus poised to produce much higher-quality imagery at much lower cost than current technologies, thus opening up new markets and bringing new capabilities to existing markets such as public safety, real estate, construction, environmental monitoring, disaster mitigation, and disaster recovery. By economically providing virtual "see for yourself" access, ALTA imagery will capabilities to civic and real estate land data and imagery, which are already multi billion dollar markets. In addition, it is expected that retail markets of socially networked users will approach hundreds of billions of dollars. It can also be used in public safety, homeland security, government and military arenas wherein ALTA can replace UAVs and drones with lower cost and longer, more stable flights, the potential markets are estimated to be in excess of $500 million.

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Automated Asset Management in Data Centers

Capture Rack ID + Asset image with iPad

Identify asset from image and compare with the entry in the database

Overlay real time server health on iPad

Raise alarm if servers are misplaced
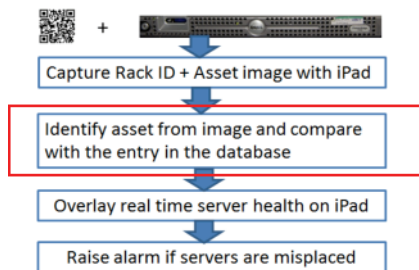
Visual identification of computing assets for efficient data center operations

CAKE researchers at Florida Atlantic University developed an innovative solution for visual asset identification using visual features of an image. Visual features of asset images are computed using complex mathematical methods. These visual features are used to identify and match asset images. A database with visual features of asset images was built for every distinct asset that is typically present in large data centers.

A data center is a facility that hosts computer systems, servers, power supplies, storage systems, and other related computing equipment, referred to as assets. The size and number of these data centers are continuously increasing to accommodate the need and demand for web based applications and services. Assets are mounted in racks and a typical rack can accommodate up to 42 assets depending on the asset size. Large data centers have thousands of racks and keeping track of these large numbers of assets manually makes it very tedious and highly prone to errors.

Human errors continue to be the greatest cause of unplanned downtime in data centers. Downtime of assets in data centers lead to slow or unavailable information services on the Internet. Solutions that minimize human input in asset management will lead to higher productivity and reduced downtimes.

Portable devices such as tablets and mobile phones are ideal devices to perform asset management operations in data centers. Information technology (IT) personnel can effortlessly carry these devices in data centers to conduct management operations. Such devices have become computationally powerful and are equipped with cameras and other sensors. Cameras on these devices provide a unique opportunity to simplify asset monitoring in a data center. Cameras on mobile devices can be used to visually recognize the assets in a rack and provide real-time information about the operating health of the assets. With a camera-based solution, IT personnel have to just point the camera at a rack and select the device to monitor. Any mismatch between the asset identified in the rack and the asset that was expected is immediately flagged. Additionally, the health of the asset is instantaneously displayed on the mobile device without having to login to the asset.

Assets needing identification are captured using a camera on a mobile device. The device then extracts and transmits the visual features to the server for matching and asset information retrieval. This breakthrough, an optimized version of visual feature extraction and comparison methods, was developed to improve matching accuracy and reduce computational complexity of feature extraction as well as matching. This innovation introduced methods to prioritize and reduce the number of visual features used to identify and match asset images. This reduction in complexity enables efficient asset management solution on mobile devices.

Data Center Rack

Assets in data center racks are identified using the camera on a tablet and real-time asset information is displayed on tablet.

This work represents an improvement over previous state-of-the-art technology because it introduces simplified asset management tools based on visual features of assets. This innovative asset management system allows IT personnel to assess the state of computing assets by just pointing a mobile device camera at the asset.

Economic Impact: The advantage of this process is that it enables immediate identification of problematic assets using real-time operational data from the assets without having to explicitly and manually logging into the asset management system. This leads to reductions in data centers' operational costs by using relatively inexpensive portable devices, such as mobile phones and tablets to minimize human errors, while improving productivity and reducing downtime. According to Emerson's Networks white paper, the average cost of a single data center downtime event was approximately $550,500 or $5,600 per minute; or one third of the total cost when indirect and opportunity cost was taking into consideration. This illustrates the importance of this project and the potential impact on this industry sector. This new approach to asset management using visual asset identification methods and mobile devices has the potential to significantly reduce the time spent on identifying problems in data centers. This should lead to improved uptime of servers and computing assets and thus increase the profitability of information service providers. Improved uptime of computing assets has direct impacts on the revenue generated in the Internet economy. The economic impact could total multibillions of dollars. This technology is being deployed in commercial products. Doing so requires minimal research and

development. In addition to favorable economics, implementation of the technology will relieve pressure on data center management thereby reducing chances of consumer dissatisfaction over delayed or unavailable services and minimize any economic impact on the service providers.

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System for Reducing Hospital Readmissions
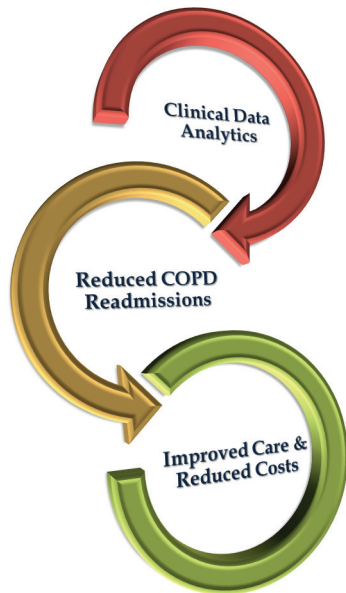
Reducing COPD readmission costs through analytics

In the United States., hospitalization is one of the largest factors impacting healthcare expenditures. Hospital readmissions are one of the indicators of the quality of care. Hospital readmission rates have direct monetary relationships with patients' financial burden and the government/private medical care organizations such as Medicare, Medicaid, and insurance companies.

There is enough evidence to conclude that almost 70% of readmissions are related to four diseases. These are Congestive Heart Failure (CHF), Chronic Obstructive Pulmonary Disease (COPD), Diabetes (DM), and Syncope (fainting or passing out). Deploying technologies to avoid such readmission should not only improve the quality of patient care but should also help offload a great deal of mounting financial burden.

Researchers at CAKE, in partnership with Soren Technology, developed a system for reducing hospital readmissions. The system integrates several telemedicine, patient care coordination, and clinical decision support systems to identify patients at high risk for re-admission. This is all based on data mining and a statistical analysis engine. The current system focuses on the readmission issues related to COPD.

Predictive modeling of readmission is a complex effort. This work represents an improvement over previous state of the art because it enables comprehensive autonomous statistical analyses based on the mining of patient data using a unique process/algorithm. The clinical decision support system developed at CAKE is designed to predict hospital readmission risk for COPD using electronic health records (EHR) information. The COPD clinical decision support system is based on predictive analytics using structured and unstructured patient data to develop a readmission risk profile for a patient being discharged after an initial COPD related hospital admission. The data in most hospital systems are unstructured, such as in physician's notes, patient discharge summaries, and X-ray radiology reports. In this new approach, information is extracted using a breakthrough clinical natural language processing system. This system automatically extracts useful information. It identifies in patient records the use of clinical named entities such as diseases and disorders, signs and symptoms, anatomical sites/ and procedures, and drugs. This information is combined with structured data from EHRs that include relevant laboratory test results and appropriate non-clinical patient demographic data. The system then uses statistical models to predict the patient's readmission risk. This CAKE system enhances prediction reliability by integrating unstructured

and structured data. Since readmission rates have remained nearly constant for the past few years, such efforts are not just timely, but they are also critical in helping improve quality of service while reducing associated healthcare costs.

> **Economic Impact**: A study reported in 2009 that 19.6% of Medicare fee-for-service beneficiaries who had been discharged from a hospital were readmitted to the hospital within 30 days, 34.0% within 90 days, and more than half (56.1%) within one year of discharge. MedPAC also reported that readmissions, within 30 days accounted for $15 billion of Medicare spending. Medicare is the payer for about half of these readmissions. Current data shows that COPD accounts for about 22% of readmissions, hence taking this into account together with the 76% of preventable readmissions yields a 16.7% of potential readmissions reduction or potentially over $4 billion of annual savings. This new decision support system is well positioned to help quantify these savings. Hospitals and clinics can integrate the developed system with their current medical information systems to leverage clinical data and provide meaningful clinical decision support. This should result in improved care and reduced hospital readmissions. The system can be further expanded to include other diseases such as Congestive Heart Failure (CHF) that would further reduce the overall hospital readmissions and thereby provides much higher savings. While this technology will have significant economic impacts through cost savings associated with reduction in COPD hospital readmissions, the greater potential economic impact could be realized as the solution is expanded to include other diseases and chronic medical conditions.

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TerraFly Maps Enable Monitoring of Airborne Cameras

TerraFly is a technology and tool for the visualization and querying of geospatial data. It provides users with the experience of virtual "flight" over maps comprised of aerial and satellite imagery overlaid with geo-referenced data. The data drilling and querying component of the system allows the users to easily explore geospatial data, create geospatial queries, and get instant answers supported by high-performance multidimensional search mechanisms. TerraFly's server farm ingests, geo-locates, cleanses, mosaics, and cross-references 40TB of basemap data and user-specific data streams. The interface allows rapid deployment of interactive Web applications. It is accessible from anywhere via any standard Web browser, with no client software to install.

Although video surveillance recording is the state of the practice, the video collected is normally used only after the fact - it cannot easily be accessed in real time, does not have accurate geolocation capabilities, and cannot be easily integrated with other forms of critical information. This state-of-the-practice lack of situational awareness will be overcome by the Context Aware Rich Media Extensible Middleware technology (CARMEL) TerraFly system. This system integrates cutting-edge CARMEL technology from IBM Research Haifa (http://www.haifa.ibm.com) with the TerraFly Geospatial System at CAKE. The CARMEL-TerraFly system provides geographically anchored streaming services, delivered via IBM's state-of-the-art technology and accessible via TerraFly's intuitive spatio-temporal interface. This integrated system offers innovative situational awareness technology, while helping expand the Center's international influence and connections. By combining IBM Haifa's Geographic Information Systems (GIS) and streaming technology research, CARMEL is a geographically anchored, video-on-demand streaming infrastructure that provides: 1) scalable, end-to-end low-delay and resilient streaming technologies; 2) on-demand bandwidth

adaptation (transcoding); 3) highly accurate geographical searches; 4) real-time, geo-located notification; and, 5) high performance, service-oriented, architecture-enabled technologies.

The novel CARMEL-TerraFly technology is transforming public safety assurance systems. It is also making possible more timely responses to situations by providing geographically anchored streaming services. These can be combined with and accessed via the intuitive TerraFly user interface. Users are able to select a geographic area of interest, retrieve multimedia data from sensors in the area, and view streaming video of moving objects in real time (e.g., vehicles, people, animals, etc.). Users are also able to set temporal and geographic constraints to view the path traversed by a specific moving object or group of objects.
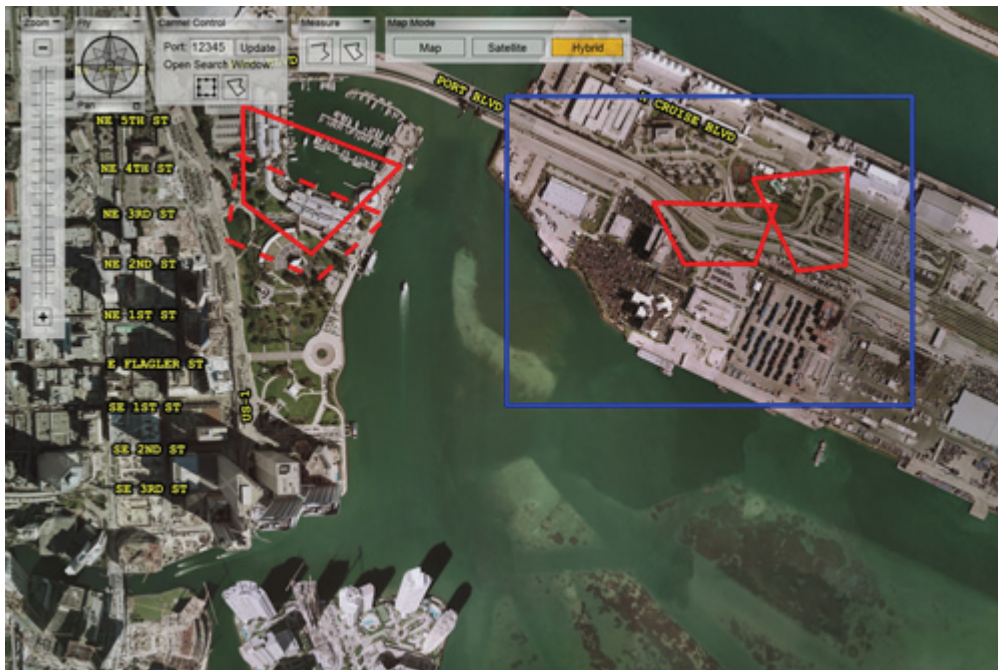
CARMEL-TerraFly user interface. The map shows the Port of Miami with moving traces of areas videotaped by airborne cameras. Solid trapezoids are ground projections synchronized with playback and dotted trapezoids are real-time projections of camera views. The blue rectangle allows selection of video fragments at times and locations of interest.

There are numerous potential applications for this advanced technology, particularly for command and control operations such as homeland security, law enforcement, and disaster response. For example, using the CARMEL-TerraFly system, law enforcement could be alerted to a situation such as a hit-and-run accident. Officers would be able to quickly pin-point the geographic location, view streaming media of the current location to quickly assess the situation, and, through the use of additional sensors, track the offender's vehicle.

Economic Impact: The potential economic impact of CARMEL-TerraFly is substantial because it can be a cost-effective public safety tool. It reduces law enforcement costs, increases effective-

ness of situational evaluations and responses, and contributes generally to the economic improvements of municipalities and regions. Litigation costs should also be decreased as more timely and accurate evidence becomes available for use in and out of the courtroom. In addition, the system could improve the effectiveness of situational evaluations and subsequent responses by providing tools for better resource allocation, thus improving the safety of responders and the public, ultimately saving lives and property. Finally, use of this system could ultimately reduce crime, which, in turn, would lower the cost of doing business and contribute to local and national economic improvement. CARMEL-TerraFly is the subject of an NSF SBIR Phase II project awarded to NOA, Inc., DBA TerraFly. IBM and NOA, Inc. have entered into an agreement concerning the project and are currently in the process of strategizing how best to propose the CARMEL-TerraFly System to government agencies in addition to the current CARMEL clientele. To support this, IBM and NOA Inc. have already produced a showcase video (please see: http://cake.fiu.edu/Carmel-TerraFly-video/). Our estimate is that this project will be producing $5 million in annual revenues by 2017 and will have beneficial consequences to consumers in the range of $50 million per year.

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Business Continuity Information Network: Faster Community Driven Disaster Recovery
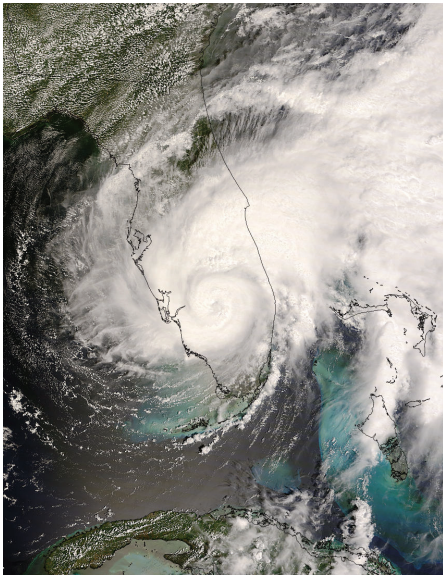
Technology used during the storm Fay, which impacted Florida.

In coastal areas throughout the United States, information sharing is critical for community resilience and protection of economic interests. Studies indicate that following hurricanes, approximately 40% of companies fail within 36 months when they were closed for 3 or more days. Years of meteorological data have demonstrated that South Florida is particularly prone to extensive damage from hurricanes. There are a myriad of toolkits, checklists, and other business continuity tools available that address how to prepare businesses for disaster. None of these stand-alone tools provide a means for business users to connect with local governments to monitor ongoing situations before, during, and after natural disasters.

The Business Community Information Network (BCIN), at CAKE, provides a platform for public and private sector communities to work in a coordinated fashion, providing the right information to the right person at the right time in the right format. Florida International University, its public and private sector partners, including Office Depot, Wal-Mart, IBM, the Greater Miami Chamber of Commerce, and county and city government agencies, have developed BCIN; a unique information sharing web-based software that provides a means for

at-risk local businesses to receive and share timely and vital preparedness, response, and recovery information. This information helps protect critical infrastructure and provide high demand recovery resources.

CAKE researchers have captured processes, workflow, and continuity "best practices" in an intuitive user interface that displays, queries, and reports on over 26 different situational categories such as ports, roads, utilities, fuel, and other critical infrastructure and recovery resources. The BCIN is available year-round as a service. This business-to-business community network provides participating companies with a new powerful tool to track their key employees and supply chain status and locate needed recovery goods and services. The system helps government agencies assess damage and prioritize recovery needs.

> **Economic Impact:** Based on training exercises, surveys, and other feedback, our participants feel they will significantly benefit by utilizing the system and its capabilities. Information sharing is critical for community resilience and overall economic well being in coastal areas throughout the United States. Since May 2009, the system has been operational in four South Florida counties: Miami-Dade, Broward, Palm Beach, and Monroe. The system was tested in response to storms Fay (see photo), Gustav, and Ike and used in numerous state and local hurricane and terrorist disaster training situations. Hundreds of individuals from government agencies, NGOs, and businesses have been acquainted with and trained on the system. Based on data from the Insurance Information Institute, if 5% of the companies in South Florida could gain the capability to speed up their hurricane recovery by one week, then $220 million of non-property economic losses could be avoided.

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Distributed Cloud Computing: 3-D Visualization Services for Climate Data on Demand

This breakthrough results from very successful collaborations involving two I/UCRCs, the Center for Advanced Knowledge Enablement (CAKE) at Florida International University (FIU) and Florida Atlantic University (FAU) and the Center for Hybrid Multicore Productivity Research (CHMPR) at the University of Maryland, Baltimore County (UMBC). See the entry called "Distributed Cloud Computing: 3-D Visualization Services for Climate Data on Demand" on page 97.

Satellite imagery enables precise measurement of global temperatures. This image presents the 8-year global average surface temperature (as Brightness Temperature colors higher on the scale are representative of warmer temperatures); by comparing successive average surface temperatures, global temperature changes can be detected.

Measuring the surface temperature of the entire earth on a daily basis is a difficult challenge because 75% of the planet is covered with oceans and ice. Continuously determining, for several days to weeks, the vertical thermal (i.e., temperature) field around a hurricane surrounded by dynamically rotating clouds is needed for more accurate landfall predictions. Thus, for applications ranging from climate change to hurricanes, satellites measure the earth's emitted infrared radiation twice daily with sufficiently high spatial and spectral (related to the spectrum) resolution to provide an estimate of vertical profiles of regional or global surface brightness temperature (BT). However, in order to assess global warming, these temperatures need to be measured to within an accuracy of 0.10 °C per year since models indicate CO_2 warming of ~20-30 °C over 100 years. Moreover, to resolve the structure around hurricanes, infrared data at resolutions of 1-5 km are needed. Not until 2002, when the Aqua (Latin for water) satellite was launched, has there been a single satellite with instruments that can meet both the accuracy and the precision required.

This breakthrough work makes it possible to deliver a decade of 3-D animated visualizations of spectral infrared (IR) satellite radiance data from instruments on Aqua. These animations use 3-D to show the vertical structure of a decade of global and regional temperature trends occurring at the surface and lower troposphere. In addition, the algorithms developed by CHMPR have been providing CAKE with 3-D temperature profiles that specify the thermal structure around hurricanes in order to improve their landfall prediction.

Center for Advanced Knowledge Enablement (CAKE)

Atmospheric temperature layers up to 20,000 meters (65,619 feet). The vertical axis shows the height above sea level. The coldest (blue) and hottest (red) points in the eye of the hurricane are shown. The horizontal axes show the location of the hurricane (latitude and longitude).

CAKE and CHMPR have implemented a distributed cloud computing web-based service, called SOAR. This service incorporates visualization as a public service available on a multi-core IBM-based server cluster. This system provides researchers and students with the ability to select regional and chronological periods and automatically transform IR orbital satellite data into spherical grid arrays of 3-D temperature profiles for viewing the continuous changing thermal structure of the atmosphere. The FIU site at CAKE added value to the satellite data visualization by providing spatiotemporal (i.e., space-time) visualization and animation of the data (http://cake.fiu.edu/SOAR) using the FIU TerraFly Geospatial Data Management Service (http://terrafly.com). The FAU site at CAKE developed tools for 3-D visualization of the vertical temperature profiles; when coupled with CHMPR's data-gridding techniques, this partnership has created the first integrated, scientifically-validated, multi-year infrared brightness temperature record.

Economic Impact: Fundamental Decadal Data Records are highly desired products recommended by the National Academy of Science/National Research Council. The SOAR distributed cloud computing web-based service enhances NASA's ACCESS program by providing fundamental brightness temperature records. This can go a long way towards improving scientific and public understanding of the nature of global and regional climate change. As a result, everyone can be better positioned to design policies and actions for mitigating negative climate impacts on the economy, which could include billions of dollars of property value lost to sea-level rise and billions of dollars of insurable losses due to increases in extreme weather-related disasters.

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Center for Advanced Processing and Packaging Studies (CAPPS)

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Center website: http://www.fst.ohio-state.edu/CAPPS/index.html

Continuous Microwave Sterilization of Fluid Foodstuffs

Research at the Center for Advanced Processing and Packaging Studies (CAPPS) has developed technology that allows fluids to be continuously and very rapidly heated, in a tube, by a focused microwave source. To eliminate microorganisms, the food must be exposed to a certain target temperature for a defined period of time; slow heating will degrade the quality of food during heat-up. This is a particular problem with highly viscous fluids that tend to have poor heat transfer rates from a heated wall. By conducting heat with microwaves, heating rates can be substantially increased with dramatic improvement in quality, without the need for scraped surface heat exchangers and large surface area heat exchangers. Continuous microwave processing may be further extensible to food systems with particulates.

Equipment for pasteurization will benefit from continuous microwave sterilization technology.

Aseptic processing of fluid foods has been practiced by industry for a fairly long time, but the quality of foods produced conventionally, by indirect heat transfer through the walls of a tube, has been limited by the rate at which the food can be heated to pasteurization/ sterilization temperatures.

Economic Impact: Continuous microwave processing makes possible a number of viscous food products to be prepared with a significant improvement in quality. It should result in substantial economies in the food processing industry.

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Center for Advanced Studies in Novel Surfactants (CASNS)

In 2008, CASNS was absorbed into CPASS (the Center for Particulate and Surfactant Systems), also at Columbia University

Columbia University, Ponisseril Somasundaran, Director, 212.854.2926, ps24@columbia.edu

Center website: http://www.columbia.edu/cu/iucrc/

Greener, More Sustainable Solutions for the Mining Industry

Mineral separations have been becoming increasingly challenging due to the emergence of problematic ores in several existing operations. It is well known within the mining industry that in selective flotation separation of valuable minerals from complex ores, certain silicates and slime-forming minerals have significant detrimental effects. Until recently, such effects were attributed to chemical factors such as hetero-coagulation between the silicates and valuable minerals, which is generally referred to as slime coating. Previous approaches to this slimes problem have been unsatisfactory because they consume too much energy and water and are not sustainable.

Researchers at CASNS, in cooperation with Cytec Industries and centers' sponsor Vale-Inco, have developed new techniques to study rheological properties of such ore pulps. This research program, which was designed to develop a scientific understanding of contributions from both physical and chemical factors of slimes to selective mineral separation and suspension rheology, has discovered the large role played by morphology of certain silicate minerals, when present in even small amounts in a complex mixture of minerals.

Less harmful sludge and more efficient separation of valuable minerals from complex ores leads to greener and more profitable mining.

When the CASNS research program was initiated, there were no established methods to monitor the rheological properties of ore pulps, which typically have a wide size and specific gravity distribution, due to difficulties caused by the rapid settling of coarse and heavy particles. These techniques are based on sedimentation and determination of various rheological parameters such as viscosity, yield stress, and torque values at high shear rate.

Economic Impact: This advance has made smelting more energy efficient. Findings have led to the derivation of better pathways for enhancing selective separation of valuable minerals from complex ores containing slimes and development of robust solutions to the long-standing prob-

lems related to slimes. Most importantly, this work has resulted in the design of greener, more sustainable solutions for the mining industry: new processes that consume less water and energy. They use green reagents that significantly reduce the overall environmental footprint of mining. This has made the mining industry more economically productive. It should extend the lifetime of existing mining operations and save jobs and resources.

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Novel Technologies for Superior and More Sustainable Consumer Products

This work leads to more effective use of surfactants generally in cleansing product lines and to higher performing products.

Researchers at the Center for Advanced Studies in Novel Surfactants (CASNS) studied complicated systems that involve interaction among multiple ingredients, including surfactants, polymers, enzymes, solid particles, solvents, and electrolytes in water and with substrates such as skin and fabric materials. They examined novel materials and commercial ingredients in attempts to identify greener, more environmentally friendly cleaning ingredients.

By investigating the physical properties and micro-structures of surfactant systems and their associations with material performance, the researchers were able to advance the science that led to a new generation of less expensive product formulations that continue to have equal or higher performance characteristics and smaller environmental footprints.

This research enabled the development of a newer generation of laundry detergent formulation that had better textile skin feel, greater resistance to pH variation, more robust profiles of stain removal in the laundry washing process, and was more cost effective. It led to more effective use of surfactants generally in cleansing product lines and to higher performing products.

Economic Impact: This work is providing opportunities for member companies in their R&D efforts to develop products with higher performance and lower costs and smaller environmental footprints. It is providing a knowledge base and framework of learning for industrial applications in the personal care and household cleaning sectors. Applications of this new knowledge are impacting the production and quality of soaps, shampoos, and other cleaners, thus making them milder, less irritative, and more effective.

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Center for Advanced Vehicle Electronics (CAVE3)

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Center website: http://cave.auburn.edu/

New Experimental Techniques to Study Solder Materials and Processes

Work in CAVE3 has led to the development of several new innovative experimental techniques to study solder alloys. A unique scanning electron microscope has been developed that allows for real-time and in-situ studies of the melting, wetting, and spreading of solder alloys and pastes. The system allows for microscopic observation of the advancing molten solder with simultaneous analysis of alloy-substrate chemical reactions during wetting. It is highly unusual to undertake studies of liquids in expensive and high-performance vacuum systems due to potentially high vapor pressures and flux outgassing.
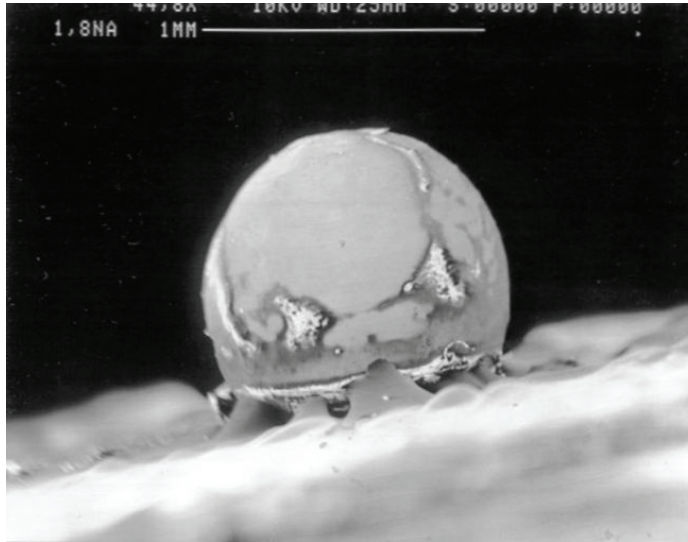
A molten solder ball.

In addition to the ability to study molten solders, CAVE3 is the first organization to develop a scanning electron microscope to measure strains in materials during repetitive temperature cycling processes such as those common in under-the-hood electronics. A third unique apparatus developed by CAVE3 is a custom-made surface analysis system that enables in-situ studies of surface segregation during melting and wetting processes.

> **Economic Impact:** Results from the use of this novel facility have especially benefited CAVE3 industrial sponsors who use solder materials and technology. The ability to study fundamental properties of electronic materials in-situ has reduced the development costs associated with new electronic platforms. In absence of these new experimental methods, significant system level testing would have to be undertaken for validation of the material performance in electronic manufacturing process. The reduced material development time is expected to result in faster time to market.

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Center for Building Performance and Diagnostics (CBPD)

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The Robert L. Preger Intelligent Workplace (IW)

The Robert L. Preger Intelligent Workplace (IW) is a living and lived-in laboratory designed and engineered by the Center for Building Performance and Diagnostics (CBPD) in close cooperation with architects and engineers and the Advanced Buildings Systems Integration Consortium (ABSIC). As a living laboratory, the IW is frequently adapted and updated to incorporate new materials, components, and systems. The IW pioneered the focus on hands-on, integrated research involving robust, innovative systems for multiple performance goals. It has partnered with over 50 companies and governmental agencies worldwide to develop energy-effective daylighting, natural ventilation, and passive/active heating

An exterior view of The Intelligence Workplace with additional inset exterior and interior views. Compared to United States. standard average the IW uses one-fifth of the energy to create optimal air, thermal, visual, and spatial ergonomic qualities with the lowest artificial energy consumption.

and cooling with advanced lighting, mechanical, structural, and interior systems. The work of the CBPD and the ABSIC was awarded the 2013 Alexander Schwarzkopf Prize for Technological Innovation by the Industry-University Cooperative Research Center Association.

In the United States, about 40% of all energy and 70% of all electricity is used for building operations. The capabilities of the IW lab have resulted in a series of ongoing research projects with industry partners, including: Gartner Facades, Zumtobel Lighting, PPG glass, Alcoa Aluminum, Steelcase, Armstrong, Carrier, Lufttechnischegesellschaft (LTG), Mahle GmbH, Johnson Controls, Siemens, and OSIsoft. The most recent IW collaboration involves an American Recovery and Reinvestment Act (ARRA) project led by Siemens Controls that is dedicated to profiling control systems to achieve 40% energy savings in existing buildings.

The IW pioneered the concept of integrating horizontal load bearing structure, mechanical ventilation ducting, cabling for power, communication and controls, and floor-based infrastructures to support ongo-

ing spatial dynamics. The work has resulted in unprecedented levels of user accessibility, organizational flexibility, and technological adaptability, while eliminating the concept of obsolescence and material waste. The IW test bed has led to the development of Air Conditioning, Heating and Refrigeration Institute publications and has influenced innovative buildings across the United States and internationally. The concepts pioneered by the IW team improve upon the previous state-of-the-art methods by employing multi-disciplinary, inter-disciplinary and trans-disciplinary decision-making processes, as well as by integrating public/private partnerships into policies, practices, and operations.

The IW living laboratory also demonstrates the advantages of and opportunities for hybrid conditioning., integrating daylighting with artificial lighting, and natural ventilation with mechanical conditioning, passive and active heating and cooling strategies for highest air, visual, and thermal qualities. Compared to United States standard average primary energy (considering the energy demand to generate electricity) and site energy (measured energy use in the buildings), the IW uses one-fifth of the energy to create best air, thermal, visual, and spatial ergonomic qualities for the occupants with the lowest artificial energy consumption. It concurrently combines minimal material resource use with zero waste in production, construction, and internal reconfigurations.

The IW also encouraged the creation of comparable IW labs at the University of British Columbia, Syracuse University, and Purdue University. The R&D that occurs in these labs fosters the development of advanced technologies and integrated systems and educates students and professionals to ensure the more rapid introduction of architectural building innovations in the marketplace. The Building Investment Decision Support (BIDS) tool developed by the CBPD and applied in major, breakthrough projects, has been based on over 450 case studies published nationally and internationally. These case studies identify energy, environment, human health, organizational productivity, learning, and teaching benefits of building performance. Many of these are related to the *10 Strategies for Living, Bio-climatic Facades for Sustainability, Human Health and Performance* posters (developed by the Center for the CBPD with the University of California, Berkeley, Berkeley Lab and supported by industries and governmental agencies). These strategies are: 1) Access to Nature; 2) Daylighting; 3) Natural Ventilation; 4) Heat Loss/Heat Gain Control; 5) Solar Heat and Glare Control; 6) Load Balancing Heat and Power Generation; 7) Passive and Active Solar; 8) Water Management; 9) Enclosure Life; and 10) Systems Integration. The IW continues to have world-wide impacts.

> **Economic Impact:** The economic impacts of this innovation in building systems and systems integration for performance are multi-dimensional - affecting energy and operational costs, system reliability, product market share, and indoor environment quality for building occupants. Building innovations used in the IW, such as energy dashboards (which show consumers how much power they are using), daylighting, and electric lighting integration, have been shown in studies to significantly decrease the amount of energy expended to power buildings. A *Wall Street Journal* article from September 22, 2013 entitled "Energy Dashboards Enter the Office Cubicle," highlights research by both the CPBD and the National Renewable Energy Laboratory (NREL) that addresses the potential for a national reduction in energy consumption through the use of dashboard technology by office workers. Separately, CPBD research on daylighting control indicates "the net impact of daylighting and electric lighting integration is significant energy savings and improved workplace satisfaction." This research also states that other, emerging research "...is revealing that day-lit offices, classrooms, and hospitals measurably contribute to greater health and performance at tasks," thereby directly reducing companies' operating costs, in addition to reducing workers' health costs. By implementing IW floor-based plug-and-play systems in new large office buildings, the average cost per person can be decreased from $450 to as little as $100 per person, resulting in net annual savings of nearly a million dollars. In addition, employees

experience improvements in overall health, as measured by the number of sick days taken. This can make it possible for companies to renegotiate health insurance contracts, thereby providing significant savings.

For more information, contact Volker Hartkopf, 412.268.2350, hartkopf@cmu.edu.

National Environmental Assessment Toolkit (NEAT™)

NEAT™ combines portable instrumentation with questionnaires and expert walkthroughs to create robust assessments of workplaces' thermal, visual, acoustic, and air quality. This is the indoor environmental quality (IEQ). Development and refinement of the Toolkit continues with direct support from the General Services Administration and corporate and industry partners. The Toolkit is used nationwide for before and after field evaluations of cutting edge corporate buildings and federal facilities. NEAT studies combine online and on-site user satisfaction questionnaires with objective on-site IEQ instrumentation, as well as with assessments of the technical attributes of building systems (TABS). These ensure that conclusions are linked to system design decisions. In addition to developing robust data collection techniques, the CBPD team has developed innovative data analysis tools ranging from scatter plots to environmental "EKG for buildings" that can be linked to the quality of building systems and facilities. As of now, field data from over 1,000 workstations provide in-depth analyses for achieving better indoor conditions and energy savings.

NEAT portable sensors and datalogger suite

Most post occupancy evaluation (POE) is subjective only, with facility manager and user satisfaction questionnaires attempting to capture the perceived quality of the building. Results from CBPD field studies are coming to be viewed as central for informing critical investments for improving indoor environmental quality and for building the business case for high performance buildings. This is accomplished via simultaneous linking of facility management costs, health and productivity to indoor environmental quality.

The NEAT field studies support opportunities for energy conservation while meeting IEQ standards. The Toolkit collects data on IEQ, occupant satisfaction, and the physical characteristics of buildings. Cross-sectional analyses of datasets provides recommendations for building owners and managers to reduce energy consumption while enhancing indoor environmental quality and occupant satisfaction.

Center for Building Performance and Diagnostics (CBPD)
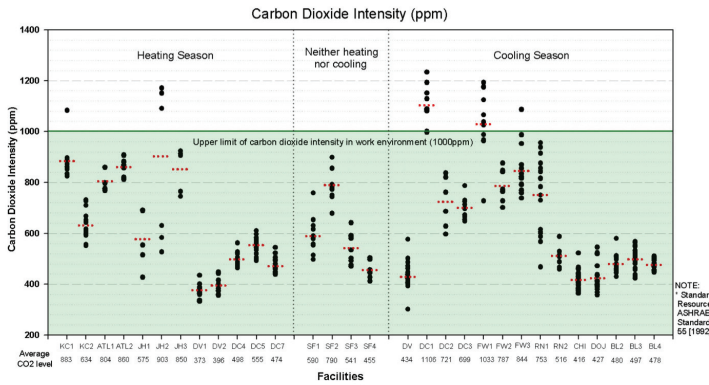
Spot measurements of CO_2 at multiple facilities

Before and After user survey comparison at one facility
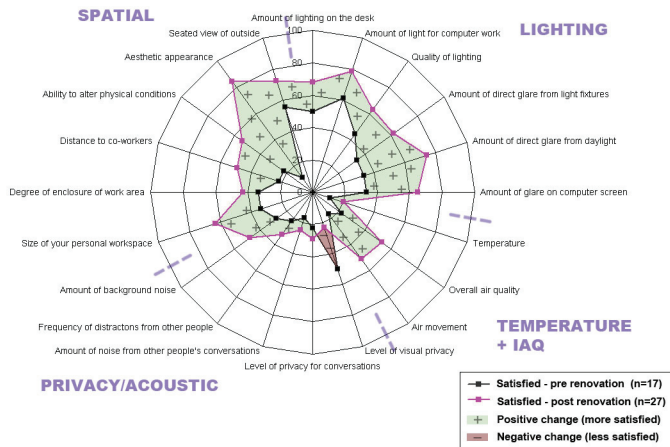
Economic Impact: There is often a significant discrepancy between the designed and the actual total energy use in buildings. The reasons for this discrepancy are generally poorly understood and often have more to do with the role of occupant behavior and building operations than the building design. Field data collection on IEQ, user satisfaction, and the technical attributes of building systems can reveal inefficient building operations and is one of the most important efforts for energy consumption reduction. An analysis of the General Services Administration portfolio data collected using the NEAT Toolkit concluded the following: 1) 4% total energy savings can be attained by raising summer set points; 2) 40% lighting energy savings can result from reducing ambient lighting; and, 3) 25% reductions in lighting energy can be achieved by daylight harvesting. Ongoing work with the Department of Energy will lead to more robust cross-sectional analyses. Findings from these analyses will provide better economic estimates to support the importance of investing in quality built environments.

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Center for Child Injury Prevention Studies (CChIPS)

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Telecenter: Collaborative Review of Children's Injuries in Motor Vehicle Crashes
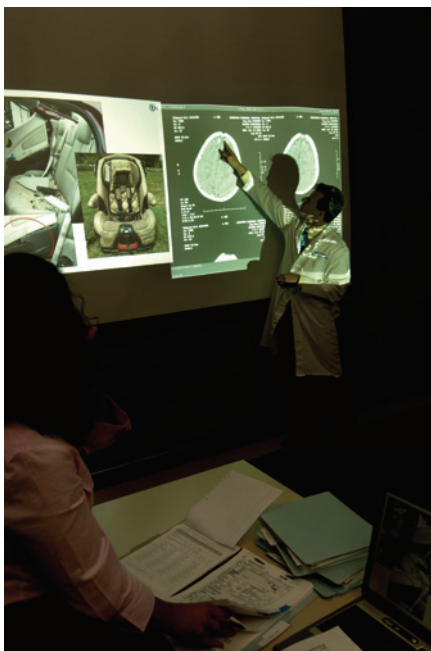
Telecenter conferences enable experts from multiple sites to share sensitive information from multiple sources via secure transmission lines with strictly controlled access. The web-based conferences help improve prevention efforts by aiding in the determination of mechanisms of injury.

Road traffic injury remains the leading cause of children's death and acquired disability. Multidisciplinary teams of university-based engineers, scientists, and physicians must collaborate with peers in government and industry to investigate crashes, determine mechanisms of injury, and develop safety technology to prevent similar injury in the future. To review the circumstances of each crash, multidisciplinary expertise is essential. Such expertise is seldom available at any one institution. This results in the need for remote collaborations, which require the ability to share sensitive information from multiple sources via secure transmission lines with strictly controlled access.

With funding from the National Science Foundation and guidance from the I/UCRC Industrial Advisory Boards, a team of researchers from two IUCRCs, the Center for Child Injury Prevention Studies (CChIPS) at The Children's Hospital of Philadelphia, the University of Pennsylvania, and the Center for Autonomic Computing (CAC) at the University of Florida developed a collaborative review networking system. This system makes it possible for remote, collaborative reviews of mechanisms of injury to children in motor vehicle crashes. Referred to as Telecenter, this innovative application of information technology enables: 1) distributed, asynchronous collection of digital content needed for crash case reviews, with consistent organization of content across cases; 2) secure, Web-based, remote participation in review meetings characterized by multimedia sharing of case content via visual images, real-time written and oral communication and various Web resources; and 3) archiving for post-review access and follow-up involving statistics, search, and networking.

Center for Child Injury Prevention Studies (CChIPS)

The Telecenter system's design supports conferencing and remote image-sharing. Its capabilities extend beyond existing solutions via: workflow and content organization well-suited to traffic injury reviews, spatio-temporal, role-based access control, distributed content management, and seamless integration of services.

To further leverage the investment in Telecenter, an adaptation was developed within the public health sector. Telecenter was reconfigured to meet the needs of state-mandated Child Death Review teams. Similar to crash investigation reviews, Child Death Review teams require multidisciplinary expertise in order to determine how and why children die, as well as how to prevent future child deaths, even when the needed expertise may not be available locally. Initial real world results demonstrated that Telecenter for Child Death Review could help states enhance the quality of reviews without the financial burden of travel for experts. Telecenter also helped states increase efficiency in the timely transfer of information to those that can implement actions to improve the health and safety of children. The collaborative nature of this project spurs innovation, as it promotes involving the appropriate multidisciplinary experts on specific projects.
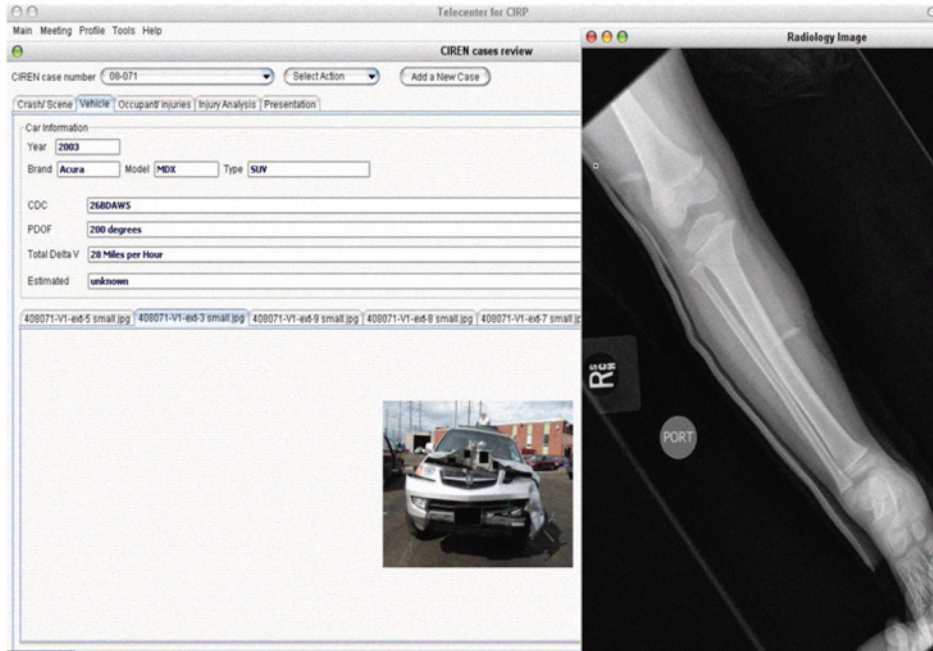
Telecenter screen of in case review mode showing textual and pictorial information about a case.

Economic Impact: Telecenter was pilot-tested to enhance the quality and value of National Highway Traffic Safety Administration (NHTSA) crash injury case reviews by virtually bringing together remotely located experts without the burden of additional travel costs. Telecenter allows investigators to complete multidisciplinary reviews of crashes in order to ultimately improve engineering-related prevention and medical treatment of crash injuries. These in-depth investigations require input from multiple individuals, including physicians, epidemiologists, engineers, govern-

ment regulators, vehicle and child restraint manufacturers, and insurance company representatives. Use of the secure, customized, Telecenter technology eliminates the need for time and resource-intensive in-person collaboration. It also provides for significant cost savings for travel and housing for these collaborators. In addition, Telecenter makes possible more reviews of particularly unique or complicated crashes in rural or international regions. Additionally, by advancing the field of child occupant protection, Telecenter contributes to the reduction of future costs from fatal and non-fatal injuries as well as savings from acute and chronic medical care expenses, wage and productivity losses, and reduced quality of life costs.

For more information, please contact Flaura Winston, 215.590.3118, flaura@mail.med.upenn.edu or Kristy Arbogast, arbogast@email.chop.edu, 215.590.3118.

Identification of Common Serious Teen Driver Crash Scenarios

Motor vehicle crashes are the leading cause of death and acquired disability among teenagers in the United States. Despite the societal burden of these events, how and why teens get into crashes has not been well understood on a scientific level. The previous state of practice was to have engineers develop driver assistance technology based on performance of adult drivers.

Researchers from the Center for Injury Research and Prevention Studies (CChIPS) at The Children's Hospital of Philadelphia and the University of Pennsylvania School of Nursing have analyzed data from the National Highway Traffic Safety Administration's (NHTSA) National Motor Vehicle Crash Causation Survey (NMVCCS) to determine the leading scenarios of serious crashes among teen drivers and the primary causal factors leading up to those crashes. With results from this breakthrough research engineers finally have the needed knowledge to target crash prevention efforts specifically toward young drivers, the group at highest crash risk.

How and why do teen drivers get in serious motor vehicle crashes? By identifying the most frequent crash scenarios and causal factors of crashes, researchers provide key information to develop more effective crash avoidance technologies.

The multidisciplinary team of researchers has documented the five most frequent crash scenarios for teen drivers involved in serious motor vehicle crashes. They are: rear-end crashes, two types of left turn intersection crashes that occurred when the teen was turning left into or across the path of another vehicle, and two types of running-off-the-road events that occurred after either negotiating a curve or after going straight. Rear-end and left turn intersection crashes were primarily due to recognition errors, which include poor driver surveillance and distraction, and decision errors, which include following too closely and traveling too fast for conditions. The majority of run-off-road events, however, resulted from decision errors or poor driver performance (e.g., overcompensating) or from non-performance errors (e.g., fatigue).

This research is helping to identify how and why teen drivers get in serious motor vehicle crashes. By identifying the most frequent crash scenarios and causal factors leading up to a crash, this study provides key information to engineers and automobile companies on how to better develop crash avoidance technology for teen drivers.

Economic Impact: The Centers for Disease Control (CDC) has estimated the cost to the nation of teen driver crashes at $33 billion annually. Findings from this and related teen driver studies are providing more nuanced understandings of the circumstances of teen motor vehicle crashes. These new understandings are helping leading to advancement of behavioral and educational crash prevention efforts, including teen driver training curricula, assessment tools such as simulated driving assessments, and more effective in-vehicle driver assistance technologies.

For more information contact Allison Curry, 215.590.3118, currya@email.chop.edu or Catherine McDonald, 215.746.4462, mcdonalc@nursing.upenn.edu.

Comparing FMVSS 213 Sled Test to the Full-Scale Vehicle Crash Environment

Through Federal Motor Vehicle Safety Standards Test Requirements, the National Highway Traffic Safety Administration (NHTSA) and Transport Canada have similar longstanding sled test protocols that all child seat manufacturers must pass to sell child restraints in the United States and Canada. This "vehicle seat" or "bench" in the sled test was originally modeled from a General Motors (GM) sedan rear seat from the 1970s.

Developments in both vehicle interiors and seat designs, as well as advancement in child seat design and construction, have significantly changed the safety technologies offered by both industries. However, since the current test bench is based upon old vehicles, its characteristics in today's crashes may not be representative of current real world vehicle seats. This limitation may hinder safety technology advancement of the various forms of child restraint designs and systems.
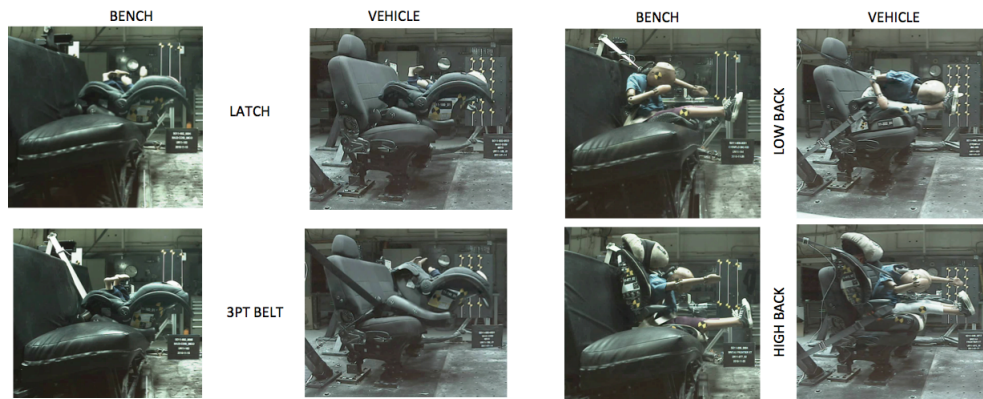
Rear facing and booster child restraints at maximum excursion on the FMVSS 213 Bench and the Vehicle Seats.

This study, supported by Transport Canada and CChIPS resources, provides a valuable method for comparing and determining the critical factors that should be considered in potentially modifying the current sled bench. The project represents a unique opportunity for the child seat industry and federal government to work together to improve child seat regulation. This type of testing is normally costly and labor-intensive

but is financially feasible through collaboration. Without the benefit of this work the child seat, motor vehicle, and ATD industries would have less applicable regulations to jointly impact and guide such research.

This research will result in recommendations to NHTSA and Transport Canada on crash sled bench testing standards and will help child restraint and vehicle manufacturers interpret the performance of restraints tested under the current child restraint test protocol. This may improve the performance and enhance the safety of child seats in real world motor vehicle crashes.

> **Economic Impact**: As all infant carriers, child restraints, and booster seats are tested using this NHTSA-mandated sled bench, this research will impact all such products in the child seat industry. The work will save tens of thousands of dollars in research and testing expenses for each child seat manufacturer that may wish to engage in this type of analysis. It is impossible to even estimate the reductions in health care costs that could be realized and the associated suffering that will be possible to avoid when these safety devices are improved based on results from this work.

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Child Injury Prevention: Enhancing Child Safety In Side-Impact Crashes

Side-impact crashes account for 25% of motor vehicle crashes (MVCs) but represent more than 40% of MVC-related injury costs. To discover better ways to protect children in side-impact crashes, a project at the Center for Child Injury Prevention Studies (CChIPS) sought to document the probable vehicle interior contact points in side-impact MVCs to children in child restraint systems (CRS). Two in-depth crash investigation databases, the Crash Injury Research and Engineering Network and the Partners for Child Passenger Safety Study, were queried for rear-seated, CRS-restrained children ages 0 to 8 years in side impact crashes who sustained clinically important injuries.
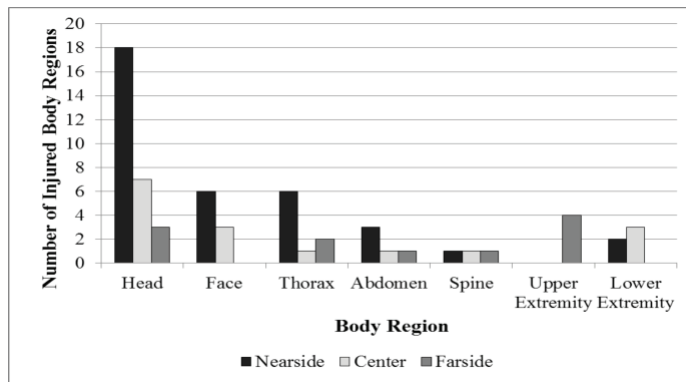
Distribution of body region of injury by seat position for children in side impact crashes highlighting the importance of head injury prevention.

A multidisciplinary team of physicians and engineers reviewed the cases to describe injury patterns, injury causation, and vehicle components contributing to the injuries; 41 occupants met the inclusion criteria (average age 2.6 years), with 24 seated near the side of the crash, 7 seated on the far side, and 10 seated in the center. The most common injuries were to the skull and brain, with a greater proportion of skull frac-

tures occurring with increasing age. Lung contusions and spinal injuries were also reported. Near-side head and face contact points occurred along the rear vertical plane of the window and the horizontal plane of the windowsill. Head and face contact points for center- and far-side occupants were along the edges of the front seat back and front seat head restraint.

> **Economic Impact**: Results of this breakthrough research will inform innovations by the automotive and child restraint industries in vehicle and child restraint design. In particular, the findings will lead to: 1) new generation child restraints with side wings; and, 2) energy management features on vehicle door interiors to reduce head and traumatic brain injuries (TBI) sustained by children in crashes. TBI continues to be a major worldwide health epidemic, with an annual incidence in the United States alone in excess of 1.5 million per year. This leads to an estimated 50,000 fatalities and 3.7 million individuals needing to live with long-term disability. Worldwide, the incidence of TBI has been estimated at 500 million new cases annually (circa 1985). Because of increasing global automobile use and declining deaths due to infectious diseases, TBI is becoming the global dominant source of mortality and morbidity. TBI is particularly devastating to the young. Hospitalization costs associated with pediatric TBI are estimated to exceed $1 billion annually. By implementing design strategies for child restraints and vehicle interiors based on this project's findings that manage the impact energy when head contact occurs in crashes, the potential to reduce these costs is substantial. Furthermore, this technical breakthrough led to the development, in part, of new regulations for the testing of child restraints in side-impact crashes. This advancement is particularly important as side-impact crashes represent a significant portion of MVC-related injuries and fatalities and therefore injury costs.

For more information, contact Kristy Arbogast, 215.590.3118.
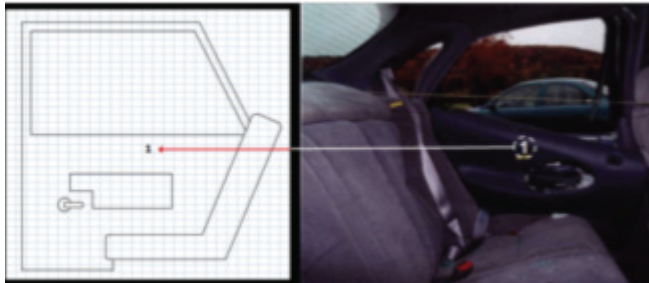
Screenshot of program developed to allow researchers to transfer occupant contact points from vehicle photos to a simplified vehicle interior drawing. Typically, contact points are summarized to provide vehicle and child restraint designers with details on which regions of their products need improved energy management for head injury mitigation.

Center for Cloud and Autonomic Computing (CAC)

A CISE-funded Center

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CometCloud Manages Business Workflows on Federated Cloud Infrastructure

Public clouds have emerged as an important solution that enables the renting of resources on-demand and supports a pay-as-you-go pricing policy. Furthermore, private clouds or data centers, which cater to a restricted set of users within an organizational domain, are exploring the possibility of scaling out to public clouds to respond to unanticipated resource requirements.

Rutgers and Xerox collaborated to develop and deploy an innovative framework for executing business workflows using a dynamically federated cloud infrastructure. The framework builds

Test bed based on Supervisory Control and Data Acquisition (SCADA) systems provides a platform for testing both hardware and software.

on CometCloud, an autonomic cloud engine developed at Rutgers, and dynamically federates hybrid infrastructure, such as private clouds, enterprise data centers, grids, and public clouds, on demand, to meet the requirements and constraints of the business workflow. An enterprise workflow typically consists of an ordered set of heterogeneous applications (stages), each of which may have specific resource requirements and constrains in terms of performance, completion time, cost, data privacy, etc. Using CometCloud, different workflow stages can be deployed on the appropriate mix of resources to satisfy application requirements and constraints.
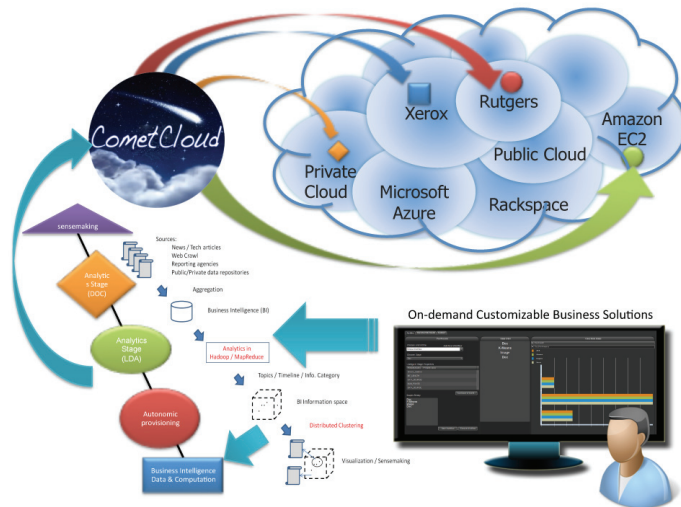
Center for Cloud and Autonomic Computing (CAC)

The breakthrough enabled Rutgers and Xerox to demonstrate for the first time a number of key capabilities in a single framework: 1) Dynamic cloud federation - managing resources across multiple private and public clouds in order to dynamically scale the execution of application workflows up, down, and/or out and/or to compose appropriate capabilities, according to high-level policies; 2) Programming management - resource scheduling and provisioning within the federated cloud infrastructure; and 3) Workflow deployment - deployment of real-world application workflows running on the federated cloud infrastructure. Specifically, the hybrid infrastructure used in the demonstration dynamically integrated private clouds at Rutgers and ACS with the Amazon EC2 public cloud.

Such an autonomic workflow framework can dynamically select an optimal mix of resource classes (clouds or grids provider, types of nodes, the number of nodes, etc.) based on application QoS and resources requirements (e.g., performance, latencies), user policies (e.g., budget, deadline), and constraints (e.g., security/privacy). The workflow framework can also monitor the execution of the applications services within the workflow, and can adapt both the resource provisioning as well as the services to ensure that the application requirements and user constraints continue to be satisfied. Adaptations may involve scaling resources up, down, or out within the federated cloud infrastructure and can allow the system to handle unanticipated situations such as workload bursts, system performance degradation, or resource failures.

> **Economic Impact:** In spite of being in its early stages, cloud computing is already reshaping the IT world. In fact, according to *The Wall Street Journal*, four out of five businesses are moving or planning to move some of their business functions to Cloud services. A recent report by Gartner estimates that Cloud services will be a $150 billion industry by 2015. Enabling on-demand provisioning and construction of hybrid federated cloud infrastructures has the potential to reduce computational costs and improve efficiency of cloud computing service centers. These structures can support heterogeneous and dynamic workloads and on-demand cloud bridging. Federated cloud infrastructures also provide opportunities to improve application quality of service and lower cost by mapping applications of scientific or business workflows to appropriate resource providers.

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Autonomic Critical Infrastructure Protection System (ACIP)

Numerous serious cybersecurity exposures occur because of widespread use of Supervisory Control and Data Acquisition (SCADA) systems that were never designed with security in mind. Consequently, SCADA systems become a prime target for cyberattacks due to the profound and catastrophic impacts they can have on our economy and on all aspects of our life. In fact, critical infrastructures have expanded to include not only the energy critical infrastructures, but also many process control systems, networks, and infrastructures of which approximately 85% are privately owned.

A recent Forrester survey reported that 75% of organizations experienced Distributed Denial of Service Attacks (DDoS) even though they implemented cybersecurity solutions. One third of attacked organizations experienced service disruptions.

Test bed based on Supervisory Control and Data Acquisition (SCADA) systems provides a platform for testing both hardware and software.

The problem is that many of the systems are ineffective against novel and well-organized attacks. The nation's critical energy infrastructures (power, water, gas and oil) are moving to modernize their industrial control systems to build what is referred to as "Smart Grids" that use advanced computing and communications technologies to bring knowledge so they can operate far more robustly and more efficiently.

Motivated by these exposures, researchers at the Center for Autonomic Computing (CAC) and industrial center members (Raytheon and AVIRTEK) are collaborating to develop an innovative cybersecurity approach based on autonomic computing technology. It is analogous to the human nervous system where computing systems and applications can be self-configured, self-optimized, self-healed, and self-protected with little involvement from the users and/or system administrators. CAC has successfully developed and implemented an Autonomic Critical Infrastructure Protection (ACIP) appliance and currently being tested and evaluated. This involves evaluating the appliance's self-protection capabilities using an industrial process control test bed that offers multiple capabilities for both hardware and software experimentation.

This breakthrough technology is validating the thesis that autonomic paradigms have the potential to detect and mitigate cyber threats launched against industrial control systems. Responding faster than a human operator, SCADA and their associated control elements can effectively immunize against cyber malware and mitigate the effects of control.

Economic Impact: Enhancing the ability of the nation to provide undisrupted service of electric power, clean potable water, transportation, and other necessary societal support services, saves lives, preserves the domestic tranquility, and can help protect industry's and the nation's economic vitality. The economic impacts of avoiding such cyber attacks are difficulty to estimate. That said, a study conducted by the same group, Forrester Consulting, indicated that organiza-

tions that provide online services as their core business stand to lose millions of dollars per hour when their services are down. The ACIP technology when fully matured can be exploited by western world societies to immunize critical infrastructures against being targeted by malcontents and terrorists.
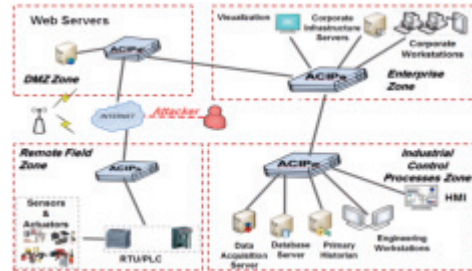
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Demand-driven Service and Power Management in Data Center

Power consumption represents an increasingly significant percentage of the cost of operating large data centers. One approach to reduce power consumption in the data centers is to keep the computers in standby or off modes except when the data center workload requires them to be fully on. This approach depends on being able to effectively monitor performance, workloads, and to anticipate the need for resources required to meet the users' service-level agreements of that generate the workload.

Data centers are used by banks, investment firms, research organizations, major municipalities and by homeland security.

This project has generated: a) mechanisms to monitor, model and predict workloads associated with individual services; b) models for prediction of global resource demands; c) data management methods based on control theory and market-based approaches; d) mechanisms to minimize the cost of providing individual services while globally minimizing power consumption; and e) development and evaluation of software that implements all of the aforementioned methods. Ongoing experimental evaluations on an IBM BladeCenter have shown that the proposed approach can efficiently and stably reduce thermal hotspots, power consumption and performance degradation caused by virtual machine consolidation, while balancing conflicting objectives.

Economic Impact: Annual energy and administration costs associated with today's data centers amount to billions of dollars; power and cooling rates are increasing by an alarming 8 fold every year and are becoming the dominant part of IT budgets. The high-energy consumption of modern data centers causes excessive heat dissipation, which, in turn, increases cooling costs and server failure rates. One of CAC's main research thrusts aims to address these problems because doing so lowers data center ownership costs in all sectors of today's economy. Doing so can also increase the reliability of the infrastructure that provides critical services.

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Noise-Coupled Analog-to-Digital Data Converters

As wireless and wired communication and digital broadcasting proliferate, there is increasing demand for wideband analog-to-digital data converters (ADCs). The signal bandwidth requirement gets more stringent in direct conversion receivers. Along with the wide signal bandwidth, high dynamic range and linearity are also required in these applications. This performance should be achieved in a power-efficient way, since power dissipation determines the battery life for mobile devices. Delta-sigma ADCs can deliver high performance with low-power consumption over wide signal bandwidths, and it is hence the ADC architecture of choice in

Delta-sigma data converters will result in more efficient cellular phones.

many wired and wireless receivers. Under a CDADIC-funded project, researchers developed a novel delta-sigma ADC based on noise coupling that provides excellent linearity and power efficiency for wideband communication devices and cell phones.

During 2012, we developed novel data converters based on incremental and extended-counting analog-to-digital conversion. A particularly efficient new configuration was found for extended-counting converters, which multiplexes internal blocks of the circuit. It can achieve lower power dissipation than earlier data converters, and can be shared by many (hundreds) of channels. Hence, they are often the best choice for the interfaces of multi-sensor networks. Such networks are needed in many biomedical and environmental applications.

> **Economic Impact:** There is considerable interest at large companies in our results, as shown by gifts received from several CDADIC companies (and many outside ones) to support more research in this field. Noise-coupling converters allow the translation of analog signals into digital form with less distortion and lower power requirements than earlier circuits, and will result in less

expensive mixed-mode structures. These have recently been among the most rapidly growing product areas in microelectronics. Since the proposed converters can be shared among many sensors, and require minimal amount of power, they are excellent choices for such applications. Particularly strong economic impacts will be in improved cost-performance ratios of wideband battery-operated systems, including cellular telephones, digital radios, and other wireless devices. Though difficult to quantify, since these products represent a significant percentage of the annual sales of electronic devices, the economic impacts can be anticipated to be substantial. The integrated circuit industry will particularly benefit by this innovation.

The newly developed incremental and extended-counting analog-to-digital data converters are particularly effective in applications involving multi-sensor networks. They are used, for example, in wearable biomedical devices and environmental sensor networks. This photo shows a biomedical sensor network for detecting brain signals.

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Enabling Metal-Fill-Aware Design of RF/Mixed-Signal Integrated Circuits

Semiconductor manufacturers impose strict density requirements for each metal layer in a chip to maintain manufacturability and production quality. To achieve the required minimum density, metal fill is inserted in each layer as needed. The added metal fill can have significant electrical performance impacts on an integrated circuit (IC), especially in high speed or radio frequency (RF) applications. These impacts are not well characterized and have been poorly represented in IC design tools. This research addresses the electrical performance impacts of metal fill on an IC, enabling designers to accommodate and even leverage these effects to their advantage. This work has large potential economic benefits for the US semiconductor industry as well as the US economy at large.

RF designs become extremely sensitive to all electrical effects

Top view of a fabricated integrated circuit component surrounded by square-shaped metal fills. The metal fills are required by semiconductor foundries to maintain manufacturability and production quality; however, they also impact the electrical performance of the integrated circuit. The impact of metal fills needs to be considered in integrated circuit design.

related to the metal layers at frequencies above 5 GHz. In the past, foundry-imposed metal fill rules have been accommodated for some designs by adding chip area around the perimeter whose only purpose is to increase the percentage of area covered by metal to meet minimum metal density requirements while not impacting the performance of the circuit. The added chip area results in significant waste of silicon, impacting costs and miniaturization. In the drive to add value at decreased cost, the semiconductor industry pushes toward finer and finer geometries, scaling the minimum dimensions of chip-level feature sizes toward fundamental limits. Current and future semiconductor technologies with minimum dimensions of 45 nm and below no longer allow the strategy of increasing chip area to accommodate metal fill density rules while keeping metal fill outside critical areas. Furthermore, each step to a more advanced fabrication process node adds additional cost to both the manufacturing as well as the design of such products. This increases the risk and expense of missing design issues, including that of the impact of metal fill on the functionality and performance of advance products.

Center for the Design of Analog-Digital Integrated Circuits (CDADIC)

This research lays the fundamental groundwork for analyzing and simulating the effects of metal fill on designs to create more robust designs. The results of this research make it easier for designers to plan metal fill placement within the boundaries of a minimum sized chip, while understanding and mitigating the parasitic electrical impact of metal fill and even use metal fill to advantage in their circuit design.

Radio frequency integrated circuits (RFICs) and high-speed digital ICs used in a wide range of end products, including mobile communications and computing devices, will benefit through greater miniaturization, reduced design effort and cost, and improved performance. The performance of phased array antennas for automotive and avionic communications and radar applications should also be improved as a result of this work.

Economic Impact: Semiconductor technology companies will benefit from this work through reduced design effort, improved performance, and greater miniaturization of their RF and high-performance mixed-signal integrated circuit products. In the drive to add value at decreased cost, the semiconductor industry pushes toward finer and finer geometries, scaling the minimum dimensions of chip-level feature sizes toward fundamental limits. Each step to a more advanced fabrication process node, however, adds additional cost to both the manufacturing as well as the design of such products. This increases the risk and expense of missing design issues, including that of the impact of metal fill on the functionality and performance of advance products. This research lays the fundamental groundwork for analyzing and simulating the

The design and performance of avionic communications and radar systems should benefit from this research.

effects of metal fill on designs to create more robust designs. Furthermore, each mask layer (photomask) in advanced lithographic processes is becoming increasingly expensive; e.g., mask costs for a 28 nm CMOS process are $5 million or even higher. This added expense increases the cost of each design fabrication spin, and increases the emphasis on advanced modeling and simulation capability prior to fabrication.

The research is expected to strengthen the leadership of US semiconductor technology companies in RF and high performance mixed-signal IC design and manufacturing, which directly impacts the large and growing economic sector of wireless communications with more than $1 trillion in global annual revenues, as well as the important sector of avionic communications and radar technologies. Furthermore, the research should benefit the US automotive industry by improving the performance of automotive radar systems for emerging applications including driver assistance and autonomous driving. This, in turn, will benefit society by potentially saving lives and property through reduced traffic accidents.

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Understanding Dielectric Materials

Motherboard of a smart phone, having many capacitors supporting the CPUs.
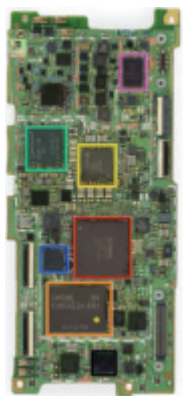
Research at the Center for Dielectric Studies (CDS) has furthered understanding of dielectric materials, including the requirements for raw materials and the properties that result from various compounds and processing approaches. The Center's research has shed new light on understanding the defect chemistry of barium titanate, a key ingredient of many of the dielectric powders. Fast firing has enabled devices to be produced with less porosity in the electrodes and smooth electrodes.

In this work, CDS researchers have highlighted a new theory and equation that provides for more accurate prediction of the lifetime of devices. This, in turn, provides much better estimates of the reliability of electric systems and subsystems. Electrical devices across consumer electronics, automobile, telecommunications, computer, aerospace, military, and medical fields, all require the use of multilayer capacitors. Their reliability is critical and is often the initial weakness in failed electronic systems.

Multilayer capacitors on average have a 40:1 ratio over integrated circuits in terms of circuit components. It is an industry that impacts all aspects of electrical systems. There are 3 x 1012 multilayer capacitors manufactured and sold every year. The image shows many surface mounted capacitors on the motherboard of a smart phone.

This work is aimed to replace a 50-year-old empirical equation that no longer holds and requires extensive testing that is costly to estimate long-term reliability. The new CDS theory and equation only requires three independent measurements, a major cost savings, and also is a much more accurate lifetime performance predictor.

Economic Impact: The world market for capacitor components is estimated to be $16 billion annually. Passive electronic components in handheld electronics are constantly evolving to support system trends in functionality and miniaturization. Reliability is essential to their value. However, indirectly we are considering the impact of all electronic systems that rely on using capacitors, and this then impacts all aspects of the high-tech economy.

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Center for e-Design

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Complexity Management Methodology: A Tool for Developing Product Families

In today's market, in order to have a substantial advantage over competitors, companies must be able to respond quickly and efficiently to the rapidly changing customer demand. While increasing variety and choices pleases customers and supports market share increase, the costs of doing so can be significant.
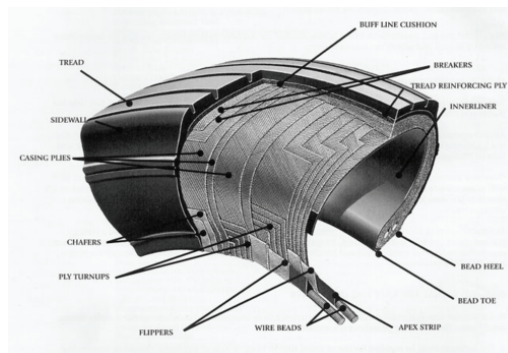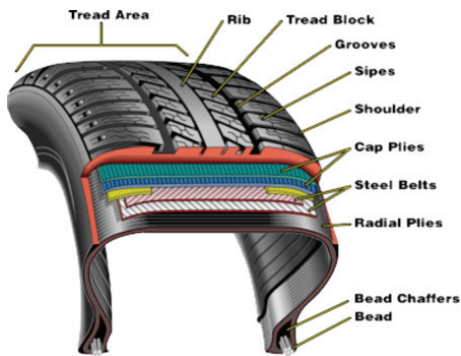
A tire is a very complex product, with dozens of components and hundreds of raw materials.

Center for e-Design

The proliferation of products entails managing a variety of components, functional requirements, quality standards, and production processes, all of which are considered main sources of product complexity. Variety is just one commonly known cause of product complexity. Other sources related to functionality, structure, and production of products have been identified as elements that further cause product complexity. Many have attempted to classify and categorize product complexity (PC) on an application-specific basis, yet unfortunately, to a large degree PC still remains a theoretical concept with no unified and commonly validated approach or measurement. This makes it difficult for companies to understand and manage PC.

In this collaborative Complexity Management Methodology (CMM) researchers at the Center for e-Design tackle the challenge of managing variety and product complexity. The CMM collaboration led to a comprehensive quantitative methodology to support product family development decisions that consider sources and impacts of complexity. Four main dimensions of PC within the context of a generalized definition were identified. Product complexity indicators suitable in product design, development, and production were then derived. By establishing measurements for identified PC indicators and using clustering techniques, a complexity evaluation approach for product family designs was developed. The breakthrough evaluation approach also supports the identification of Critical Components that are main sources of and contributors to PC within product families.

The approach also identifies cost saving redesign opportunities through complexity management by standardizing identified Critical Components. It has been tested on several tire product lines. Tires are a product that consists of hundreds of raw material and tens of components. They go through several assembly and integrative production processes. This makes tires good examples to study and understand complex products and to support the generalization analyses of the developed approach.

Research has documented many disadvantages associated with product complexity. A complex product typically results in complicated product design and development processes that lead to inefficiencies at the product realization stage. Manufacturing of complex products entails less efficiency, higher set-up costs, higher quality control requirements, more complex product scheduling, and difficulty in balancing assembly lines. All of this will cause various managerial and logistical problems in supply chain systems. In other words, PC can cause operational inefficiencies as well as increases in direct and indirect costs throughout the different stages of products lifecycles.

> **Economic Impact:** It is reasonable to conclude from available research that the new CMM method and tool will have significant favorable economic and efficiency benefits. Outcomes of CMM application on selected tire product lines further highlights these benefits. Results identified significant complexity reduction and cost saving re-design opportunities. For example, production cost reduction opportunities for one of the analyzed product families and related components ranged from 10% to 40%, or approximately $230,000 in savings annually for that product family. There are cases in the literature that report impacts and costs of product complexity affecting manufacturers throughout the US and globally. For example, one company identified over $4 million in cost savings through managing PC. Another study estimated an additional $600 million required in production to manage complex products/parts. With ever-increasing pressures to provide variety, quality, and high value at reduced costs, the need for solutions and strategies to minimize PC is dire.

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High Speed Link Path Analyzer: A Toolset for Decreasing Time to Market

Computer, Internet, and wireless communication generally are the revolutionary technologies that continue to significantly impact everyday life in our modern era. Every year new products are developed with new functionalities, improved performance, and easier user interfaces. The hardware designs required by these products are increasingly based on high-speed link-path analyses to ensure that the developed circuits operate properly with ever increasing speed, as well as diminishing size and power consumptions.

While high-speed link-path analysis is critical to achieve the normal operation of today's computer and electronic devices, the tools to simulate and model the geometries/components used in the link paths are often too basic and not easily consolidated. To analyze new products, engineers must use multiple tools from different vendors, a process that demands much time and deep knowledge and understanding of how the tools work. However, most designers of high-speed products often lack the resources to acquire the needed analytical tools or the time to become proficient at using them.

(Left) A massively parallel computing platform that uses high-speed links for data communication: an example end product that can benefit from the developed tool set; (Center) Laboratory measurement of a high-speed link: expensive instruments and expertise in high-frequency measurement are needed; (Right) A screenshot of the developed tool set for high-speed link-path analysis: cost-effective and no need for extensive training for the user.

To address the myriad of challenges faced by the high-speed design community, the Center for Electromagnetic Compatibility (CEMC) has developed a dedicated tool suite for high-speed link-path analysis. This innovative tool set not only consolidates most - if not all - of the tools needed to model and simulate high-speed designs, but it also provides holistic views of designs from die levels inside the chip to full system architectures. In addition, the tool set includes power integrity and power-distribution-network analysis,

Center for Electromagnetic Compatibility (CEMC)

enabling the co-simulation of signal and power integrity that is necessary when the products are operating at ever increasing speeds.

Within the unique partnership model of the I/UCRC, tool development was guided by the center's industry partners. As a result, the tool set fits well with "real-world" engineering practice. It can be easily integrated into the design process because it removes the need for users to understand the back-end theories, algorithms, and mathematics.

This work represents a significant improvement over the previous state of the art because it: 1) reduces the high costs involved with procuring multiple tools (often over $200K a year); 2) does not require extensive training of hardware designers; 3) can provide flexible signal and power integrity for co-simulations; 4) covers all aspects of the design from chip to system levels; and, 5) enables new features to be easily added. Recent research is enabling the tools to be more accurate and more capable of handling complex real-world problems more efficiently.

The software runs on multiple PC/workstation/server platforms and can import geometries from almost any design tool. A variety of features are available in the tool for users to perform, for example, eye diagram analysis, channel optimization, jitter decomposition, and other parameters and methodologies that are needed to validate advanced designs. Then, when results appear satisfactory, users can use the data to finalize and/or make necessary design modifications.

> **Economic Impact**: The developed tool set has been used in several CEMC member companies including Cisco, IBM, and Altera. In Cisco alone, use of the tools has already resulted in a cost reduction in commercial tool purchases in the amount of approximately $200K a year. When the tool set is further rolled out the total estimated cost reduction can reach as high as $2M a year. Because tool use does not require extensive training, Cisco has been realizing cost reductions of roughly $100K annually. Increased productivity of their engineers has been estimated to be approximately $300K. Lastly, time to market can be reduced because fewer prototypes are needed. We estimate related savings of about $300K per year for Cisco and up to $3M per year across all CEMC members. On the R&D side, having an integrated tool set helps evaluate new technologies needed for next generation products, which is extremely valuable for pre-development research.

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Reducing Emissions From DC-DC Converters Without Sacrificing Efficiency

Electronic Products

Efficiency   Noise Radiation

Improved Performance

"quiet" to Environment

DC-DC Converter
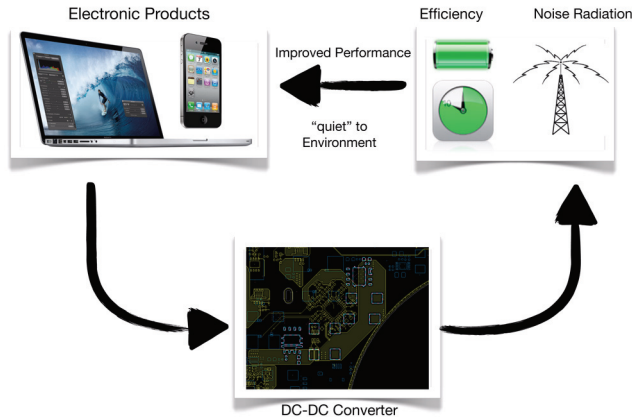
This research provides a more thorough understanding of the noise radiation mechanisms in the circuit and proposes innovative solutions to eliminate noise while maintaining circuit performance.

High-speed digital electronic devices, such as computers and cell phones, utilize signals that change rapidly, often on the order of nanoseconds or even picoseconds. These rapidly changing signals are generally transmitted from one integrated circuit to another or to one or more peripheral devices through a network of electrical conductors. The conductors in turn can exist in various forms including cables, wires, circuit board traces, and circuit board planes. However, as the signal transitions become more rapid and occur more frequently, the voltages and currents associated with the transitions can create a weak electromagnetic field in the proximity of the device. The electromagnetic field produced by the device then adds to the ambient electromagnetic fields produced by both natural events (e.g., lightning) and man-made events (e.g., radio and television transmissions). In this way each device contributes to the electromagnetic environment. While the electromagnetic environment is generally imperceptible to the senses, it can be detected with suitable electronic equipment. More importantly, excessive noise introduced into the electromagnetic environment by one device can cause interference to other devices located in proximity. The need is to determine how to design reliable electronic equipment that meets or exceeds regulatory constraints without significantly compromising other important design objectives.

Researchers at the Center for Electromagnetic Compatibility (CEMC) have made a significant technological contribution with their work on reducing emissions from DC-DC converters without sacrificing efficiency. Conventional solutions to reduce noise often reduce the efficiency of the circuit. This breakthrough work conducted at CEMC provides a more thorough understanding of the noise radiation mechanisms in the circuit and proposes innovative solutions to eliminate noise while maintaining circuit performance. A design guideline has been developed and is used during the product design stage to optimize the design of DC-DC converters for minimal radio emissions.

Economic Impact: The design guideline is enabling designers to more quickly optimize the performance of DC-DC converters in various products. Doing so can reduce the number of developmental cycles. This, in turn, substantially reduces developmental costs. Several corporations have implemented this work into a number of products. The guide is helping produce better products at reduced cost to the consumer, and this will help industry realize reductions of electromagnetic emissions from the DC-DC converters that are often used multiple times in each product. Since

Center for Electromagnetic Compatibility (CEMC)

DC-DC converters are used in almost all electronic devices, this breakthrough will have profound impacts on the electronic industry. Implications of this work for end-users include reduced cost, fast-to-market product development, and products that are "quiet" to environment while offering improved functionality and performance.

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Center for Embedded Systems (CES)

A CISE-funded Center

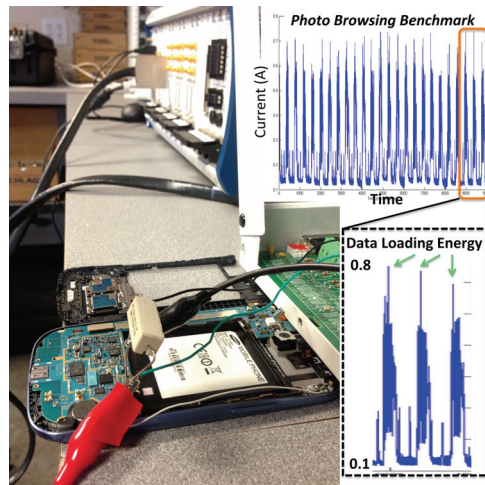Arizona State University, Sarma Vrudhula, Director, 480.727.4152, vrudhula@asu.edu

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Optimizing Energy Efficient Mobile Computing: Explicit Data Communication and Power Management Tool

For manufacturers of microelectronic systems such as smart phones, tablets, and other mobile computing devices and for SoC (system-on-a-chip) designers, manufacturers, and vendors, system power consumption represents a major consideration. SoC designers must optimize power within SoC units, such as CPUs, graphic controllers, display controllers and memory controllers. However, on modern mobile platforms most energy is consumed by data moving between CPUs and memory and display controllers. Researchers at Arizona State University's Center for Embedded Systems (CES) have been working to make SoC architecture and systems more power efficient. This breakthrough work led to the development of a tool that better analyzes power consumption of mobile applications within each unit so as to optimize SoC power efficiency by separating data movement and computation power.

MobileBench is a mobile platform benchmark suite that runs on the Google Android's operating system. MobileBench contains a suite of commonly used smart phone applications that model interactive user behaviors to extract real-world energy usages for mobile platforms. SoC designers are beginning to use the tool for more effective assessments of power consumption. This work is helping the electronics industry produce more efficient SoCs for use in devices that will require less power support. Furthermore, with the insights provided by MobileBench into smart phone application

Mobile platform energy consumption is measured using the National Instrument Energy Measurement and Data Collection Equipment. With the availability of the MobileBench workloads, CES researchers are a step closer to quantifying the increasing amount of data movement energy for modern smart phone architectures. This new CES-developed data communication and power management tool represents an improvement over previous state of the art because it is open source software instrumentation that SoC and other companies can use.

characteristics, the ASU researchers hope to influence the design of future smart phone platforms toward having simpler architectures that lead to lower power consumption and higher performance.

Economic Impact: This energy-efficient mobile platform research tool addresses some of the most critical problems facing society at large, namely, improving microelectronic system energy efficiency, which continues to proliferate at exponential rates. Successful outcomes of the MobileBench tools will result in IAB member companies licensing this CES technology. Mobile-Bench's novel approach to energy consumption is beginning to be used by member companies (e.g., Marvell plans to use this work to better analyze current products for embedding into smart phones and tablets) to create more energy-efficient mobile computing platforms that provide longer lasting connectivity in urban, rural, and energy-challenged areas. This, in turn, should allow for a more ubiquitous computing paradigm. For example, arctic exploration teams could harness the computing power and sensors of mobile computing devices for data extraction, computation, and publishing without having to carry electric generators, thus saving significant energy and resources. The approach also can be applied to even lower-power devices that make up the internet-of-things. This will make it easier to study and optimize energy consumption and should help make computing platforms and devices more connected and unplugged for longer periods. The work has the potential for significant positive economic benefits to the nation and to the electronics industry beyond national boundaries. It may also have significant positive impacts on the environment. Such impacts are difficult to quantify economically. Even so, it is likely that more efficient and lower power processors and other SoC processing elements will have direct impacts on consumer electronics that rely on a billion kWh of electricity. This alone could generate savings of nearly a billion million metric tons of CO_2. Even if this project resulted in only a 5% reduction in energy consumption of the billions of such mobile platforms world-wide, that could reduce the amount of CO_2 released into the atmosphere by hundreds of millions of metric tons per year and annually realize ten of millions of dollars in energy cost savings.

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Design Tool for Mobile Low-power Processors

Mobile low-processor chips have evolved from single core processors into multi-core architectures that integrate 10-20 processor cores, 40-60 customized hardware units or accelerators, and many memory blocks. In other words, the state-of-the-art mobile processors integrate upwards of a hundred fairly complex intellectual property (IP) blocks into a single chip.

There are incessant calls for higher performance, lower power requirements, and shorter times to market. The on-chip interconnection architectures that connect these IP blocks together in cohesive systems have emerged as a key determinant of mobile processor performance and power consumption. These interconnected architectures are implemented as a Network-on-Chip (NoC) that consists of interconnected routers and IP blocks.

Embedded smart devices such as cellular phones and tablets have emerged as the new technology drivers for the semiconductor industry.

CES researchers have developed a computer-aided design (CAD) tool chain for developing the NoC architecture for future Qualcomm mobile processor chips. The NoC tool chain automatically generates high performance, low power on-chip interconnection architectures that are able to successfully address multiple traffic classes, multiple use-cases, deadlock avoidance, multiple clock islands, and bit-width optimization. In minutes, the tool chain is automated and performs design task that can take several weeks of manual effort. Consequently, the synthesized interconnection architecture and the overall mobile processor depict better performance, lower power consumption, and less time to design. The next generation smart phone products will have much higher performance requirements with the same or incrementally longer battery life times. Consequently, future generations of mobile processor chips will integrate ever-increasing numbers of IP blocks on the same chip. The NoC design tool developed by the CES team is a key technology that will enable Qualcomm to maintain its dominant position in the mobile low power processor market.

> **Economic Impact:** A center sponsor, Qualcomm Inc., is the market leader in mobile low-power processors aimed at smart phones and tablets. There are an estimated 5.2 billion cellular phone subscribers worldwide. It is expected that the number of low power mobile processors that are utilized by such devices will hit the 500 million mark by 2015. The increases in efficiency and development savings can be expected to have substantial economic impacts on the electronics industry and on the nation's competitive position.

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Safer In-Vehicle Control Systems and Medical Devices

Embedded computing devices are becoming ubiquitous in our modern societies. It has been estimated that in developed countries there are about 30 embedded computing devices per person. Such devices are mostly operating safety critical systems such as medical devices, flight control systems, communication systems, and safety control features in automobiles; high-end vehicles alone often contain upwards of 60 embedded processors.

Automotive, aerospace, and medical device systems are safety-critical. Design methodologies that can improve confidence in overall system design are highly sought after by industry. One such design methodology is the Model Based Development (MBD) framework where the design of the system starts with a model of the system. Such models are usually developed in a modeling environment that supports a block diagram Graphical User Interface (GUI). GUIs enable modeling of both the physical components of a control system (e.g., modeling of an automobile engine), as well as the cyber components (e.g., modeling the software that controls engine performance).

CES Researchers in collaboration with researchers from University of Colorado, Boulder, and engineers from Toyota have developed S-TALIRO. S-TALIRO is a software tool that systematically checks a given system's model by searching for an input that demonstrates that a functional requirement is not satisfied. Such a functional requirement could be that the engine never stalls while the vehicle is cruising. The process of discovering operating conditions that produce a system behavior that violates a functional requirement is referred to as falsification. Even when falsifying behaviors cannot be found, system behaviors that come "closest" to violating the correctness property are typically returned to system designers.

The advantage of this technology over previous approaches is its applicability to industrial systems. Most alternative verification methods seek a mathematical proof that a property is satisfied. Unfortunately, these mathematical methods do not scale to the complexity of typical industrial control applications, nor do they mathematically "understand" the model's semantics. Because S-TALIRO is a simulation-based approach, it is immune to these difficulties and, thus, is a more robust 'model-based verification' framework that for the first time is being made available to industry.

Economic Impact: Embedded systems must remain operational and reliable for many years. Their software cannot be easily updated. Failures in such systems due to software programming or logic design errors can have catastrophic consequences to human lives and large economic costs to our societies as a whole. Model Based Development (MBD) practices can help eliminate implementation errors. More importantly they can discover design errors very early in the design process. There is a clear need for tools that verify the correctness of a system with respect to functional requirements early in the design process. S-TALIRO can support such verification activities at multiple stages of the MBD cycle. In 2009, the global embedded systems market was estimated to be $208 billion with a yearly growth rate of about 10%. The embedded software itself grows at a rate of 10-30% depending on the application area. Over a decade ago NIST estimated that the annual costs of inadequate infrastructure for testing general purpose software could be as high as $59.5 billion. It is within the realm of possibility that S-TALIRO could help reduce development costs by at from 5% to 37%.

Modern medical devices, airplanes, and cars include embedded software that interacts with the physical environment. Errors in the software can have catastrophic impact both in human lives and in economic costs to the society. S-TALIRO can support testing and verification of embedded software.

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Bulk Tank Allocation Project Leads to Improved Asset Utilization

Faced with a challenging resource allocation project, researchers at the Center for Excellence in Logistics and Distribution (CELDi) at Virginia Tech, in collaboration with personnel at Air Liquide, developed a Bulk Tank Allocation (BTA) tool to reallocate resources and reduce annualized tank investment and distribution costs. This CELDi project targeted increased productivity with bottom-line impact.

An important strategic level decision in the industrial gas industry involves the allocation of bulk gas tanks to customer sites. This project generated a novel approach for resource allocation that analyzes strategic level decisions while incorporating operational-level characteristics. The approach leads to improved distribution efficiency and reduced costs.

For a set of customers having specified demands, the bulk tank allocation problem determines the preferred size of bulk tanks to assign to customer sites in order to minimize tank investment costs and gas distribution costs for the industrial gas distributor. The problem is

An Air Liquide bulk tank. The bulk tank allocation problem determines the preferred size of bulk tanks to assign to customer sites in order to minimize tank investment costs and gas distribution costs for the industrial gas distributor.

modeled as a mixed-integer program and then solved using a decomposition approach. A heuristic method for clustering customers and developing routes is proposed based on a sweep algorithm. These potential routes serve as input for the bulk tank allocation problem, which selects routes and assigns tanks to customer sites.

Economic Impact: Before the development of the BTA tool, bulk tank decisions were often made for individual customers, without the ability to consider interactions with other customers. The BTA tool now allows for the interrelationships between customers to be considered when allocating tanks, providing a system level assessment. The distribution cost savings are also provided at

the system level. The BTA tool has been evaluated using data from Air Liquide to demonstrate the improved efficiency of gas distribution. The tool is currently being deployed as part of the strategic planning system at Air Liquide. The results of this project have appeared in two conference presentations, a journal publication, and the Air Liquide annual report.

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Center for Experimental Research in Computer Systems (CERCS)

A CISE-funded Center

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Attaining Predictably Fast Responses: The "Travelport Flight Shopping Engine"

Researchers at the Center for Experimental Research in Computer Systems (CERCS) have been working with industry to improve the performance of and consider new services and functionality for Travelport, a shopping engine for making travel arrangements (flight shopping). Several prototypes have been developed to address topics that include early problem detection, traffic distribution, multi-core processing, and new services.

These technology breakthroughs improved an existing product for airline shopping, i.e., Travelport's flight shopping engine. These breakthroughs are relevant to all products that require extensive calculations such as flight shopping, ticketing, hotel reservations, and

This work results in a 35% improvement in the average response time of end user requests for travel options (e.g., possible flights) and a 10% reduction in failures to meet response time requirements for such requests.

similar. More importantly, they are relevant to any application for which the amount of processing performed for each request can vary significantly depending on the nature of the requests.

Recent work with Travelport is exploring new services and service opportunities, the idea being to find new ways to monetize the rich shopping and booking information available to Travelport. Prototype software built by CERCS students has demonstrated that such monetization based on online data analytics can even be done online, by observing and then mining customer traffic.

Economic Impact: The economic impact of the breakthrough translated into 20% less hardware purchases by Travelport (the shopping engine provider) and a more competitive position for Travelport's shopping engine in the market place. Well-positioned to capitalize on increasing

travel activities worldwide, Travelport operates both domestically and internationally. By helping local companies develop new services, we help protect and strengthen its financial position, creating jobs in the Atlanta area.

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Scalable Management for Cloud Computing Environments: Monalytics

Cloud computing offers tremendous benefits to organizations by providing on-demand access to configurable computing resources, while lowering costs and enabling entities to increase computing assets with minimal effort. Data centers are the backbone of cloud infrastructures. They must be able to efficiently and rapidly adapt to support the increasing demands of cloud clients. As a result, automation in facility management is a key challenge, particularly when given the large-scale nature of data center and cloud systems.

Cloud providers have difficulty dealing with variability, both in the demands of client applications and in the resources available for the computation. By monitoring all aspects of hardware and software performance, service providers can detect and address performance problems. Unfortunately, for very large scale cloud environments, this cannot be done, since the amounts of monitoring data generated would be staggering. Therefore, cloud vendors are hampered in extending and growing their facilities to meet future demand.

Data centers are the backbone of cloud infrastructures. They must be able to efficiently and rapidly adapt to support the increasing demands of cloud clients.

Researchers at CERCS have developed Monalytics, a manageability software program that facilitates the development of next-generation scalable data center management products for very large cloud computing environments. It operates like the many '"big data" applications used by companies to mine data about customer preferences, but in contrast to those systems, its purpose is to flexibly perform management functions in a manner that scales to the size of the task. It enables cloud service providers to more effectively operate the ever-increasing numbers of hardware and software components in the data center, to make vast amounts of computing power available on demand, and to enable cost savings and reduced energy demands. With this scalability, Monalytics will make it possible for future cloud data centers to provide levels of computing

power equivalent to today's largest supercomputers, thereby realizing the full potential of cloud computing. It does so by processing monitoring data online – to rapidly extract data of interest, in place – where data is generated so that data center networks are not overwhelmed.

Monalytics has attracted attention of multiple companies, such as HP and VMWare. These entities are particularly interested in the ability of the technology to enable significant performance improvements in large scale cloud environments while reducing system management costs. At HP, groups have used the approach to monitor utility data centers. At VMWare, online management methods like those enabled by Monalytics are routinely used to consolidate data center systems.

> **Economic Impact:** This breakthrough enables cloud service providers to more effectively operate the ever-increasing numbers of hardware and software components in the data center, to make vast amounts of computing power available on demand, and to enable cost savings and reduced energy demands. The manageability software market for clouds, in particular, is estimated by International Data Corporation to be a $2.5 billion market by 2015. Monalytics will directly contribute to this market and will accelerate the growth and scope of cloud computing by allowing cloud environments to grow ever larger. It will allow cloud service providers to better meet the challenges of system management for the millions of managed objects in future large cloud environments. Experimental evaluations have shown the Monalytics approach yields up to 92% reduction in time to insight and 86% lower cost compared with traditional approaches to performance management. This advance will result in lower-cost, more efficient data centers run by public and private cloud providers. It will also improve end-users' online experiences, ensuring consistent and reliable performance in their cloud applications, leading to greater adoption of clouds and their use. This can lead to new business opportunities in clouds, such as improved efficiencies offered by online methods for managing data center power consumption, or better service offerings like premium services that provide improved service quality to end users.

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Littoral Combat System with Improved Welding Technologies

The Center for Friction Stir Processing's (CFSP's) research on Friction Stir Welding (FSW), stir spot welding and friction stir structural design and application has resulted in significant improvements to weld strength and durability by, among other things, replacing fusion welds and rivets. Over 12 miles of FSW has been used to fabricate the Littoral Combat Ship (LCS), the USS Freedom, that was commissioned in September of 2006.

The welded aluminum panels for the superstructure were fabricated by Friction Stir Link, Inc. and delivered to Marinette Marine for final assembly. "The collaboration between the CFSP and our company has contributed to the success of the implementation of FSW on the LCS Freedom" stated John F. Hinrichs, Founder and Vice President of Technology, FSL, Inc. FSL has opened a new production facility in Slidell, LA to support continued production of the LCS.

The USS Freedom.

In 2009, this technology was awarded the Alexander Schwarzkopf Prize for Technological Innovation by the I/UCRC Association.

> **Economic Impact:** The use of the solid-state friction stir welding process has resulted in improved strength and fatigue life, reduced distortion, an economical, robust, and repeatable process.

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MacMullin Number for PEMFC Gas Diffusion Media

For proton exchange membrane fuel cells (PEMFC), the porous media of interest has been commonly referred to as gas-diffusion media (GDM) and used as gas-diffusion layers (GDL) in the assembly of the unit cell, even though this media is critical for transport of liquid water as well as gases. A simple technique consisting of a four-electrode system, which uses a square-wave form of current, was developed for measuring the MacMullin number for GDM. The MacMullin number relates the free-stream properties with the actual liquid and gas transport in the GDM. This ratio was successfully measured for different carbon-cloth and carbon-paper GDM, for which, in the absence of information for PEMFC, the Bruggeman expression has been commonly used to correct the free stream properties for the actual path length.

Fuel cell vehicles are one example of a potential application. Photo courtesy of GM.

This technique helps to understand critical properties of gas diffusion media that impact directly the liquid water and gas transport in fuel cell and electrolyzers. It includes assessing the length through which these phases travel. Previously, only measurements of the porosity were used to characterize the GDM and still product data sheets only use porosity. Mathematical models for fuel cell and electrolyzers are also improved by the use of the actual path length that leads to more accurate calculations on liquid and gas transport through the GDM.

> **Economic Impact:** This technique allows for the scientific community to understand that the Bruggeman equation is not valid for carbon paper GDM and that a different relationship exits as a result of the differences in the path length created by the orientation of the fibers in each type of GDM. It provides industry the knowledge to improve the design of GDM and reduce their cost. It is leading the industry to consider the path length for liquid and gas transport as part of their research. This benefits the development of the fuel cell and electrolyzer technologies by provid-

ing optimum designs that improve the efficiency of these devices. This is a significant step forward for moving these technologies from a niche market into a broader market.

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Center for Glass Research (CGR)

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Glass for Toxic Waste Encapsulation

Specialized glasses and glass melting processes are at the heart of toxic waste vitrification, particularly of low-level and high-level radioactive waste, for long-term storage. Collaborative CGR research at Alfred University, the Virginia Military Institute and at the University of Washington's "Center for Process Analytical Chemistry (CPAC)" resulted in major insights into understanding the oxidation state of such glass melts, including the degree and mechanism of mutual interactions (oxidation-reduction reactions) among the many multivalent elements present. This work is at the heart of understanding and predicting chemical durability of the glass, which is essential for assuring long-term stability during underground storage. Results have been found extremely valuable by at least one of our member companies, the Westinghouse Savannah River Company, as have several national laboratories involved with nuclear waste vitrification.
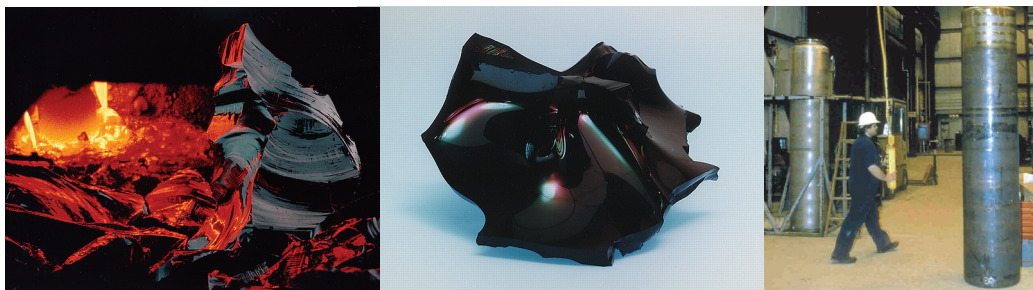
Waste vitrification chemically processes heavy metals and radioactive elements into a durable, leach-resistant glass, which is then placed into a canister. Images courtesy of Pacific Northwest National Laboratory.

Economic Impact: This technological advance contributed essential technical knowledge that has helped the nation and the world deal with the nearly intractable dilemma of what to do with the vast amounts of nuclear waste produced by modern society. The economic impacts of this incredibly important innovative technology are undoubtedly huge but almost impossible to quantify.

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Detection/Intervention System for Individuals with Neurological Movement Disorders

The goal of this breakthrough research is to advance the early detection and management of neurologically induced movement disorders (e.g., Parkinson's Disease) through the use of low cost, non-invasive sensors. The long-term goal of this research is to develop a patient-centered approach to health management using remote, real time feedback between patients and healthcare providers. The developing system is non-invasive, automated, and usable from the comfort of one's home, allowing for remote diagno-

A researcher conducting Parkinson's Disease diagnosis test.

Sensor hardware and visual output of individuals performing related activities.

sis and management of neurologically induced movement disorders. This will eventually empower individuals to play more active roles in their health management.

The main limitation of existing neurological disease diagnosis and management systems is that diagnosis of neurological diseases often occurs at the latter stages of the disease, after severe neurological damage has already occurred. The challenge facing healthcare officials is the ability to develop a proactive system of healthcare management, where individuals actively participate in their own health status and progress. Furthermore, existing diagnosis tools for neurologically induced movement disorders rely on MRI scans which can be expensive.

This detection and intervention system being developed by CHOT researchers at Penn State provides a platform for exploring how digitized health information from video can be safely and securely collected and mined in order to facilitate early detection of motor/gait dysfunction as well as long-term disease management. The system is based on advancements in sensing and information technologies that make it pos-

sible to capture body movement (in a non-invasive, privacy preserving manner) and model and predict the emergence (or lack thereof) of neurologically induced movement disorders such as Parkinson's Disease.

System components include: 1) acquisition and transformation of non-invasive skeletal tracking data relating to each patient; 2) use of data mining algorithms to identify latent patterns in behavior-related patient gait movement; 3) use of those models to quantify, evaluate, and investigate effective methods for early detection of Parkinson's Disease, and then to gauge progression and therapeutic effects; and 4) support for the development of customized healthcare solutions that promote patient safety at different stages of Parkinson's Disease (i.e., predicting falls). An initial research study involving Parkinson's patients and controls revealed a predictive accuracy of over 92.3% using 10-fold cross-validation.

> **Economic Impact**: This may be an increasing important area of research and development for IT companies to explore because early diagnosis of neurological movement disorders is essential and low cost sensors for use in homes and offices are becoming more prevalent.

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Multi-Project Interdependency Mapping

Multi-project interdependency mapping is used to increase the absorptive capacity of health care organizations to effectively implement and sustain innovations.

Health care organizations are frequently faced with the problem of simultaneous projects, initiatives, implementations, or transformations, without always a clear understanding of how these efforts interrelate or support each other. Multi-project interdependency mapping is a tool applied to multiple transformations in order to increase the absorptive capacity of health care organizations to effectively implement and sustain innovations.

The project relies upon both narrative and numeric responses to standard interview items in detailed interviews with dozens of leaders in each health system. Subsequent mapping is based upon leader's discussion of such interdependencies or linkages among projects, prioritization assigned by leaders to each transformational effort, and these leaders' perceptions of the relative reliance of each effort upon each of four organizational technologies – administrative, information, clinical/work, and social technologies. The organizational technologies framework is derived from theories of control and coordination and socio-technical conceptualization of organizations. The organizational technologies framework was developed by CHOT researchers and has been used to compare and contrast a number of major transformation efforts and is currently being applied in two studies of organizational change.

Economic Impact: Top leadership in two large health systems identified this study as being of critical importance to their organizations' learning and bottom lines. The health systems studied were engaged in numerous transformational programs such as the electronic medical record implementation, Six Sigma, culture change, physician engagement, Baldrige review, and ongoing initiatives around quality, patient safety, and cost-effectiveness.

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Advancing Emergency Department Workflow and Operations

In this Center for Health Organization and Transformation (CHOT) project, a novel emergency department decision-support system was designed that couples machine learning, simulation, and optimization. The system allows healthcare providers to optimize workflow globally, taking into account the uncertainties of incoming patient diseases and associated care, thereby significantly reducing the length of stay (thus the wait time) of patients. This was achieved without changing physical layout, focusing instead on process consolidation, operations tracking, and staffing.

The Advancing Clinic Workflow and Operations (ACWO) project has resulted in a patient flow optimization model that improves the operations of emergency departments, both in terms of efficiency and quality of care. The large-scale computerized system model developed by CHOT researchers at Georgia Institute of Technology models emergency department operations with greater realism and accuracy than was previously possible. The ACWO model is generalizable and has been tested and implemented successfully at seven other emergency departments. ACWO was named the second-place winner for the 2013 the Institute for Operations Research and the Management Sciences Daniel H. Wagner Prize for Excellence in Operations Research Practice.

This work optimizes resource allocation in emergency rooms by improving scheduling and workflow efficiency.

The clinic workflow operations model takes into account major elements in emergency departments, including patient flow, clinic workflow, staffing, equipment, and beds. It seeks to optimize emergency department systems to optimize results for patient outcomes. It allows for systems optimization and global intervention that affect both the quality of care and efficiency of delivery. The model is helping organizations deal with critical issues within emergency rooms. It helps address over-crowdedness, where the presence of over 40% of patients with non-urgent medical conditions results in long wait times. Such misalignments of services also result in unnecessarily long lengths of stay, and, at times, decreased quality of care and patient satisfaction.

This work is impacting operations within the emergency department at Grady Memorial Hospital in Atlanta and should be applicable in any emergency department setting. Technically, the model uses an extensive and time-motion study of patient arrival patterns and service process distributions that are more comprehensive than previous studies. Results are important both for understanding the bottleneck, as well as serving as input for the optimization system model.

Economic Impact: This work aims to optimize resource allocation in emergency departments and to improve scheduling and workflow efficiency. Implemented at Grady Memorial Hospital in Atlanta, Georgia, the system has helped reduce length of stay by roughly 30% (from over 10 hours to roughly 7 hours). By identifying patients who may return and place them in observation before discharge, the hospital has realized a 32% of the non-urgent-care cases from the ED. At Grady, emergency department non-urgent case reduction translates to millions of dollars savings. The readmission work should help hospitals avoid penalties as noted in the Affordable Care Act. Reduction in length of stay allows the hospital to see more urgent patients. All of these savings and revenues are essential, not just for Grady, but for the entire United States healthcare system.

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Center for High-Performance & Reconfigurable Computing (CHREC)

A CISE-funded Center

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Space Processor

For over a half century, the United States space program has been a leading contributor to the health and growth of our nation from the perspectives of science, technology, economy, and defense. Given the nature and purpose of past, present, and future spacecraft, from earth science to space science and exploration to defense surveillance, one of the most critical needs and daunting challenges is on-board computing. The major challenges come in two major areas: compression and/or processing of data from on-board sensors; and, processing of data for autonomous-control functions such as landing and docking. In both areas, demands are rapidly accelerating because of technology advances in other areas and because conventional on-board computing technologies are lagging behind in terms of performance required in a harsh space environment. This is due to their size, weight, and power constraints, as well as the inherent hazards of radiation effects outside our planet's atmosphere.
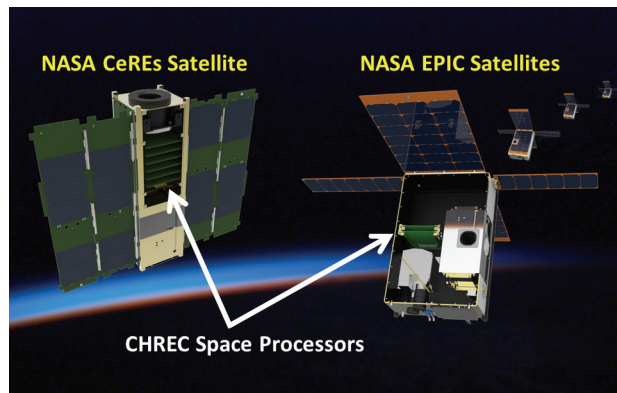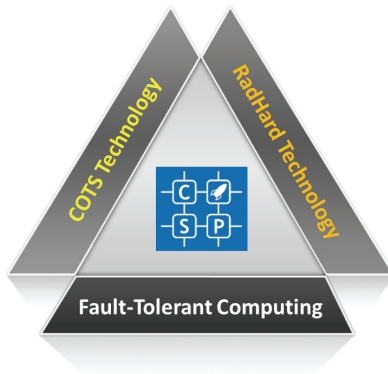
Artist illustration of CeREs and EPIC Satellites with CHREC Space Processors.

Research on the CHREC Space Processor (CSP) takes a multifaceted approach to on-board computing for use in small satellites (CubeSats or NanoSats). The CSP is a scalable device that can support spacecraft of all

sizes. Working closely with NASA, researchers in CHREC at the University of Florida and at Brigham Young University are developing hybrid space computers that feature an innovative combination of three technologies: commercial-off-the-shelf (COTS) devices, radiation-hardened (RadHard) devices, and fault-tolerant computing.

Modern COTS processors provide the utmost in performance and energy efficiency but are susceptible to ionizing radiation in space, whereas RadHard processors are virtually immune to this radiation but are more expensive, larger, less energy-efficient, and generations behind in speed and functionality. Using COTS devices for critical data processing, supported by simpler RadHard devices for monitoring and management of the COTS devices, and augmented with novel uses of fault-tolerant hardware, software, information, and networking within and between the COTS devices, the resulting system can maximize performance and reliability (called performability) while minimizing energy consumption and cost.

Based upon success to date with this CHREC research, the NASA Goddard Space Flight Center has adopted the CSP concept and technology with plans to feature CSP modules on two upcoming space missions: 1) a new technology mission (STP-H5/ISEM: Space Test Program, Houston 5, ISS SpaceCube Experiment Mini) on the International Space Station; and, 2) a new science mission (CeREs: Compact Radiation bElt Explorer to study charged Particle dynamics in Geospace) on a small NASA satellite. On these two space missions, and others expected to follow, such as a constellation of four satellites (EPIC: Earth Photosynthesis Imaging Constellation) that is proposed by NASA for earth science, CSP will provide an unprecedented combination of performance, reliability, size, weight, and low cost for space-based computing.

> **Economic Impact**: The hybrid approach of CSP has the potential to dramatically increase capabilities and reduce costs associated with spacecraft and space-based processing. The breakthrough work could lead to significant economic impacts in the US space industry. In terms of direct economic impact, instead of having to develop new RadHard processor technologies (at an estimated cost of $20 million for each new processor) and then exclusively rely upon these expensive and slower RadHard devices for reliable space systems (an estimated $10K to $100K per unit), the CSP approach enables future systems to reliably achieve higher performance and lower cost and do so with less size, weight, and power. Moreover, for the first time, the space industry will be able to rapidly exploit technology breakthroughs from the consumer marketplace in the form of new and emerging COTS processors. The indirect economic impacts may even be more significant. By incorporating the space processor technology innovative space missions may be made more feasible. Major savings may come from spacecraft and launch vehicles that are smaller and less expensive than otherwise would be necessary, thus resulting in scientific discoveries and economic benefits that otherwise would have been lost. The nature and economic impacts of the latter are impossible to calculate.

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Novo-G: Reconfigurable Supercomputer

The Novo-G Reconfigurable Supercomputer is the most powerful computer capable of hardware reconfiguration in the world. Each of its 416 reconfigurable processors is highly adaptable in hardware structure to match the unique needs of each application. When compared to conventional supercomputers, Novo-G is orders of magnitude smaller in power, cooling, size, weight and cost.

Computers are at the forefront of technologies serving the needs of society in health, science, commerce, defense, entertainment, and more. In many of these areas demands for computing speed are insatiable, with ever increasing challenging problems requiring increasingly powerful machines, the pinnacle in 2013 being Petascale supercomputers completing quadrillions of complex operations per second.

Virtually all computers in the world today, from smartphones to supercomputers, are alike in terms of the nature of the processing devices employed. These processors (e.g., CPUs, GPUs) are predefined and inflexible in terms of their key architectural attributes such as: the format and precision of data and the mathematical operations supported in hardware; the width and depth of parallelism; the size of their processing cores and how they connect to one another; and, the structure of their memory systems. When applications are developed for these systems, they must be partitioned and mapped to these predefined features. With applications that cannot be mapped effectively, there is consequently much loss of efficiency, leading to systems that are much higher in power, size, weight, and cost than would be necessarily required.

The NSF CHREC Center (pronounced "shrek") conducts research on new and alternative forms of computers for the future. They feature processors with flexible structures that can be adapted to match the unique needs of a vast variety of applications. The foremost of these machines is Novo-G, which was created and is under continuing development by CHREC. It is the most powerful reconfigurable computer in the known world. Note: The Novo-G was awarded the Alexander Schwarzkopf Prize for Technological Innovation by the I/UCRC Association in 2012.

This Novo-G features more than 400 special processors known as field-programmable gate arrays (FPGAs), each of which is capable of being reconfigured with custom data types, operation types, width and depth of parallelism, cores, and core interconnects. A broad variety of applications can benefit from this approach, in domains such as signal and image processing, bioinformatics, computational finance, cryptol-

ogy, and many more. In some cases, results on Novo-G are dramatic, achieving speeds comparable to the largest supercomputers in the world that are orders of magnitude higher in cost, power, size, and weight.

Since the first prototype crafted in 2009, Novo-G has continued to successfully fulfill its primary purpose, namely, to accelerate applications from diverse sets of domains. Recently, the machine has also shown promise and been selected for a new area of research known as behavioral emulation. The focus of this new research is exploration of future computers up to Exascale, a thousand-fold faster than Petascale, where unprecedented challenges lie ahead in basic research on new architectures, networks, systems, applications, tools, and services. The new research must reach this scale in reliable, energy-efficient, and sustainable manners.

Recognizing that existing analytical and simulative methods may not adequately scale to analyze these extremely massive systems of the future with the necessary accuracy in reasonable response times, CHREC researchers developed a fast and scalable approach for the study of future-generation supercomputers and applications up to Exascale. This new approach, which features behavioral emulation to mimic the behaviors of various objects in the system with the reconfigurable processors of Novo-G, is being funded by a $2 million, five-year grant (2014-2019) from the U.S. Department of Energy.

> **Economic Impact:** The Novo-G machine can rival the speed of the world's largest supercomputers on important applications at a tiny fraction of their cost, size, weight, power and cooling. Conventional supercomputers, some the size of a large building, can consume millions of watts of electrical power, generating massive amounts of heat. This is in contrast to the Novo-G, which is about the size two home refrigerators and consumes only about 15 kilowatts. With the emerging field of reconfigurable computing, and innovative forms of reconfigurable machines like Novo-G, the potential exists to realize significant economic impact. By solving a broadening range of major problems required of computers, and doing so with hundreds or even thousands of times less resources, untold billions of dollars could be saved annually in energy and other costs versus conventional machines. Moreover, with severe limits in higher integrated-circuit density with ever smaller transistors being predicted for the coming decade, processors of the future must make more efficient use of each and every transistor, thereby making reconfigurable computing even more promising and economically important as a new solution. Finally, and perhaps most importantly, faster computers by nature lead to new solutions from evermore challenging problems too computational-intensive to be previously attempted. This is resulting in new knowledge that can revolutionize fields of study in the physical and health sciences and beyond. The benefits of such advances to science and the nation, made possible by innovations in reconfigurable computing, are difficult to quantify but will undoubtedly be substantial.

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Center for Hybrid Multicore Productivity Research (CHMPR)

A CISE-funded Center

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GrowthTracker: Diagnosing Unbounded Heap Growth in C++ Software

Robust, mission-critical software is a fundamental requirement of any nation's cyber infrastructure. This breakthrough by CHMPR researchers at the University of California, San Diego site creates essentially a set tools that make possible robust, mission-critical execution of software by efficiently tracking use of computer systems' memory resources.

As time to market shrinks and programmers use mash up techniques to rapidly bring software systems live on the Internet, it becomes impossible to test all input conditions of a software system. This breakthrough monitors memory usage during run time executions of programs to avoid program failure and provide a software system with higher reliability and availability.
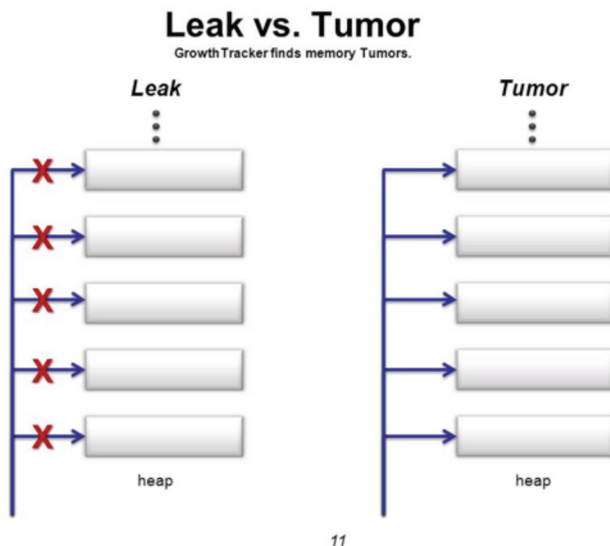
This graphic shows the difference between a memory leak, in which memory is continuously allocated without being utilized, and a memory tumor, which our tool detects where memory allocations unintentionally continue to grow.

Programs that allocate memory but do not occasionally free it up can be detected using tools known in prior art. C++ Programs where memory growth happens in unbounded fashions are detected in literature using staleness techniques - based on the last time it was accessed. The current techniques are not robust and create many false positives and false negatives. The current breakthrough is more robust and allows

memory growth to be tracked at an appropriate granularity to reduce the number of false positives and false negatives. This technique has been peer reviewed and published at the ICST 2013 (IEEE International Conference on Software Testing and Validation).
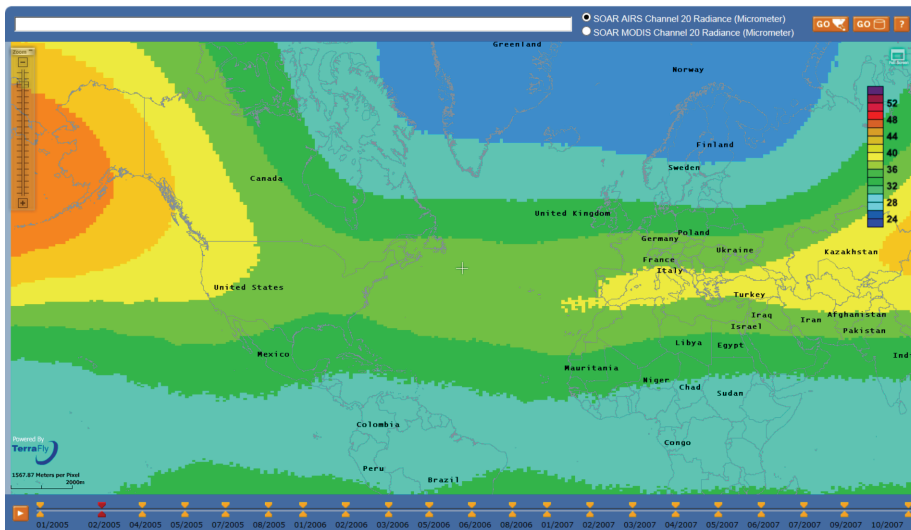
Software systems with extremely large set of C++ objects and threads where the number of objects to be created is not known *a priori*, for example, in large virtual worlds nor in large cloud-based in-memory databases. GrowthTracker can also be applied to embedded systems with very small memory footprints where efficient memory management is critical for system availability, like mobile devices.

> **Economic Impact**: As the number of cores increases exponentially in datacenters and mobile devices, efficient techniques for memory management are becoming increasingly important. In today's increasingly complex computing systems, the reliability and scalability of systems becomes critical. This work greatly improves the robustness and reliability of software. We have deployed this approach to find heap management errors in popular software such as Google's Chrome web browser, Apple's WebKit (Safari Browser), the Ogre3D rendering engine, and the Bullet physics simulation toolkit. We submitted fixes to all of these software systems, greatly improving their stability. The economic impact on widespread adoption of GrowthTracker will likely have significant impacts on the stability of software systems, ranging from increases in productivity gained by software not crashing, to preventing catastrophic failures of software systems whose memory usage aberrantly grows over time in manners that were heretofore very difficult to detect. Not detecting aberrant growth eventually causes systems to crash. We call this growth a "tumor" as it is analogous to the biological phenomenon. We disseminated our approach to identifying and solving these software engineering problems in publications and conference presentations. This allows industry to learn from and be influenced by the methodology. It also helps industry to prepare for new challenges in scale and efficiency.

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Distributed Cloud Computing: 3-D Visualization Services for Climate Data on Demand

This breakthrough results from collaborations between two IUCRCs, the Center for Hybrid Multicore Productivity Research (CHMPR) at the University of Maryland, Baltimore County (UMBC) and the Center for Advanced Knowledge Enablement (CAKE) at Florida International University (FIU) and Florida Atlantic University (FAU). See the "Center for Advanced Knowledge Enablement (CAKE)" on page 27 for more information.
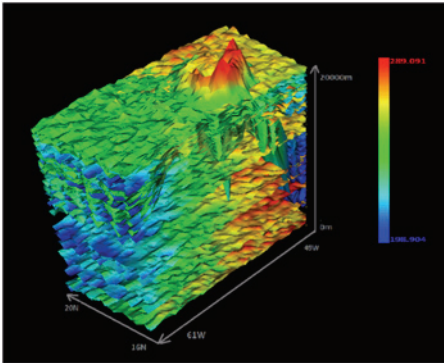

Satellite imagery enables precise measurement of global temperatures. This image presents the 8-year global average surface temperature (as Brightness Temperature colors higher on the scale are representative of warmer temperatures); by comparing successive average surface temperatures, global temperature changes can be detected.

Measuring the surface temperature of the entire earth on a daily basis is a difficult challenge because 75% of the planet is covered with oceans and ice. Continuously determining, for several days to weeks, the vertical thermal (i.e., temperature) field around a hurricane surrounded by dynamically rotating clouds is needed for more accurate landfall predictions. Thus, for applications ranging from climate change to hurricanes, satellites measure the earth's emitted infrared radiation twice daily with sufficiently high spatial and spectral (related to the spectrum) resolution to provide an estimate of vertical profiles of regional or global surface brightness temperature (BT). However, in order to assess global warming, these temperatures need to be measured to within an accuracy of 0.10 °C per year since models indicate CO_2 warming of ~20-30 °C over 100 years. Moreover, to resolve the structure around hurricanes, infrared data at resolutions of 1-5 km are needed. Not until 2002, when the Aqua (Latin for water) satellite was launched, has there been a single satellite with instruments that can meet both the accuracy and the precision required.

Center for Hybrid Multicore Productivity Research (CHMPR)

This breakthrough work makes it possible to deliver a decade of 3-D animated visualizations of spectral infrared (IR) satellite radiance data from instruments on Aqua. These animations use 3-D to show the vertical structure of a decade of global and regional temperature trends occurring at the surface and lower troposphere. In addition, the algorithms developed by CHMPR have been providing CAKE with 3-D temperature profiles that specify the thermal structure around hurricanes in order to improve their landfall prediction.

Atmospheric temperature layers up to 20,000 meters (65,619 feet). The vertical axis shows the height above sea level. The coldest (blue) and hottest (red) points in the eye of the hurricane are shown. The horizontal axes show the location of the hurricane (latitude and longitude).

CAKE and CHMPR have implemented a distributed cloud computing web-based service, called SOAR. This service incorporates visualization as a public service available on a multi-core IBM-based server cluster. This system provides researchers and students with the ability to select regional and chronological periods and automatically transform IR orbital satellite data into spherical grid arrays of 3-D temperature profiles for viewing the continuous changing thermal structure of the atmosphere. The FIU site at CAKE added value to the satellite data visualization by providing spatiotemporal (i.e., space-time) visualization and animation of the data (http://cake.fiu.edu/SOAR) using the FIU TerraFly Geospatial Data Management Service (http://terrafly.com). The FAU site at CAKE developed tools for 3-D visualization of the vertical temperature profiles; when coupled with CHMPR's data-gridding techniques, this partnership has created the first integrated, scientifically-validated, multi-year infrared brightness temperature record.

Economic Impact: Fundamental Decadal Data Records are highly desired products recommended by the National Academy of Science/National Research Council. The SOAR distributed cloud computing web-based service enhances NASA's ACCESS program by providing fundamental brightness temperature records. This can go a long way towards improving scientific and public understanding of the nature of global and regional climate change. As a result, everyone can be better positioned to design policies and actions for mitigating negative climate impacts on the economy, which could include billions of dollars of property value lost to sea-level rise and billions of dollars of insurable losses due to increases in extreme weather-related disasters.

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Specialized Graphic Processors

Until this year, supercomputers were based on tens of thousands of commodity processors like Intel and AMD multicore chips with 2 to 8 processors found in ordinary personal computers (PCs). These PCs contain specialized graphics cards that use hundreds of processors on their chips to render animations for games, simulations, and videos that are very fast and cheap. The graphics chips (GPUs) have evolved software and hardware that can not only do more than graphic renderings but can also perform complex floating point arithmetic.

Lockheed Martin, a CHMPR member, supported a project at UMBC to study and test the performance of these GPUs when added to commodity based clusters. The company wanted to know whether such GPUs can accelerate the performance of the solution of a system of equations with more than a million unknowns.

Such problems lead to enormous matrices of 1 million by 1 million terms or more than 30 Terrabytes (32×10^{12} or 32 million million), well beyond the capability of any computer to hold all these data internally in memory. Thus, this data intensive problem requires continuous moving of data from disks in and out of memory so that the processors can compute on them and then store them back on disks for future operations. It requires that all of the operations work in parallel. The method chosen for solving such equations is known as Gauss elimination and for implementation uses a transformation of the matrix into lower and upper triangular forms for direct and very fast solutions. These problems are commonly used in economics, chemistry, computer science, physics, and engineering.
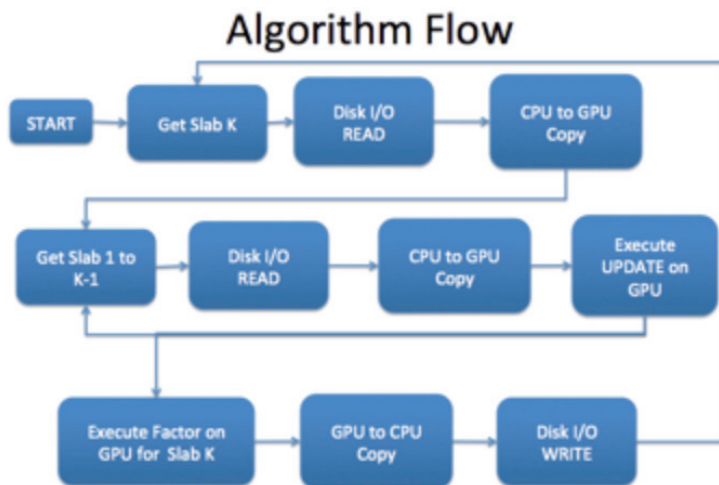
The algorithm performing operations in disk IO, CPU, and GPU.

Even with high speed interconnects, disks, and CPUs, the solution time for 1 million unknowns exceeds 25 days on a single multicore commodity chip. As a test case for Lockheed Martin, this project used two sys-

tems to perform timing tests. One system was based on their Cray computing node with an AMD chip and an Nvidia GPU. The other system used the CHMPR computing node with an Intel chip and also an Nvidia GPU processor. A key result obtained with the additional graphic co-processor added to the system (the Nvidia GPU) was a reduction in clock time for solving a problem of 40,000 unknowns from 5 hours of solid computing to 40 minutes. Further studies indicate that the potential exists for reducing this time to less than 2 minutes when more recent available GPUs are used, combined with solid-state disks.

Other government sponsors such as the NOAA/National Center for Environmental Prediction, which is responsible for operational weather and climate forecasting, and The NSA/Laboratory for Physical Sciences are supporting research into the resiliency of such hardware configurations when scaling to hundreds of millions of such processors.

> **Economic Impact:** This work exploited the extraordinary computational power of GPUs to accelerate data- and compute-intensive applications, which had not been investigated previously. Findings are being used to help improve the efficiency of computing systems. When using the capabilities developed at CHMPR for capitalizing on the parallel nature of the architecture, significant cost benefits, savings, and new performance studies are possible for many critically important real world applications. This work has made general accelerator technologies more feasible for solving large 64-bit complex valued matrices that exceed 1 million unknowns. In addition, more efficient use of accelerators such as GPUs will make possible significant reductions in cooling costs. For large production-quality computer systems the annual saving can be expected to approach a million dollars.

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Center for Identification Technology Research (CITeR)

A CISE-funded Center

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Automated Virtual Agent for Truth Assessments in Real Time (AVATAR)

An AVATAR kiosk conducts natural credibility assessment interviews automatically. AVATAR avoids bias, favoritism, or fatigue by using non-contact sensors to determine credibility risk.

Researchers at CITeR have developed AVATAR, a kiosk-based automated screening system for credibility assessment. AVATAR automatically conducts natural, brief interviews for trusted traveler application programs, personnel reinvestigations, visa application reviews, or similar scenarios where truth assessment is a key concern. AVATAR uses non-invasive sensors to identify suspicious or irregular behavior that deserves further investigation. Unlike human interviewers, AVATAR's credibility assessment is free of biases, profiling and distractions. They may be capable of delivering more valid risk score than interviewer's "gut instincts." AVATAR also incorporates identity confirmation, biometric identification, document authentication, and payment processing. Using AVATAR technology, customers can automate organizational and security processes that normally require costly, labor-intensive interactions. This technology emerges at a critical juncture when organizations, particularly in government, have increasing workloads, but few additional manpower resources. Finally, kiosks never have bad days, unless they freeze or become non-operations; nor do they get fatigued at the end of 12 hour shifts.

Whereas current state-of-the-art products take extensive human skill and uses contact sensors like electrodes or blood pressure cuffs, the AVATAR uses a suite of non-contact sensors to monitor patterns in an interviewee's physiology and behavior. It then analyzes those patterns to guide the interview conducted by the system. In addition, the AVATAR includes biometrics (like iris scans) and document scanning to facilitate full self-service interviewing and screening. For example, an airport traveler can scan their passport, complete a screening interview, be identified biometrically (fingerprint or facial recognition), pay for additional services with a credit card, and receive a print out of their transaction.

While AVATAR researchers have spent many years conducting basic research and prototyping systems, they have also acquired a deep understanding of the most likely operational environments. All AVATAR kiosks

are networked wirelessly and securely to an administration tablet that can be monitored by a human screener. The system can be used to complement a human interviewer by presenting enhanced analysis of behavior and physiology, or it can serve as a stand-alone, completely automated solution.

A personalized interviewer may be desirable because all interviewees are not the same and would be expected to respond differently to diverse situations. AVATAR systems can be customized to speak and understand any language using advanced speech recognition. They can draw upon information from existing organizational databases to inform the interview (e.g., refer to the interviewee by name, ask personally relevant questions) and can store collected data such as spoken interview responses and interaction statistics.

In many setting where large-scale processing of people and data are required, AVATAR kiosks could relieve people from the most mundane, repetitive tasks so that their skills and training are put to better use, but can also detect subtle indicators of threat, risk, or misrepresentation that might be missed by all but the most experienced and skilled humans. The AVATAR kiosk is not limited to security screening. Other commercial applications are numerous. For example, businesses with a large employee base could use AVATAR to streamline employment applications by collecting preliminary demographic data, searching out prior employment history and gauging a person's truthfulness and suitability for a given workplace. In financial fields, AVATAR's sensors have already been tested for their ability to detect fraud in written statements and during interviews. In the medical environment, AVATAR systems could be equipped to do routine medical exams (e.g., collect heart rate), triage patients, dispense health information and encourage more candid disclosure of compliance or noncompliance with medical regimens. In the educational context, AVATAR systems might administer skill tests while detecting levels of stress or loss of attention. For written exams, AVATAR might reduce opportunities for cheating.

> **Economic Impact**: In today's security conscious environments, border screening is a time and labor intensive process. It requires a vast work force to provide efficient and effective screening for the millions of crossers entering the US daily. Border security organizations have been early testers of prototype versions of AVATAR. The Department of Homeland Security (DHS) has tested it with its Trusted Traveler program. The European Union border control agency has tested it for imposter detection, deception detection and risk assessment. Automating the screening process and providing customs and border agents enhanced information on individuals seeking entry can significantly reduce labor costs by having one officer oversee a bank of kiosks. For DHS, AVATAR could serve as a force multiplier that frees personnel to focus on other mission-critical tasks while at the same time improve outcomes by providing more accurate decision support and risk assessments. This could be accomplished by automating interviews and document/biometric collection and by delivering real-time multi-sensor credibility assessments. Successful large-scale implementations could lead to multibillion dollar operational savings and perhaps even real improvements in security. A new company has been established to work on customizing AVATAR for specific contexts and uses, such as border screening, border adjudication, personnel investigations and re-investigations, and asylum and refugee applications. The potential economic benefits are therefore only limited by one's imagination.

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Automated Detection of Altered Fingerprints

For over 100 years, fingerprint identification has been successfully used to identify suspects and victims, primarily in law enforcement and forensics. Now it has become the backbone for broad security applications at border crossings, civil registration, and access control to secure buildings, or computer login. With the widespread deployment of Automated Fingerprint Identification Systems (AFIS), there have been growing instances worldwide where individuals, particularly criminals wish to conceal their true identity and illegal aliens wishing to enter another country. Such individuals have altered (mutilated or destroyed) their fingerprint patterns by means of abrading, cutting, burning, or performing a plastic surgery on fingertips in order to evade AFIS.

Images of altered fingerprints. (Left) Fingerprint pattern destroyed by biting the finger skin. (Right) Transplanted friction ridge skin from sole.

Fingerprints of Gus Winkler before and after alteration.

Center for Identification Technology Research (CITeR)

One of the urgent tasks faced by law enforcement and border control agencies worldwide is to detect the altered fingerprints automatically so that individuals with altered fingerprints go through a secondary inspection to establish true identity. Because law enforcement officers handle millions of fingerprints every day, this detection needs to be extremely fast and reliable; meaning very few false alarms (as is the Department of Homeland Security's US-VISIT system and the FBI's IAFIS system). Research supported by the Center for Identification Technology Research (CITeR) has led to the development of an innovative approach for automatically detecting altered fingerprints based on pattern analysis techniques and mathematical modeling of fingerprints. Altered fingerprints are detected by observing abnormality in two fundamental fingerprint features – orientation field (fingerprint ridge flow) and minutiae (ridge bifurcation and ending points).
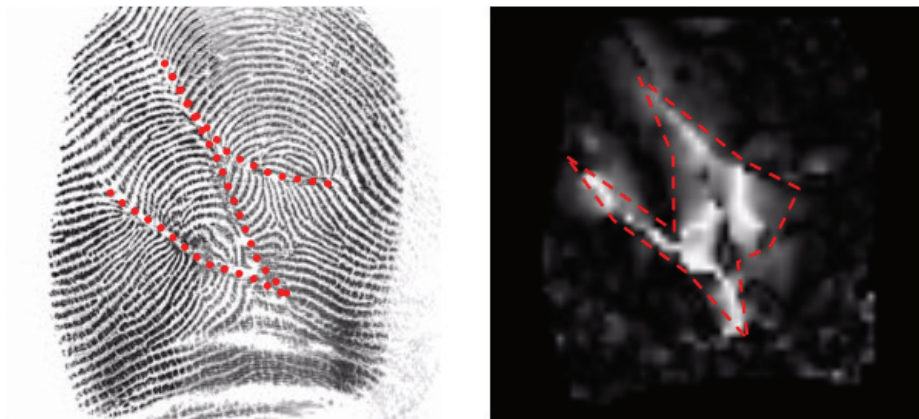
Detection of altered fingerprints. (Left) Altered fingerprints with 'Z'-shaped cut and (right) automatic detection of fingerprint alteration based on orientation field discontinuity. Brighter pixels in (right) represent discontinuity in orientation field and correspond to the scarred region in the altered fingerprint in (left).

With CITeR funding, Anil Jain and his students at Michigan State University (MSU) have developed algorithms for automatic detection of altered fingerprints. The resulting software for detecting altered fingerprints has been licensed to Morpho (Safran Group), one of the world's leading suppliers of identification, detection, and e-document solutions. Morpho customers include the Federal Bureau of Investigation (FBI) and more than 450 government agencies in over 100 different countries. The technology for automatic detection of altered fingerprints, developed by the MSU team through CITeR funding, will be integrated in Morpho products to prevent criminals and asylum seekers worldwide to evade identification through AFIS. This is an example of a successful transition from university research to a proof-of-concept to a commercial product.

> **Economic Impact:** The expected economic benefits of this breakthrough technology will come from the fact that it will foil most attempts by criminals and terrorists to alter fingerprints. This innovative advancement is expected to have many major, albeit hard to quantify positive economic impacts, mostly in avoided security breaches and the of the associated, oft incalculable costs. They will also result in economic benefits resulting from: 1) welfare programs secured by
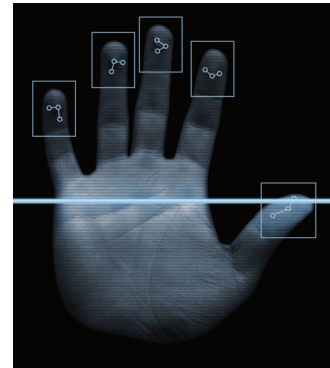
fingerprint recognition, effectively preventing fraud through fingerprint alteration; 2) prevention of criminals and other undesirable individuals from crossing national borders; and, 3) forestalling asylum seekers with prior history of criminal conviction from gaining entry where they are not wanted.

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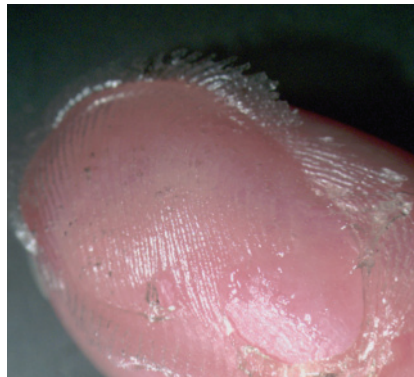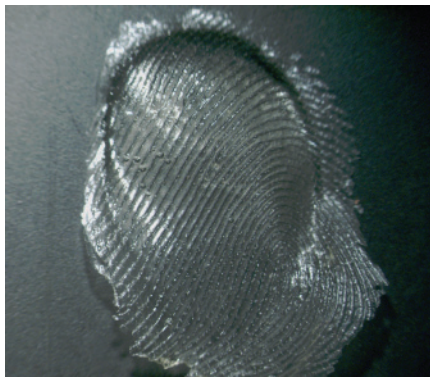
Fingerprint Liveness Detection

Researchers at CITeR have shown that fingerprint biometric scanners, used for secure authentication, can be deceived easily, using simple, inexpensive techniques with fake or dismembered fingers, called spoofing. In this CITeR breakthrough, it has been demonstrated that perspiration can be used as a measure of liveness detection for fingerprint biometric systems. As a result, the potential for spoofing biometric fingerprint devices, one major vulnerability in the industry, in being minimized. Unlike cadaver or spoof fingers, live fingers demonstrate a distinctive spatial moisture pattern when in physical contact with the capturing surface of the fingerprint scanner. The work has considerate applications for homeland security.

Fingerprints are useful as a convenient form of authentication, used alone or in combination with other forms such as passwords.

The pattern in the fingerprint images begins as 'patchy' areas of moisture around the pores spreading across the ridges over time. Image processing and pattern recognition algorithms have been developed to quantify this phenomenon using wavelet and statistical approaches. Previously, commercial biometric devices did not have a mechanism to prevent spoofing. Prior to the Fingerprint Liveness Detection (FLD) research, the main approach to spoofing prevention was to combine the biometric with additional hardware to measure liveness signals such as the electrocardiogram, pulse oximetry, or temperature. Disadvantages included the need for additional hardware that was bulky and inconvenient and possibility spoofable by a live (un-authorized) finger in combination with the spoof finger.

The CITeR breakthrough is a software method for fake fingerprint detection. The left image is an example fake finger and on right is a fake finger masking a real.

The work has considerable application for homeland security and mobile applications. The advantage of this new CITeR approach is that the biometric itself is naturally integrated with the liveness measure, requiring only an additional software algorithm to protect from spoofing. This research has raised the visibility of these major security issues through presentations, publications, and mainstream media (Discovery Channel, New York Times, National Public Radio) featuring FLD. As a result, industry has moved towards developing biometric devices that incorporate liveness, as well as other anti-spoofing measures. With three awarded patents, the CITeR-developed algorithms are being used by major biometric companies around the world.

> **Economic Impact:** The center's universities have licensed the intellectual property to a start-up company, called NexID Biometrics, LLC, incorporated, owned by the researchers. Further development and commercialization was performed by NexID Biometrics, LLC, which now has three permanent employees. The algorithm has been customized to provide liveness detection for variety of fingerprint sensors. The company has licensed the software to biometric industry and to system integrators for integration with their biometric systems. Its commercialization pathways have included integration with single print fingerprint scanners and four print scanners, as well as integration in mass market swipe fingerprint sensors integrated with laptops. At this time, well over 1,000,000 laptops worldwide include versions of fingerprint liveness detection approaches derived from CITeR research.

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Center for Information Protection (CIP)

A CISE-funded Center

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Identity Theft Awareness & Prevention

Fraud prevention is fundamental to the survival of any business (or government for that matter), as is prevention of consumer/customer identity theft. Researchers at the Center for Information Protection have made advances in ID theft awareness research, evaluation, and education. They have developed company awareness policies and lists of behavioral traits that make employees vulnerable to behavior that can lead to sensitive personal data loss of customers. Data collected from surveys and interviews of insurance professionals, as well as of consumers, provided the basis for this work. The literature in behavioral and workplace psychology and busi-

Fraud prevention is fundamental to the survival of businesses and governments.

ness/behavior was qualitatively scrutinized for insights into high risk and careless behavior of employees and customers. Public policies and best practices for due diligence were analyzed to more precisely identify avenues for remediation that can reduce future identity theft losses. Deliverables of this work included books on ID theft, manager and employee training materials, and presentations for corporate and public education.

> **Economic Impact**: This work is fundamental to enabling sustainable economic development. The theft of identities has become an epidemic and threatens to disrupt business at all levels as well as the personal lives of the business's employees. Prevention of this theft can only be accomplished through the systematic training and education of individuals.

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Center for Integration of Composites into Infrastructure (CICI)

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Fabric-Reinforced Cementitious Matrix (FRCM)

Fabric-Reinforced Cementitious Matrix (FRCM) is a composite material consisting of a sequence of one or more layers of cement-based matrix reinforced with dry fibers in the form of open single or multiple fabrics. When adhered to concrete or masonry structural members, FRCMs form an externally bonded strengthening system.

The repair, retrofit, and rehabilitation of existing concrete and masonry structures has traditionally been accomplished using materials and construction techniques including fiber-reinforced polymer (FRP) systems, steel plates, reinforced concrete overlays, and post-tensioning. The primary reasons for considering FRCM as a suitable strengthening material stems from the cementitious matrix that has the advantages of: inherent heat resistance; compatibility with the substrate (i.e., allows vapor permeability and application on a wet surface); long-term durability; ease of installation and cleaning of equipment and tools; and, absence of constituents hazardous to workers and environment.

Fabric reinforcement for a concrete surface.

This breakthrough technology has resulted in a product line for Ruredil that has obtained certification from ICC Evaluation Services (ICC-ES), according to AC434-13 "Acceptance Criteria for Masonry and Concrete Strengthening Using Fiber-reinforced Cementitious Matrix (FRCM) Composite Systems." AC434-13 establishes guidelines for the necessary tests and calculations required to receive a product research report from ICC-ES. Thus, this product can now be accepted by code officials under Section 104.11.1 of the International Building Code, which allows research reports to be used as a source of information to show building code compliance of alternative materials.

Economic Impact: Fabric-Reinforced Cementitious Matrix is a new tool in the toolbox of the construction industry to address sustainability challenges and make repair and rehabilitation of exist-

ing structures not only safer but also economically viable. By using FRCM, engineers and contractors can make repair more economical and durable. Since the tool does not require special training or expertise outside of what is already possessed by construction workers, this technology results in substantially lower labor costs. This benefit added to the ease of installation and the absence of hazardous components is beneficial to owners and more importantly the overall public.

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Extending the Service Life of Bridges with Composite Wraps

Bridge infrastructure in the United States is aging. Bridges show their age through crumbling concrete and rough roads due in large part to foregone and/or poor maintenance. Repairs and upgrades are often necessitated because of increasing traffic loads and heavier vehicles. Traditionally, the only way to remedy these problems has been to close all or part of a highway and replacing the entire structure. This process results in huge replacement costs, complicated traffic re-routings and long delays. Researchers at the Center for Integration of Composites into Infrastructure (CICI) have developed tools that allow highway departments to design structures

Before and after composite wrapping.

tures that save costs by using innovative materials to rehabilitate, rather than replace failing bridges.

Composite wraps, consisting of fiberglass or carbon fiber fabrics saturated with a resin and bonded to concrete members, are being used to repair bridge members that are deficient due to corrosion, decay, or even accidents. At CICI, these composite wraps have been demonstrated to be highly effective on a number of projects. CICI is working with the West Virginia Department of Transportation, Division of Highways to develop standard details and specifications to allow practicing engineers to design, install, and inspect composite wraps.

Composite wraps can also increase the strength of an otherwise good member. This can enable existing structures to carry higher and heavier loads than they were originally designed to accommodate. Installation of the wraps can be done very rapidly with minimal traffic interruption.

> **Economic Impact:** Using composite wraps can extend the lifespan of a structure by a decade or more. Rehabilitation time can be reduced from months to weeks. The result is reduced costs and increased structure life. The cost savings directly impact taxpayers by allowing limited transportation funding to improve more structures at substantially minimized cost.

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Design Guide for Reinforcing Bridge Decks and Railings with Longer Service Capability

Corrosion is one of the main causes of infrastructure decay. Imagine bridge decks that could last 75 to 100 years in service rather than the current 25 to 40 years. Researchers at the Center for Repair of Buildings & Bridges with Composites are enabling a whole new industry to fill the need for potentially high volumes of fiber-reinforced polymer (FRP) rebar. This is being accomplished by developing guidelines that will enable the use of FRP reinforcing bars in bridge decks in the United States.

The recently adopted design guide is the culmination of many years of research. This work means that previously funded NSF research in the field of fiber-reinforced polymers can now be used to make the nation's infrastructure more durable and longer lasting.

By using noncorrosive fiber-reinforced polymers rebar, the bridge decks will last many years longer and delay the costly replacement by decades.

The document will allow fiber-reinforced polymer producers, as well as state and federal departments of transportation, to safely incorporate well-researched design, testing, and implementation criteria to new materials for new construction and renovations. Before these guidelines had been published and adopted, there was little or no incentive for state Department of Transportation (DOT) engineers to consider as fiber-reinforced polymers.

> **Economic Impact:** A primary cause of bridge deck deterioration is corrosion of steel rebar. By using noncorrosive FRP rebar the bridge decks will last many years longer and delay the costly replacement by decades. This will save taxpayers money by not having to replace the decks and also by reducing delays related to bridge reconstruction. By establishing these national stan-

dards on the use of FRP rebar, state highway departments and manufacturers will have clear specifications to provide for the widespread adoption of FRP rebar.

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Preformed Fiberglass Grating Panel Systems (GRIDFORM)

GRIDFORM consists of fiberglass grating panel systems with fiber-reinforced polymer (FRP) plate for stay in place use. These FRP grating panels replace steel rebar in reinforced concrete bridge decks on vehicular bridges. The grating panels are shop fabricated and shipped to the job site ready for installation on the steel bridge girders and the concrete pour. Field installation time for the GRIDFORM

Construction workers walking on GRIDFORM reinforcement while placing concrete GRIDFORM panels.

panels, including the concrete pouring, is approximately 25% of normal steel rebar installation and concrete pour. This reduced installation time results in lower field installation costs and less disruption of service for people needing access to the bridge for travel. Additionally, reduced field installation time translates into a lower rate of construction workplace injuries.

GRIDFORM grating panels have become recognized as a viable alternative to traditional steel reinforced concrete bridge decks. The use of GRIDFORM panels meets the Federal Highway Administration's (FHWA) initiative of "Get In and Get Out." The emphasis by FHWA is to reduce the amount of construction time and the concurrent disruption to the traveling public by utilizing new technologies and methods for rapid construction of bridges and roads. The new technology will result in producing the FRP grating panels at the manufacturing site of the FRP grating. This new breakthrough technology has resulted in a new product line for the Strongwell plant located in Chatfield, Minnesota. Strongwell is promoting this new product line to county and state transportation officials as a time saving alternative to traditional construction materials.

Economic Impact: By using GRIDFORM panels, contractors can reduce construction time by 25%, resulting in lower labor costs and saving taxpayer's money through more efficient use of transportation funding. This will also save the traveling public money directly by reducing the closure time needed to replace or repair and existing bridge decks and the time and inconvenience related to associated lane closures and detours. An often overlooked economic factor is improved safety and less work related accidents due to much shorter exposure time for construction. The reduction of loss time accidents is a benefit to the bridge contractor as well as the overall economy and the public.

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Very High Power Ultrasonic Additive Manufacturing for Energy Applications

Next generation power plants have been designed to operate at higher temperatures to improve efficiency. To further improve efficiency, advanced cooling methods are needed. This requires complex heat exchanger designs with unique thermal characteristics. A new manufacturing process, Very High Power Ultrasonic Additive Manufacturing (VHP UAM) has demonstrated the ability to fabricate these complex shapes. In addition, VHP UAM is an approach to manufacturing that is capable of embedding sensors into finished parts. These sensors can then be used to reduce costly down time by monitoring process and structure parameters that add condition-based maintenance capabilities.
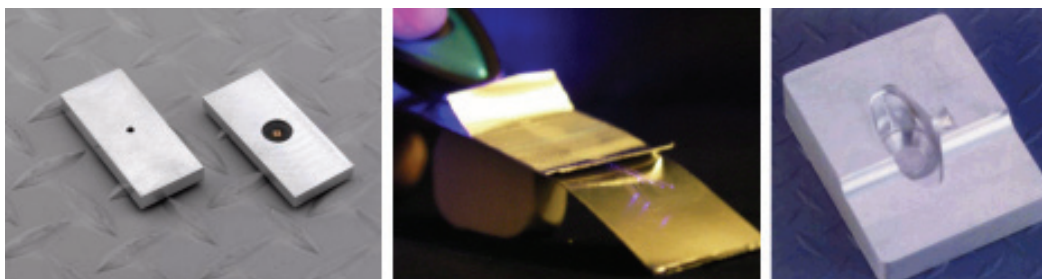
Potential hybrid examples: Embedded electronics, embedded fiber optics, and complex shapes.

VHP UAM uses a unique combination of ultrasonic energy and force to create complex metal structures with dissimilar materials. The breakthrough is that thin strips of metal(s) can now be more easily bonded to create an engineered structural component that has novel thermal, corrosion, and operational properties.

Economic Impact: VHP-UAM crosscuts many industries, including EWI and other CIMJSEA sponsors because it overcomes cost and geometry constrains typically associated with conventional bonding methods, such as explosion bonding, cladding, and brazing. The new process enables more cost effective engineering solutions that are essential for the next generation of efficient power plants. The ability to create complex parts, as well as embed sensors, will extend the lifecycle and significantly reduce the manufacturing costs of next generation power plants. A new

Center for Integrative Materials Joining Science for Energy Applications (CIMJSEA)

business venture (Fabrisonics) has been launched to market this technology in collaboration with EWI and Solidica.

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Center for Laser and Plasma for Advanced Manufacturing (CLPAM)

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Extending Damage Limits of Hydraulic Systems in Military Aircraft

Titanium tubing provides the critical arteries of hydraulic systems in military aircraft. The tubing is comprised of thin-walled tubes capable of withstanding high pressures in the range of 5,000 psi. Research at the Center for Lasers and Plasmas for Advanced Manufacturing (CLPAM) at the University of Virginia has helped in assessing the ability to expand the damage limits of the tubing; that is, how much sustained damage can be safely tolerated.

Example of military aircraft Osprey which uses Ti alloy tubings for hydraulic controls of the aircraft.
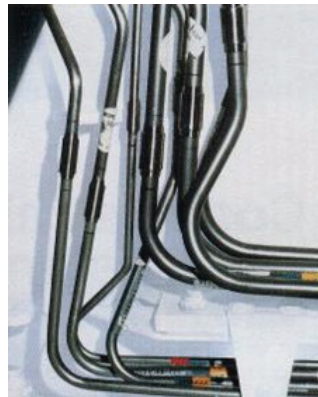
Image of hydraulic tubings made of Ti alloy used in military and commercial aircrafts.

Economic Impact: Research has demonstrated that there were additional margins in some areas that translated into expanded damage limits. Expanding the damage limit can reduce maintenance man-hours and reduce operational support costs. As a result of this work, aircraft are performing much better from a maintainability standpoint. This should result in considerable savings to the military over the next 15-20 years. Knowing the structure damage limits under realistic operating conditions can avoid the premature failure of components. The premature failure can cause loss of life and failure of aircraft. For these reasons, this work enhances safety and is having large economic impacts. After this work, other agencies such as the Air Force are looking into damage limits of Ti tubings used in military aircrafts.

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Ultra Lightweight Structures Using Carbon Nanotubes

Ultra lightweight materials capable of electronic conduction are needed by National Aeronautics and Space Administration and the military. Ultra lightweight electrically conducting materials would provide structures for Electromagnetic Interference (EMI) Shielding applications for commercial and space applications, development of advanced sensors, lower cost canopy for aircrafts, lightening protection, electronic packaging, printed circuit boards etc. Research at the Center for Lasers and Plasmas for Advanced Manufacturing (CLPAM) at the University of Virginia has shown that ultra lightweight electrically conducting materials can be obtained by incorporation of lightweight carbon nanotubes in polymeric materials.

Research has demonstrated that the weight of the nanotubes can be further reduced by conversion to foam structures. Density of 0.56 gm/cm^3 was obtained.

This graph shows that polymers are insulators, that is, they do not conduct electricity. By adding few carbon nanotubes, polymers become more valuable for electromagnetic shielding.

These kinds of flexible conductive composites may be used for typical antenna systems, lightning-protected aircraft composite panels, avionics line replaceable unit (LRU) enclosures, connector gaskets, electrostatic and space charge dissipation materials, and different types of electronic pressure sensitive switches or sensors. The University of Virginia has received a US patent (Patent # 8,424,200) on this technology due to its large commercial and defense application potentials.

Figures show the presence of carbon nanotubes in polymers and their interconnectivity which give rise to electrical conduction. Carbon nanotubes are in nm dimensions. The right image shows micron scale air pockets which reduce the weight of structures.

Economic Impact: Increasing amounts of electromagnetic signals are emanated from variety of electronic components. If they are not adequately shielded from external noise these electromagnetic signals may cause interference of nearby equipment. For example cell phones need to be protected from external static noise in order to receive clear voice signals. Electronic shielding of many components is therefore essential. Lightweight electrically conducting nanocomposites will find applications for shielding of military components, biomedical instruments, and of instruments used in daily life such as cell phones, computers, laptops, radio, CD players, etc. The economic impact of lightweight electrically conducting nanocomposites is substantial but is difficult to quantify. The lightweight structures are highly important to energy savings in transportations and in communications.

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Laser Texturing of Surfaces and Commercial Applications

Laser processing provides a unique method of modifying materials surfaces by depositing large amounts of energy onto the surface of a material in a tightly controlled manner. Research at the Center for Lasers and Plasmas for Advanced Manufacturing (CLPAM) at the University of Virginia has helped to develop enhanced textured surfaces on metals and semiconductors. The laser treatment causes pillars to form on the treated surface. These pillars provide for greater light absorption for solar energy conversion, enhanced light detection, improved tissue growth for body implants, higher catalytic activity, and better heat sinks.

This research is leading to the formation of a new high technology company for commercial products and defense applications. Because of its large commercial and defense application potentials, the University of Virginia has filed an industry

The figure shows the surface of materials after the laser process. This surface has similarity with lotus leaves where water does not wet the surface. Such non-wetting properties of materials' surfaces have applications for anti-icing (avoids buildup of ice for aircrafts, dish antenna, etc.), and corrosion protection.

supported patent application. This technology can be used for solar energy applications for efficient trapping of sun light incident at different angles. Microtextured surfaces can be used for anti-icing applications.

Economic Impact: The costs to the US military related to corrosion are estimated to exceed one-quarter trillion dollars per year. Ice buildup is also a major problem for commercial and military aircrafts, blades for wind energy generation, refrigeration systems, and outdoor antennas. The annual anti-icing market is estimated to be $250 million. The US Navy's yearly bio-fouling cost to is estimated as $2.1 billion. It is therefore reasonable to assume that the economic impacts of having surfaces that more effectively repel water would be huge. Laser microtextured materials will play important roles in various markets. Another important market where these surfaces could play an important role is in renewable energy and nuclear power generation. For these reasons, the economic impacts of this technology for key industries and for the nation are substantial but difficult to quantify precisely.

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Center for Metamaterials (CfM)

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Fast, Flexible, and Accurate Algorithms for Metamaterial Device Design

Optical modeling tools are essential in efficient development of new photonic, plasmonic, and metamaterial devices for a wide range of applications, including optical and infrared sensors, imaging systems, solar cells, and other renewable energy devices. These tool applications are important to almost all CfM member companies. Unfortunately, all commercially available modeling and design programs have significant shortcomings in that they are slow, not user-friendly, and are prone to errors when used to model realistic metamaterial structures and devices. The commercially available programs lack the ability to simulate situations that would be encountered in real-life situations and have limited ability to test the metamaterials when exposed to complex light and radiation patterns. Bottom line: with existing programs it is difficult and time consuming to extract the desired information from the modeling results.

Fast and accurate optical modeling tools are essential in efficient development of new devices for a wide range of applications, including optical and infrared sensors, imaging systems, solar cells, and other renewable energy devices.

Researchers at CfM are addressing these limitations by developing new programs and algorithms specifically designed to quickly and accurately model metamaterials. These algorithms improve the speed of modeling and simulation, provide better accuracy, and organize the data in the ways desired by photonics scientists and engineers. This CfM research project has received much sponsor interest. Soon the program will be at a state where it can be distributed to the other member companies of the CfM. This project is

ongoing and the program will be continually developed to add additional capabilities and improve its speed and ease of use.

There are several advantages of this software. First, the program improves the speed of modeling metamaterial and optical devices by a factor of 10,000 relative to existing commercially available programs. Second, it can be more accurate for designing realistic optical materials. Third, it is easy to add-on design optimization functions, scans of radiation patterns, and coupling the optical modeling to electrical and thermal modeling programs. These advantages represent a breakthrough in metamaterials modeling and design. Early versions of the software are already being tested and used by one of the CfM member companies, Phoebus Optoelectronics, to model and design an optical sensor for NASA and other projects funded by the US Army and DARPA. Phoebus is using this program to take advantage of its capabilities of scanning hundreds of possible device structures to finalize device designs.
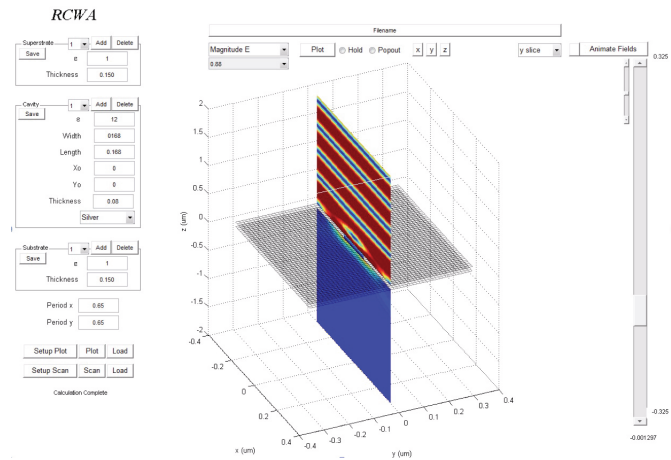
The RCWA Modeling Program from the Center for Metamaterials. This application models and analyzes several types of optical materials and offers quick graphical construction and easy data extraction. The core algorithm is fast, accurate, and employs different approximations depending on the desired speed and accuracy of the output and structure's nature.

Economic Impact: The expected economic benefit of this breakthrough technology will reduce design and development time for new photonic, plasmonic, and metamaterial devices. These can now more easily be applied in a variety of research, commercial, and defense applications. Examples of these applications include high efficiency solar cells and other renewable energy devices (hydrogen and methanol generation devices), advanced optical sensors and imaging systems, ultra-high bandwidth communication devices, and optical coatings for cloaking, stealth, and electromagnetic shielding. The resulting improvements in design and development efficiency should ultimately reduce product costs thereby enhancing the competitiveness of American industry in the global marketplace.

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Center for Nondestructive Evaluation (CNDE)

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Generic Scanner to Image NDE Data

The Generic Scanner (GenScan) is employed to make manual scans for a number of nondestructive testing modalities in the field without a motorized scanning system. This photo shows the GenScan being used in mapping out tree strike damage (white stripes in inset figure) on the lower surface of a Black Hawk helicopter rotor blade using air-coupled through-transmission ultrasonic inspection.

The concept of the Generic Scanner or "GenScan" is to combine existing portable, manually-operated nondestructive testing (NDT) flaw detectors with off-the-shelf, relatively inexpensive position encoding devices. Combining these with specially developed interface software in a laptop or tablet PC generates inspection scan images in the field. The scan images so generated are saved in the computer and placed on the web for off-site analysis by structural engineers.

This technology breakthrough made by CNDE at Iowa State University was the result of research projects funded by the Federal Aviation Administration to develop improved methods for inspecting composite aircraft structures. The economical combination is characterized by the ingenious adaptation of position encoding devices contained in systems not related to inspection. For example, a "PC NotesTaker" for capturing handwriting and drawings on a page of paper was combined with ultrasonic or eddy current flaw detector to make small area inspection scan images. The "Mimio FlipChart" and DMA (digital meeting assistant) used in conference rooms for capturing writings and drawings on flip chart or whiteboard into a PC were adopted to make larger area scan images in ultrasonic inspection of composite structures on aircraft. In addition, a motion tracking system called the "Flock of Birds" used in virtual reality applications was combined with air-coupled ultrasonic flaw detector to inspect curved parts. The main advantage of the generic scanner is that it allows inspectors to create scan images manually in the field without using more cumbersome and expensive motorized scanning systems. The images it pro-

duces provide a more intuitive and thorough inspection of relatively large areas of commercial aircraft surfaces, e.g., composite control surfaces.

Some newer NDT modalities such as laser shearography and thermal wave imaging are intrinsically image based, but the two most widely used modalities, ultrasonics and eddy current, still rely on motorized scanners for making images. The motorized scanners are often bulky, heavy, and expensive. In addition, they often require considerable operator training. Motorized scanning systems typically cost $30K to $150K.

GenScan is a simple way of producing the type of quick scan images in the field using portable, manually operated NDT instruments with which most inspectors are already familiar. The position encoding that generates the images is provided by consumer electronics devices used for capturing handwritings and drawings. The simplicity and portability of the GenScan lends to easy deployment on aircraft and field applications.

> **Economic Impact:** In commercial aviation, the term MRO (maintenance, repair, and overhaul) refers to all the services related to assuring aircraft safety and airworthiness. World-wide, the MRO market is of the order of $50B (according to IATA benchmark analysis of 2011) and the maintenance cost of an airliner accounts for approximately 10% of the total operating cost. The typical maintenance cost of a revenue-generating commercial aircraft is about $3M per year. In MRO operations, due to the large number of aircraft that require inspection, the same models of NDT instruments are usually bought in large numbers for the team of inspectors to use. For this reason, airline maintenance departments and MRO shops are more likely to purchase a large number of $5000 portable flaw detectors and much less likely to purchase one or two of $50K system such as motorized scanning systems. The GenScan approach makes use of existing portable flaw detectors and does not require the MRO facility to purchase additional hardware. The position encoding devices that make the imaging possible come from off-the-shelf consumer electronics and are relatively inexpensive. For example, a PC NotesTaker costs less than $100, the Mimio Flip-Chart and DMA are in the $600 to $1000 range. The magnetic "Flock of Birds" position tracker with 3-D capability is priced in the $3K range. The approach of making simple manually scanned images using existing portable instrument and modified position encoders, along with the help of interface software in a PC, often negates the need for the more costly motorized scanning systems (which tend to be much heavier and bulky; too much so for on-aircraft deployment) while economically providing the benefits of quality, quantitative, image-based inspection data.

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Dripless Bubbler: Portable Scanner for Aircraft Inspection

The Dripless Bubbler makes on-aircraft high-resolution images of flaws, damage, and corrosion with a focused ultrasonic beam. The figure here shows the Dripless Bubbler scanning Boeing 747 lap splices.

Researchers at the Center for Nondestructive Evaluation (CNDE) have developed an on-aircraft ultrasonic scanning system for imaging flaws, damage, and corrosion on aircraft structures. Developed by the center's Composite Group, the "Dripless Bubbler" ultrasonic scanner (DBS) is the first portable ultrasonic scanner with a closed-cycle water coupling system and uses high frequency focused ultrasonic beam. It is essentially a portable ultrasonic scanner designed and developed for on-aircraft inspection of both metallic and composite structures. It can be attached to the fuselage of an aircraft or to the upper or lower surfaces of aircraft wings to inspect for hidden corrosion in metals and in disbonds and delaminations in composites. It uses a unique closed-cycle pump/vacuum water handling system that makes possible the use of focused ultrasonic transducers.

In the past it has not been possible to apply focused ultrasonic beam for on-aircraft inspection in the field. The development of the DBS has made it possible to conduct focused beam ultrasonic inspection at relatively high frequencies. The focused ultrasonic beam leads to superior image resolution and can more accurately determine the depth of delamination or exfoliation corrosion and the amount of metal loss due to corrosion. The DBS has the unique capability to scan over protruding rivets on the skin of aircraft. The closed-cycle water-handling feature meets the safety requirement of not having wet surface on aircraft wings in maintenance hangars (a slip and fall hazard). The water recirculation system made it possible to perform high resolution ultrasonic scans in the field with image quality equivalent to that of a laboratory ultrasonic immersion tank. The high resolution afforded by the high frequency focused transducer makes it a useful tool for mapping out the depth profile of corrosion, such as exfoliation corrosion around fastener heads.

This technology received an R&D100 award and was extensively field-tested at commercial airlines (Northwest Airlines, United Airlines, and others), at the FAA Airworthiness Assurance Nondestructive Inspection Validation Center at Sandia National Laboratories, and at ARINC, Inc. The Dripless Bubbler scanner was patented and licensed exclusively to Sierra Matrix, Inc. of Fremont, California. The company supplied the system to the US Air Force for inspecting corrosion around fasteners on the wing skins of KC135 tankers. The

center supported this activity by conducting training sessions for system inspectors at the Air Logistics Center at Tinker Air Force Base in Oklahoma City.

> **Economic Impact:** The natural phenomenon of metal corrosion in aircraft has a major impact on the economy. The Dripless Bubbler ultrasonic scanner, with its superior resolution and sensitivity, is a powerful tool for early detection of corrosion. Interestingly, if caught early enough, incipient exfoliation corrosion around steel fasteners on aircraft wing skins can be eliminated by timely blending. Once corrosion becomes extensive, expensive repairs are required. Early detection of corrosion is particularly important for airworthiness and safety reasons for structures like lap splices of aluminum fuselage skin. The economic payoff for using the Dripless Bubbler can be substantial because the cost of making even major repairs is almost always lower than the cost of the aircraft component or the cost of the involved system. The direct cost of corrosion alone to the US economy is approximately $300 billion per year (2001 study by FHWA). The US military spends more than $20 billion per year battling the general problem of metal corrosion (GAO figures), out of which $3 billion per year is attributed to the cost of corrosion of military aircraft. The loss of revenue to commercial airlines when an aircraft is grounded for corrosion repair and maintenance is $100K per day. Finally, although composites are beginning to be used as fuselage, wing, and empennage material on aircraft, the great majority of aircraft today are still made of aluminum. Corrosion therefore remains a major concern in aircraft maintenance and safety. The economic impacts of the latter in particular are almost impossible to quantify.

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Aircraft Inspection: Time-Proven "Coin Tap" Automated

The use of composite materials in aerospace industry has increased dramatically since the 1970s. Carbon composites are quickly becoming the choice material for load-bearing primary structures on aircraft in recent years. The fraction of composites by weight has jumped from 12% on a Boeing 777 to 50% on the new Boeing 787. The Airbus A350XWB under development also has 50% composites. The stealth properties of composites and their ability to be molded into complex shapes are crucial to advanced bombers such as the B2.

Researchers at the Center for Non-Destructive Evaluation (CNDE) computerized and automated the hearing-based manual tap test, practiced widely by aircraft inspectors, to give it quantitative and imaging capabilities and to take the "human factor" variation out of the inspection procedure. The tapping action was automated with the invention of a magnetic cam scanning cart. Equally-spaced and uniform taps were made as the cart was pushed over the part's surface. The simple encoding method gave the tap test technique a previously unavailable imaging capability. Computer-Aided Tap Tester (CATT) has proven effective for the inspection of both composite structures and metal honeycomb structures on a wide variety of control surfaces on aircraft. It also provided the quantitative inspection results in image form that can be archived electronically.

- Carbon laminate
- Carbon sandwich
- Fiberglass
- Aluminum
- Aluminum/steel/titanium pylons

Both commercial and military aircraft have in recent years greatly increased the amount of composite materials in their structures. For example, the figure here shows the new Boeing 787 with 50% composite by weight and much more by surface area (all blue and green areas are composites). Tap test is a time proven technique for inspecting composites, but is hampered by operator dependence (human factor) and being ruefully qualitative. The computer aided tap tester developed by CNDE specifically aims at providing quantitative image data for flaws and damage in composite structures.

The CATT developed by CNDE has been extensively tested in the field at commercial airlines, aircraft OEMs, MRO (maintenance, repair, and overhaul) facilities, and military bases. The design, operating software, and manufacturing process of the system have evolved over a number of years with input and feedback from the users in the field.
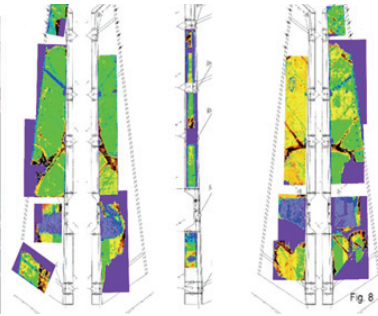
The Computer Aided Tap Tester (CATT) developed by CNDE of Iowa State University was used in the accident investigation of the Airbus A300 (American Airline flight 587) crash in Queens, New York in November 2001. The figures above show the mapping of the damaged rudder and the assembled image.

The Computer Aided Tap Tester (CATT) is better than previous technology in two important respects: first it provides quantitative engineering data on the local stiffness of the structure and second it provides an image of the inspected area using the measured stiffness data. The CATT is able to extract the local stiffness of the location it taps because it uses a high quality accelerometer with a steel tup that is much harder than the composite material it taps.

As a result, the deformation is almost entirely in the less stiff composite material. Based on the known mass of the accelerometer and tup, the local stiffness can be calculated from the contact time between the part surface and the tapper based on a simple spring model. With the semi-automated magnetic cam inspection cart, the inspected area can be tapped in a grid pattern and a map is generated using the measured contact time or the computed local stiffness. The great advantage of the image data is that the inspector can intuitively distinguish between flaws or damage in the composite and the normal substructures based on the morphology. The system is exceedingly compact and can be easily used on aircraft components in the field.

> **Economic Impact:** The primary benefits of using composites on aircraft are the reduced weight due to the superior specific stiffness (economic impacts due to enhanced fuel economy), the non-corrosive property of composites and assembly simplification. Composites cost about 35% more than comparable aluminum structure, but the higher cost is made up more than enough by the 65 to 85% lower manufacturing and maintenance costs.
>
> The CATT represents a major improvement in terms of the quantitative and structural engineering nature of the inspection results and the scanning and imaging capability. With the low cost of the automated tap test system (approximately $5K for the system from ASI, Inc.), their use can be easily justified considering the replacement costs (often over $100K) of the flight control components on an aircraft. The CATT was patented by Iowa State University and licensed to Advanced Structural Imaging, Inc., a company founded by the inventors and colleagues. This new NDT instrument has been available on the market since 2001 and was purchased by many commercial companies, R&D organizations, military units, and universities here and abroad.

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Center for Particulate and Surfactant Systems (CPaSS)

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Wear-Resistant Metal-Ceramic Composite Coatings

The cost of corrosion within the North American aircraft industry was estimated to be over $13 billion per year, with an additional few billions added on for the US military's aircraft. A significant portion of the costs of such corrosion, as well as that of erosion and abrasion of landing gear and other critical parts can be eliminated with the application of high-wear resistant coatings.

Incorporation of hard ceramic micro or nanoparticles into metal coatings is a very promising approach to improve the wear and corrosion resistance of the surfaces that must perform under harsh conditions. To be evenly incorporated, these nanoparticles must be well dispersed in very hostile plating solutions. This is challenging because of the need for dispersing reagents to function under extremely high electrolyte and pH conditions without impacting electroplating efficiency. CPaSS researchers, supported jointly by the I/UCRC and the Boeing Company, have used cationic polymers to develop a novel method for preparing stable dispersions by precoating the particles, thus avoiding any decrease in the efficiency of the plating process caused by dissolved polymers.

Harder and smoother coatings reduce the friction and eventual wear and corrosion of high impact surfaces of aircrafts
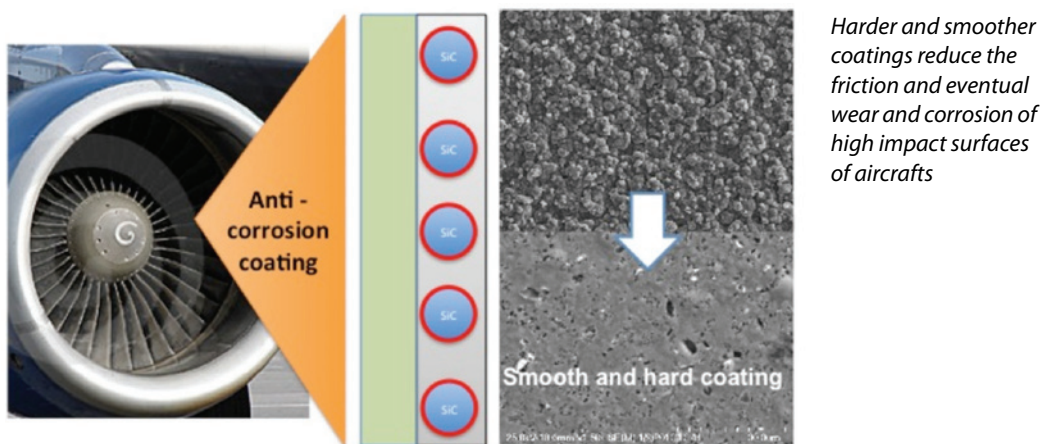
Economic Impact: This innovation is leading to new high performance composite coatings and increased revenues because of the improved lifetimes of surfaces when used under harsh conditions. Electro-co-deposited films offer exceptional hardness, durability and wear resistance for applications in numerous industries. These films enhance the product lifetime, reduce maintenance costs and promote new product developments. The breakthrough CPaSS process lowers reagent and energy use during electroplating, while improving the coating properties. The result-

ing final products are more sustainable with a reduced carbon footprint and extended lifetimes. Because of lower maintenance, repair and overhaul costs the electroplating industry can potentially generate higher revenues (5-10% increase from $6.2 billion) by introducing more durable products for end users that are primarily in the aviation and automotive industries.

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A Multi-Dimensional Greenness Index to Evaluate Chemicals Used in Processing

A problem that underpins many technologies critical to modern industries is how to selectively and effectively separate valuable minerals from undesirable ones in ores or to control dispersion in personal and health care products. Large volumes of different types of chemicals are used in mineral processing industries. Many of these have the potential to produce negative impacts on safety, health, and the environment (SHE). Consequently, they must be either well-managed or replaced with more benign alternatives.

Various separate regulations exist to constrain the manufacture, transport, implementation, or consequences of the use of the chemicals in particular applications. For example, flotation is one typical mineral processing operation in which high-value minerals are separated from low-value minerals through the use of chemicals that selectively change the surface of finely divided high-value minerals so that they adhere to rising air bubbles and become concentrated in the resulting froth. This process of flotation has been successfully used for over a century and forms a principle means of value-mineral concentration.
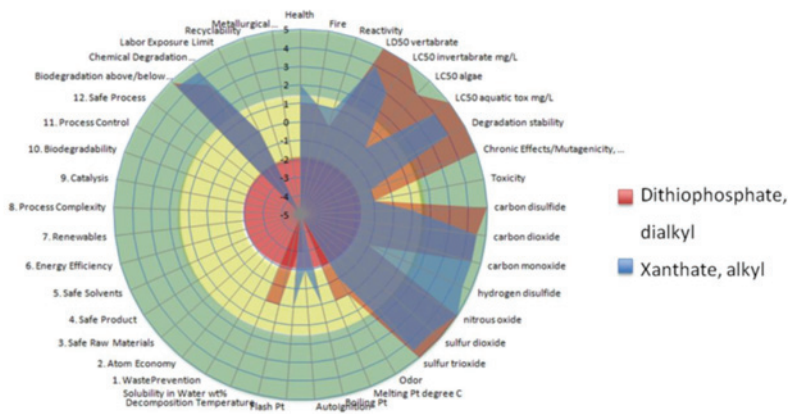
An example that shows the comparison of two typical mining chemicals (dithiophosphate and xanthate) used as collectors in the mineral processing industry. The format of presenting the greenness is a spider-diagram, on which the larger the overall area, the greener the chemical.

A full assessment of the SHE consequences of chemicals used for this purpose should include aspects along the entire chain of events from manufacture, to transport, to deployment in the application, and to final fate, disposal, or waste treatment. However, current assessments are too often done in piecemeal. For example, the chemical manufacturer designs and optimizes a safe and economical process for the produc-

tion and transport of the chemical to the mineral processing front gate; the mineral processing operator chooses and optimizes the use of a chemical within the plant to boost production and quality in a safe manner; and finally the waste management operator deals with the residuals. Compartmentalizing assessments along this chain of events can lead to myopic evaluations.

A more holistic scheme would be desirable - i.e., a means by which one could decide between alternative chemicals for a specific application with the intent to minimize negative SHE consequences across the entire chain of events. CPaSS researchers approached this by developing a Greenness Index, using the example of assessing flotation chemicals through their manufacture, use, and final fate.

The strategy behind the design of this tool was to include consideration of physical, chemical, environmental (e.g., biodegradability, human toxicity, water quality), economic, and social attributes. The mathematical algorithms that form the working machinery of this tool have been designed to be flexible and adaptable enough to allow the individual user to incorporate the particulars of their own mineral processing operations (e.g., operational specifics, economic model, and risk analysis methods). This tool establishes a framework for the evaluation of chemicals throughout their life and use cycles, and enables a more holistic comparison that can be a better basis for sustainable choices in mineral processing operations.

> **Economic Impact**: By 2015, the annual international mining chemicals market is expected to exceed $10.5 billion (http://www.mining-technology.com/features/feature117826/). Selection of greener chemicals to replace problematic ones currently used in the mineral processing industry is driven by external pressure from increasingly strict regulations, as well as by demands from various quarters for sustainable development. Our Greenness Index, an advance on the other available tools for evaluating chemicals in this manner, can be used to assess chemicals throughout their life and use cycles. One of the most outstanding features of this tool is its ability to incorporate a variety of information, including the fate of chemicals in a process and a wide selection of data from laboratory experiments, simulations, and models. This tool has been well received by several major mining companies (Barrick, Newmont, Vale and Freeport McMoRan), and has been used to evaluate several flotation chemicals in their operations. Personal care companies are beginning to explore use of the Greenness Index. The economic impacts on the mining industry will likely be substantial.

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Environmentally Benign Biosurfactants for Oil Spill Remediation
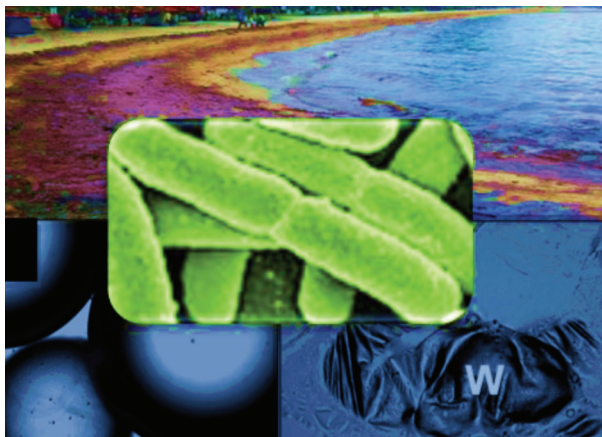
Environmentally benign bio-reagents for oil cleaning.

Surfactants are molecules that possess the ability to disperse oil in water. For that reason, they can be used to mitigate the effects of oil spills. There are concerns as to how reliably they can be used without they themselves causing toxicity to marine ecology. CPaSS researchers have used bio-reagents derived from *Bacillus Subtilis* bacteria because they are benign and exhibit similarities to oil dispersion surfactants. These bio-reagents have special viscoelastic properties that enable them to form robust films at the oil/water interface. Such films have long term durability to encapsulate oil droplets so that they can remain dispersed in water where microbes are able to degrade them.

Surfactants form self-assembled structures (micelles) where the core of such structures are hydrophobic and have the ability to entrap oil. The bioreagents tend to aggregate and form a film at the oil/water interface. Because such films are sustainable for long durations, they enable oil to be dispersed in water for long periods. These reagents are environmentally benign. Furthermore, the droplet sizes are significantly large (a few microns) as compared to micelles which are of sizes of nanometers.

Knowledge on the chemical structural, the nature of the bio-reagents, and the mechanism by which they function to disperse oil has been broadcasted on National Geographic Channel and in the Discovery Channel TV series of Brave New World by Stephen Hawking. Thus, such information is available to the industries that are seeking environmentally benign technologies for oil spill remediation.

Economic Impact: Because this research makes it possible for smaller amounts of the bioreagents to be required to effectively disperse oil, the work should have a number of difficult-to-quantify economic impacts, as well as environmental impacts with long-term benefits. Because it is also reasonable to assume that this breakthrough will be used within the personal care and pharmaceutical industries to develop novel technologies for encapsulation of target material such as fragrance or of drugs, economical benefits should accrue there as well.

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Prototype Greenness Index for Mineral Resource Development

A new Greenness Index based on an integration of the Twelve Principles of Green Chemistry and ICMM's ten principles for Sustainable Mining Development is in the prototype stage. This tool will bridge the existing gap between focused efforts in the chemical and mineral processing industries. The Greenness Index will allow mining companies to evaluate the multifarious aspects of sustainability in mineral processing operations. Supported by several major mining companies, this collaborative and comprehensive effort is the first of its kind. Over the next twelve months the algorithm will be tested and refined for chemically assisted flotation operations. This will ultimately allow the economic and environmental impact of sustainable processes to be engineered.
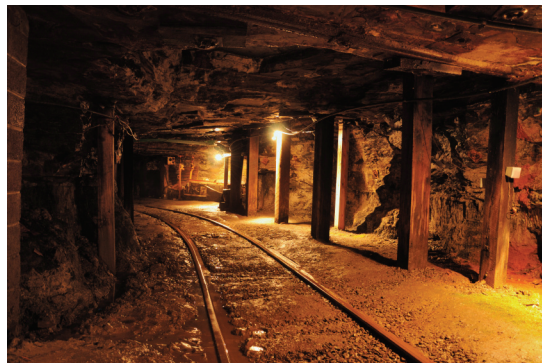
Mining companies can evaluate sustainbility in processing operations.

Economic Impact: This new initiative and the progress made in the past year has already spurred great interest in the mining and the chemical industry in terms of providing a framework and tools to evaluate and account for chemicals in the mining life cycle. The work is designed to provide the necessary metrics to evaluate current industry standards. With iterative refinements to the prototype, we plan to develop a robust tool that can suggest greener alternatives to old industry standards. Nationally it promotes awareness of the use and impact of chemicals and open accountability. The integration of the Twelve Principles of Green Chemistry and ICMM's ten principles for Sustainable Mining Development philosophy into the prototype is essential to promote greener mineral processing.

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Sustainable Mineral Resource Recovery
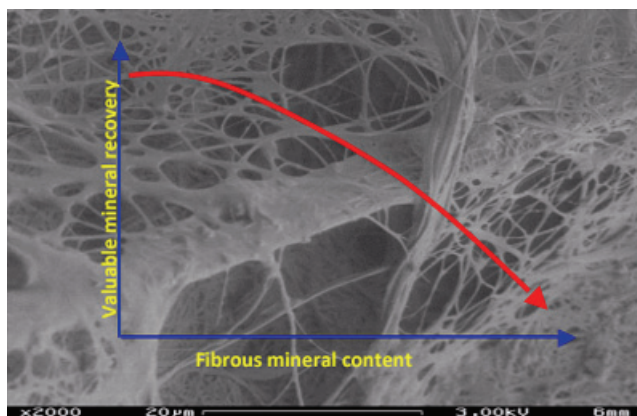
Network formation by fibrous minerals leading to poor mineral recovery and process efficiency.

One of the major sustainability challenges facing the mineral industry today is the selective and efficient recovery of strategically important valuable minerals and metals from low quality complex ores. Processing of ores is characterized by poor mineral recovery and high water and energy consumption. Flotation separation, which is still the most widely used method, is severely hampered because of the presence in ores of waste minerals, notably silicates. While the adverse effects of waste minerals are well recognized, the root causes for these effects remained elusive, thereby impeding development of robust solutions to the problem.

In collaboration with Vale and Cytec Industries, CPaSS researchers have uncovered important root causes. The pioneering work has demonstrated that the shape and morphology of the waste silicates have large negative impacts on processing efficiency; in some cases far greater than that resulting from the chemistry of such silicates. Most notably, strong evidence was found for complex fibrous networks in suspensions of the ground ores. These networks dramatically increase slurry viscosity and reduce the efficiency of gas dispersion and bubble-particle attachment; all of which lead to poor separation and process efficiency.

The prevailing belief in the scientific community was that the detrimental effect of waste silicates was due to hetero-coagulation between the silicates and the valuable minerals, generally referred to as slime coating. CPaSS research has demonstrated that platy, acicular, or fibrous particles interact and entangle in ore suspensions to form micro and macro networks, which result in dramatic changes in slurry rheology, gas dispersion, and bubble-particle attachment. Such network formation leads to several undesirable consequences: transport of large amounts of non-value silicates to the value mineral concentrate by bubble flux, reduction in valuable mineral recovery, and high water and energy consumption. Our initial discoveries were made in Ni ores.

> **Economic Impact:** This novel research will have a significant scientific and technological impact, allowing us to devise ways to enhance selective separation of valuable minerals from complex and poor quality ores while consuming less water and energy, thereby addressing the sustainability challenges facing the US industry for the foreseeable future. Plant operators will benefit by implementing our recommendations and solutions, particularly in diagnosing the problem before processing, and making better decisions related to selection of reagents and conditions.

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Center for Pharmaceutical Development (CPD)

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Improving Tablets Manufacturing

When reading the ingredients on the prescription bottles one will likely see magnesium stearate as one of the ingredients. The magnesium stearate is an inactive ingredient, or excipient, found in most solid tablets. It is typically found at relatively low levels (~1%) because it lubricates the stainless steel tablet forming machines used to process powders to form tablets. Without magnesium stearate, the powders that are compressed into tablets will build up and stick to the machines, leading to malformed tablets that cannot be sold and will result in significant loss of profits. This is a huge problem when hundreds of thousands of tablets per day are being produced.
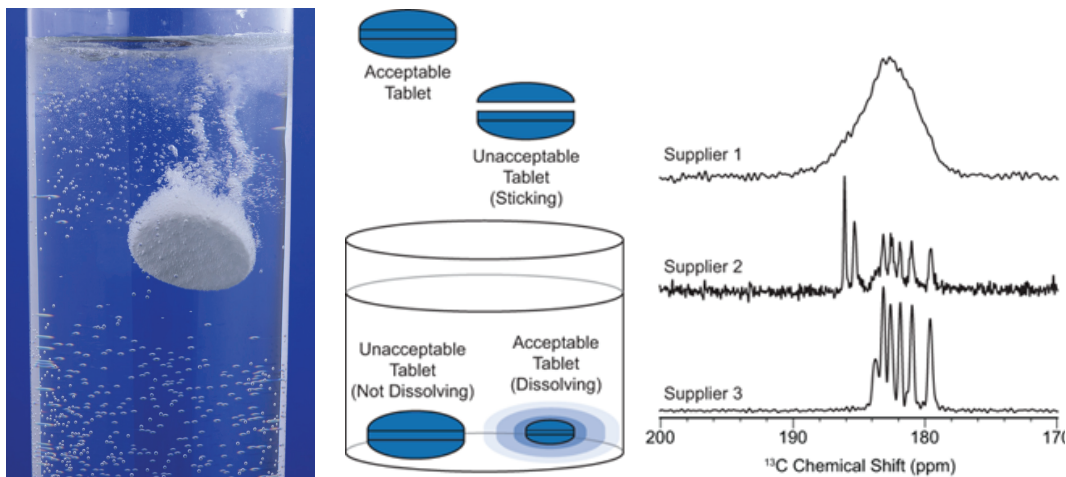
A tablet remains intact when the proper amount of magnesium stearate is used in the tableting process (acceptable tablet). It breaks apart when too little magnesium stearate is used (unacceptable tablet). Center: Illustration of the tablets dissolving, where one is not dissolving because of too much magnesium stearate, and the other one is dissolving because it has the right amount of magnesium stearate. Right: Analytical data for three different suppliers of magnesium stearate, showing that the magnesium stearate is different from each supplier. Researchers are working to correlate the analytical data with tablets dissolving and breaking apart.

Center for Pharmaceutical Development (CPD)

Even though magnesium stearate has been used for years in powder processing, failures are not well understood. Too much magnesium stearate can also result in soft tablets and slower dissolution. A confounding factor is that magnesium stearate from one supplier may behave differently from magnesium stearate from another supplier. This means that a manufacturing process may be fine one day and fail the next just because of the different batches of magnesium stearate.

Studying magnesium stearate, especially in a tablet, is difficult for several reasons. First, magnesium stearate is made from natural sources of stearic, palmitic, and other fatty acids. This means that it is a more complex material than the name implies. Commercially available magnesium stearate is a highly variable material and the differences in composition have significant impacts on the pharmaceutical manufacturing processes. This CPD work aims to understand how differences in composition affect the performance of the tablets.

CPD researchers have been using a powerful analytical technique to peek inside the tablets and determine how the active ingredient and excipients interact within a tablet. This technique, called solid-state nuclear magnetic resonance (NMR) spectroscopy, provides information about the chemical composition of the magnesium stearate, as well as about the changes that might have occurred when powder are processed. It even works on whole tablets that have not been broken.

Researchers are beginning to understand why one lot or supplier functions better than others. This is leading to improved understandings of how this excipient functions and will lead to the design of better pharmaceuticals and manufacturing processes.

> **Economic Impact**: Understanding how magnesium stearate functions in tablets will improve the manufacturing of both innovator drugs as well as generic tablets. In particular, CPD studies are helping to predict why some tablets fail to dissolve properly, which results in large scale batch losses and product recalls. Avoiding large-scale batch losses will result in lower cost of medicines and help keep a constant supply of both innovator and generic tablets on pharmacies' shelves.

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Better/Cheaper Drugs: New Routes to Active Pharmaceutical Ingredients

More efficient manufacture of pharmaceuticals is helping drive down the cost of drugs to patients. It is also helping to keep high-end pharma industry manufacturing jobs in the United States.

Many active pharmaceutical ingredients, the part of a drug formulation responsible for its beneficial action, contain an amine group, similar to amino acids, the building blocks of life. Moreover, such amine groups have to be present as a single enantiomer and not a mixture. In other words, the amine groups have to have a very specific orientation in space, or else the drug most often either is ineffective or even detrimental (recall the case of Thalidomide, where the presence of the wrong enantiomer causes birth defects).

Pure amines are difficult to synthesize, so difficult in fact that the Pharmaceutical Roundtable of the American Chemical Society Green Chemistry Institute listed the generation of such pure amines from easily accessible ketone precursors as the second highest priority for novel, aspirational reactions. A team of CPD researchers has developed a novel protein biocatalyst that achieves just such a transformation to amines from ketones. They started from a known protein biocatalyst and engineered it to accept ketones and to synthesize the desired amines in great stereochemical purity.

Being able to catalyze the conversion from ketone substrates to amine products is such an important addition to the toolbox that it stands to develop into a platform technology, applicable to the synthesis of a wide variety of targets in several therapeutic areas. Production of active pharmaceutical ingredients via biological routes stands to increase yields and shorten process routes via enhanced selectivity of key steps. One CPD sponsor intends to make use of this new ability for its own drug synthesis development efforts. The pharmaceutical company will receive the first batch of protein in 2012, less than one year after the ultimately successful protein template was first begun for development. The company indicated that it has several potential targets to which it will apply this new technology.

Economic Impact: This technology could impact the synthesis of drugs that contain chiral centers adjacent to nitrogen by providing more efficient methods for their manufacture. Not only is this process considerably more economical than existing processes that use the traditional wholly chemical routes, but they also leave substantially reduced environmental footprints. The impact on the manufacture of a single blockbuster drug is can be in excess of a billion dollars over the lifetime of such a drug. In a comparable case, Merck recently published an improved route to the active ingredient of Januvia® and Janumet®, a drug soon to reach blockbuster status; that route is said to be at least 25% cheaper than the current one. In addition, such biologically-

Center for Pharmaceutical Development (CPD)

inspired manufacturing with reduced environmental footprints are welcomed by most communities because processes to secure procure permits are greatly facilitated. In summary, more efficient manufacture of pharmaceuticals will help to drive down the cost of drugs to patients and help keep high-end pharma industry manufacturing jobs in the United States. As a result, this innovation can be expected to have broad economic impact across the pharmaceutical and fine chemical industries.

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Forming Advanced High Strength Steels (AHSS)

Research at the Center for Precision Forming focuses on aspects of forming behavior of high strength steels including: stamping, bending, edge cracking, die wear, lubrication, and hot stamping, etc. Knowledge gained from this research assists further implementation of advanced high strength steel (AHSS) manufacturing in the automotive industry with the obvious benefit of lighter weight vehicles with resulting improvements in fuel economy and decreased carbon emissions.
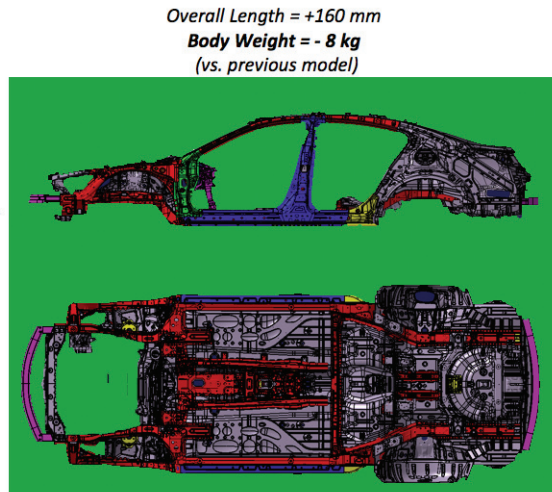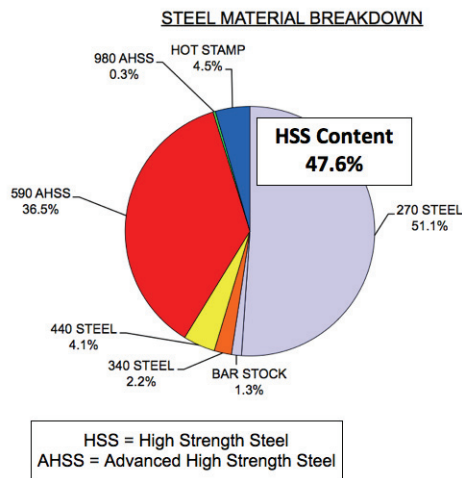
Use of AHSS in automotive industry (left) approximate percent use of various steels in auto chassis production, (right) example weight reduction when using AHSS.

Mild steel has traditionally been used for vehicle structures and closure panels because of its low cost and good formability. Implementation of AHSS can enable the use of thinner gage sheet (less volume and less mass) for comparable structural performance. The challenge is that AHSSs are much more difficult to form and assemble. This breakthrough research advances forming technology. Due to their higher strength, the automotive parts made from these steels exhibit considerable springback. Maintaining the part shape and tolerances requires a deeper understanding of the mechanical characteristics of these materials.

Center for Precision Forming (CPF)

CPF is further developing widely accepted tests of and is developing new methods for predicting spring-back and for forming these materials to defect-free components for use in automotive manufacturing. For this purpose FEM (Finite Element Method) based-computer programs are being developed and applied to forming processes. Furthermore, the scientific basis for using innovative machines and tooling, such as servo or electro AC motor driven presses and multiple-point press cushion systems, are being developed. The use of servo presses, already accepted by automotive and supplier industry, has shown 30-40% productivity increases. The direct result is cost and mass reduction without sacrificing performance and safety.

> **Economic Impact:** The advances in the scientific basis for using AHSS and high strength materials in manufacturing automotive components results in: a) mass/weight reduction leading to reduction in fuel consumption; and, b) weight resistant structures that improve vehicle safety. Thus, CPF's research contributes to the automotive industry's R&D efforts and attainment of its objectives related to meeting the government regulations for reducing fuel consumption and increasing safety. Furthermore, this research assists US-based companies to be competitive in the world market, especially with Japanese and German vehicle manufacturers. Though difficult to quantify precisely, this work is clearly contributing to increases in productivity and reductions in manufacturing costs, which results in annual savings of multi billions of dollars for the industry as a whole. These savings result in increased global competitiveness of the US automotive industry and also contributes to the maintenance and expansion of the US automotive industry work force.

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New Sampling and Sensor Initiative (NeSSI™)

Although process analyzers have undergone significant technological advances recently, the systems that deliver samples to them have hardly changed in the last fifty years. An initiative, launched in 2000 by the Center for Process Analytical Chemistry (CPAC), is primarily concerned with the treatment and continuous analysis of samples extracted from process equipment. NeSSI™ provides specifications, guidelines, and a forum for the on-going development of a Lego®-style building block platform for analytical systems. It was widely recognized that CPAC's leadership had developed NeSSI™ into a valuable global ad hoc initiative comprised of end users and suppliers and is resulting in permanent changes within the process analysis field. It has now been commercialized by several hardware manufactures and is being specified on major new-build projects. Several engineering companies now provide networked connectivity for all components of the NeSSI™ platform, opening the door to smart diagnostics and improved remote technical support. NeSSI™ is now used to enable improved process analytical measurements in the petrochemical, chemical, and oil refining industries and is being studied for applications in the pharmaceutical and biotechnology industries.
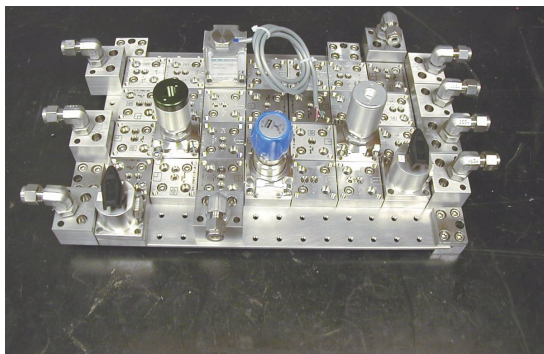
Several engineering companies now provide networked connectivity for all components of the NeSSI platform, which reduce costs.

Economic Impact: These new NeSSI™ platforms are showing reduced costs (both in the cost to build and own) with increasing reliability, and hence the value delivered by process analyzers. The combined benefits to industry are growing and will soon be measured in tens of millions of dollars per year.

Non-Destructive Spectroscopic Measurement: Inline Octane Sensor

In the mid 1980s, the Center for Process Analytical Chemistry (CPAC) pioneered a revolutionary approach to octane determination in oil refineries. This still used ground-breaking new octane sensing method uses a non-destructive spectroscopic measurement followed by multivariate calibration techniques to predict diverse physical, chemical, and consumer properties of fuel. This industry-changing advance was possible because the spectrum of the material clearly reveals the number and types of functional groups (e.g., methyls, methylenes, olefins, aromatics). In combination these determine gasoline's physical, chemical, and consumer properties. As a bonus, the octane sensor can simultaneously predict a number of important properties of gasoline such as density, vapor pressure, and percent aromatics. All of these measurements are made nondestructively on one cc of sample. Results are available instantaneously. The approach has proven an invaluable adjunct to process analytical chemistry.

In-line, real-time measures of octane at refineries means fewer costly additives. This saves millions of dollars per day; an estimated $1.5 billion per year.

Economic Impact: At the time it was developed, this octane determination method represented a vast improvement over previous octane determination methodologies because octane levels were determined by rather antiquated ASTM-CFR test engines. In the test engines each sample's performance was compared to reference fuel blends. The instrumentation required for measurements was very expensive (over $100,000), required constant maintenance, needed frequent standardization, consumed approximately one pint of gasoline per test, and, most importantly, required 20 minutes to produce results. This breakthrough real time, in-line "octane sensor" methodology is still used in refineries worldwide because it quickly and accurately predicts octane levels from the near-infrared vibrational spectrum of the inline sample. Annual savings are estimated to exceed $1.5 billion in 2012.

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Center for Research on Information Technology & Organizations (CRITO)

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The Net-Enabled Organization

With the help of CRITO, Boeing is working to improve understanding of how to orchestrate networks with internal and external partners.

The forces of globalization and networking technologies are affecting the ways that companies work and do business. The commercial airplane unit of Boeing, for example, is partnering with a large number of groups around the world to build the new Dreamliner 787 airplane. Behind that network of organizations is a backbone of infrastructure for an information-rich environment. In such an environment, information needs to be available anywhere and anytime to anyone who needs it. To make this happen most efficiently, hierarchical organization structures are needed wherein decisions are made, then information flows up and down and needed approvals can be obtained. Simultaneously, everyone can look horizontally across multiple organizations to build teams, to complete tasks and to solve problems when within their scope of responsibility. With the help of CRITO, Boeing is working to improve understanding of how to orchestrate networks with internal and external partners.

Center research is providing the theoretical basis as Boeing transforms itself into a different kind of organization. The underlying hypothesis is that those companies that are best at orchestrating these networks and at using them to provide most value to their customers will be the most successful. One important dimension of the solution is better understanding what companies need on order to keep tight internal control versus what it can or should safely network.

Benefits of this approach are less inventory, fewer facilities, and services that are market driven instead of internally driven. Profitability can be increased and companies can be more responsive. In the case of Boeing, airplanes can be built more efficiently. Using the tools of social science and business research, including case studies, interviews, surveys, modeling, and analysis, CRITO researchers are working on the conceptual aspects of the networked business model and helping to create the processes and tools to work more effectively in these new structures.

Economic Impact: Benefits of this approach are less inventory, fewer facilities, and services that are market driven instead of internally driven. Profitability can be increased and companies can be more responsive. In the case of Boeing, airplanes can be built more efficiently.

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Center for Resource Recovery and Recycling (CR³)

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Center website: http://www.wpi.edu/academics/Research/CR3/index.html

Optoelectronic In-Line Measurement of Molten Metal Chemistry
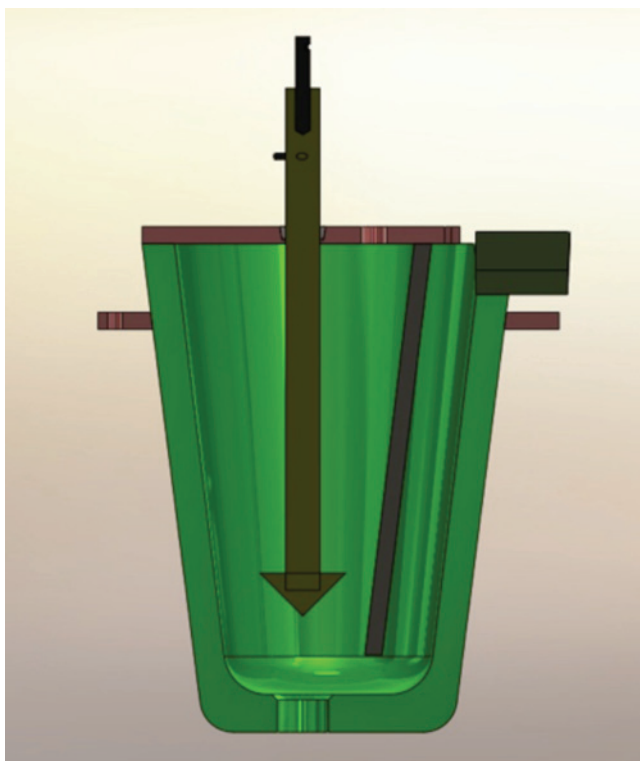
Schematic Diagram of Continuous Flow Device (CFD) enabling a continuous flow of molten Aluminum for compositional analyses or melt cognition.

An important problem that industry faces is the large amount of energy needed to produce aluminum (Al) and the commensurate gaseous emissions that the process produces. The secondary aluminum industry processes recycled scrap aluminum and expends typically 24,155 kJ/kg; to produce one kilogram of cast aluminum a considerable amount of energy is consumed. One way of reducing this energy consumption is by making better measurements of the scrap metal chemistry as it is being processed while it is molten.

The breakthrough developed at the Center for Resource Recovery and Recycling is the use of LIBS (Laser Induced Spectroscopy) to measure the melt composition as it is flowing. Such information provides process operators the ability to greatly improve the efficiency of the entire aluminum production enterprise and, in the process, significantly reduce both energy use and gaseous emissions.

Worcester Polytechnic Institute professor Diran Apelian and Dr. Ning Sun have developed an innovative and creative continuous flow device that makes possible measurements from fountains of molten aluminum, much as one might see in a water fountain. As a result, this breakthrough eliminates the sampling errors and enables these instruments to be commercially viable.

State-of-the-art instruments exist to accomplish this, but these have been plagued by measurement errors due to how they sample the melt. This continuous flow breakthrough represents an improvement over the previous state of the

Actual set up in cast house showing the LIBS and CFD devices placed on the melting ladle.

art because it enables higher-quality, field-ready instruments to more accurately measure the chemistry of molten metals. It also is more precise than previously available techniques.

This invention, termed a Continuous Flow Device, presents a clean metal stream to the measuring instruments that allow for direct detection of the aluminum chemistry without errors and provides the information instantly so immediate corrections can be made to the melt while products are being made. This level of control is unprecedented in the Al industry and should lead to large productivity gains. Current methods cannot achieve this and instead measure the metal chemistry by extracting a sample and taking the sample to an analytical laboratory. This takes time and thus does not allow for real time process control. What this breakthrough enables is reusing existing post-consumer aluminum by melting sorted scrap using melt cognition. This accordingly adjusts melt composition prior to final casting.

This breakthrough is a key piece of the Aluminum Integrated Minimill (AIM) process, a technology that will transform and revitalize the aluminum processing landscape in the US. AIM will use 100% mixed aluminum scrap as the input to produce a specification cast product in a single facility using an integrated process that only requires a single melt. The process' goal is to intelligently and effectively sort mixed scrap into a cost-effective finished product. It will reduce energy use by re-capturing the energy invested in making primary aluminum from ore and more efficiently reusing aluminum scrap to meet needs of US markets. The AIM process is to aluminum as the steel minimill is to the ferrous market.

Economic Impact: The technology will transform the secondary aluminum industry much as the advent of steel minimills transformed the steel industry. The economic benefits to industry and to the nation should be major and extremely significant. This is because energy savings should be particularly noteworthy. Use of this continuous flow instrument by the secondary aluminum industry is predicted to reduce its energy consumption by an astounding 94%. In the United States alone, this energy savings is anticipated to result in industry-wide savings of 32.9 trillion

kJ/yr and a CO_2 reduction of 1.3 million tonnes/yr. In a different perspective, much energy is required to reduce the oxide of Al to produce Al metal. By using scrap Al and upgrading it, the process will save 95% of the energy that is currently used to produce the Al from its ore. This work has spun off a number of R&D contracts to further develop the Continuous Flow Device as well as the technologies it enables. One major program is the recent award of a grant from the Department of Energy's ARPA-E Program to develop an Aluminum Integrated Minimill.

For more information, contact Diran Apelian at the Worcester Polytechnic Institute, 508.831.5992, dapelian@wpi.edu.

Enhanced Recovery in Foundries

There was unanimous agreement at a recent International Sand Reclamation Conference that the low rates of reuse of foundry sand is one of the highest priority problems confronting the industry. The annual generation of foundry waste (including dust and spent foundry sand) in the United States is thought to range from 9 to 13.6 million metric tons (10 to 15 million tons).

Researchers from the NSF Center for Resource Recovery and Recycling (CR^3) at Victaulic, a charter sponsor of the center, and at the Kroll Institute for Extractive Metallurgy at the Colorado School of Mines have developed a more efficient process to liberate beneficial products (clay and seacoal) from waste green sand foundry dust. The use of sand casting in US foundries is well established. Sand casting is the least expensive of all casting processes. It economically produces rough metal parts. Raw castings are then machined to produce finished products.

This breakthrough offers a more economical and more environmentally friendly processes for recovering clay and seacoal from green sand foundry dust and from waste green sand.

Through research, a hydrocyclone process was developed that doesn't use harsh chemicals and reclaims approximately 80% of the clay and seacoal from the dust. The advantage of this work for industry is that it offers a more economical and more environmentally friendly process for recovering clay and seacoal from green sand foundry dust and from waste green sand than was previously available. This work improves the method for disposing of green sand foundry dust and recycling of binding materials. Binders are materials added to a sand mold to bond sand particles together (i.e., it is the glue that holds the mold together).

Economic Impact: This breakthrough impacts original equipment manufacturers that use finished metal parts. It minimizes costs related to waste disposal of green sand foundry dust and the cost of buying bond. This CR^3 based innovation is estimated to save approximately $1 million

Center for Resource Recovery and Recycling (CR^3)

per green sand foundry per year. By reducing accumulations of waste materials, other economic benefits will also accrue.

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Center for Virtual Proving Ground Simulation (CVPGS)

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National Advanced Driver Simulation Facility

Researchers at the Center for Virtual Proving Ground Simulation (CVPGS) at the University of Iowa and the University of Texas at Austin have developed enabling technologies that use the world-class facility, National Advanced Driving Simulator (NADS), for operator/driver-in-the loop simulation for vehicle designs and for driving safety research. The NADS facility, completed in 2002, has been used by Deere & Co., Caterpillar Inc., Continental-Teves, Bosch, etc. for "virtual proving" experiments, and by the National Highway Traffic Safety Administration for highway safety studies.

Economic Impact: The National Advanced Driving Simulator is the only driving simulator in the world in which such activities can be carried out in a full 360° immersive virtual environment with high fidelity motion cues in all six degree-of-freedom of vehicle motion. A new approach is adopted that uses a commercially available multi-body dynamics code for real-time simulation. At this time is not possible to offer a statement on the economic impact of this work.
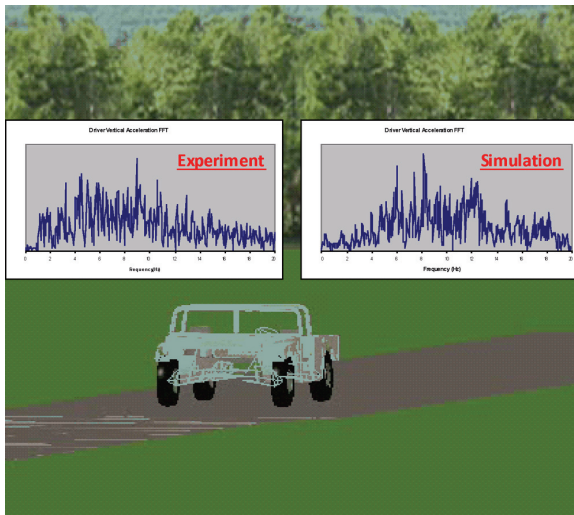
Comparison of PSD results with experimental data of a 68-body multibody dynamics simulation.

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Ceramics Composites and Optical Materials Center (CCOMC)

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Ceramics – Normally Opaque – Made Highly Transparent

Researchers at the Ceramics, Composites, and Optical Materials Center have refined ceramics that have glass-like transparency for light to pass through. For millennia ceramics have been commonly opaque and brittle.

This work, conduct at Clemson University and initially funded by the Department of Defense, has developed ceramics that are highly transparent and are considerably tougher than conventional analogs. Such materials are of value to a wide variety of applications including high power compact lasers, transparent armor, and radiological sensing technologies.

Conventional ceramics are opaque because light is scattered from residual voids in the granular microstructure. Clemson research-

Highly transparent ceramic (C), of value to next-generation laser and sensing systems, optimized from samples of lesser transparency (A and B) based on control over the granular microstructure with temperature (process temperatures noted).

ers developed processes that fully remove voids and limit structural evolution so that the new ceramics possess features that are smaller than the size of light. More specifically, a two-step temperature process was established that yields ceramics with granular structures that are only 300 nm in average diameter. For comparison, one's hair is about 300 times larger.

The attainment of full density while maintaining sub-light granular dimensions permits transparency equivalent to glass. The reduction in granular size scales also yields significant enhancements in the mechanical hardness and toughness of the ceramics as required for armor and high power lasers applications.

Economic Impact: As with many other important modern technologies, transparent ceramics were invented in the United States. However, for over a decade now, Japan has been the world leader in the production of transparent ceramics largely due to a decline in US funding and science competitiveness. This work, originally supported to help regain domestic know-how in fabricating transparent ceramics, has additionally facilitated the establishment of a domestic education and industrial supply chain critical to the future use of these materials in various defense, security, and sensing applications. While there are a few commercial examples of trans-

parent ceramics, they remain a fairly young technology. Accordingly, the exact economic impact is unclear but ceramics certainly have the potential to displace crystals and glasses in numerous high technology fields as development continues. To that end, lasers, ultra-hard materials, and sensors represent multi-billion-dollar domestic industries that will only become more important as defense and security threats expand.

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Cooling Technologies Research Center (CTRC)

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Engineered Metal Network Thermal Interface Material

Thermal interface materials (TIM) facilitate heat transfer between two mating surfaces, such as an electronic device to a heat sink that keeps the device cool. This is particularly important for cooling today's increasingly powerful electronics (e.g., graphic processors, power electronics, and highly integrated circuit chips in cell phones, etc.). This is because performance is often limited by the ability to remove heat. The contribution of interface between materials in the heat removal path sometimes accounts for more than 30% of overall resistance to heat flow. If the interface contact fails, the electronic system easily fails catastrophically due to thermal runaway - the electronics literally melt themselves.
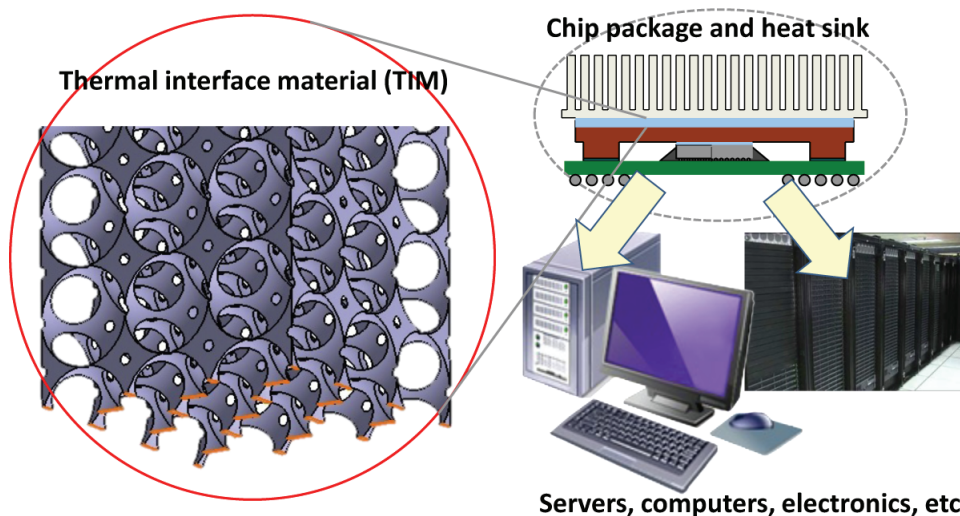
Engineered metal network is designed as a thermal interface material (TIM) to directly conduct heat from a chip to heat sink in electronic equipment.

This breakthrough focuses on the performance of a novel approach to thermally coupling the interfaces via theoretical analysis and experimental validation. It is leading to improvements in the ability to dissipate heat from today's advanced electronics.

TIMs must demonstrate three major aspects. They should: 1) be made of material that has good thermal conductivity; 2) be capable of making good thermal contacts between the two surfaces; and 3) be mechanically compliant to the target surface. This work deals with a trade-off between these three physical aspects by engineering the porous and mesh structure for making the heat transfer better across the interface.

Cooling Technologies Research Center (CTRC)

Researchers at Purdue University's Cooling Technologies Research Center (CTRC) have introduced the use of a metal mesh accompanied by a novel design that directly connects the two interface surfaces. A metal mesh allows heat to pass through the interface easily from one side to the other - the ligament acts like open highways for the heat to travel across. The surface of the metal mesh is envisioned as a naturally flexible array of small protrusions to make a good contact to the target device, which has a small roughness and some curvature.

Conventional technologies have been based on indirect contacts of many disparate metal pieces embedded in a polymer, hence, the heat must stop and go many times as it travels across the material. The most innovative part of this work is that it provides a theoretical model to determine the best design, prior to any experimental research and development (R&D) work. In contrast, conventional approaches, even state-of-the-art technologies, require experimental repetition of many R&D cycles to find a good recipe.

Based on the three-dimensional geometry of the porous metal mesh, this research will give a theoretical prediction of performance to be validated by strategically organized experiments. The work is based on aluminum porous media available in market, but the theoretical model is not limited to this particular geometry or this particular raw material, nor is it limited to any manufacturing process. Any hypothesized geometry or raw materials can be engineered analytically. The result of this research should extend the possibilities for new material developments exponentially, and the performance improvements resulting from engineering metal networks in TIMs will help to dissipate heat more effectively.

> **Economic Impact**: Networked TIMs enable the design of heat sinks that are both simpler and smaller for compact electronics design, as well as more cost effective. The economic impact resulting from the improvement of a single ingredient component for electronics is difficult to isolate due to the highly integrated nature of the systems. Making better thermal interface material should avoid costs associated with heat sinks and cooling fans. We speculate that a 30% performance improvement of the TIM over the state-of-the-art materials could relax performance requirements by as much as 17%. This would translate to a 24% cooling cost reduction (linear to 1.5 exponent of the performance). Considering that the heat sink market is in scale of a couple of billion dollars per year, the potential cost reductions for electronics could exceed tens of millions of dollars per year. More importantly, considering a higher penetration rate of electronics in the United States, the work should provide higher value electronic products to end-users. The reduction of aluminum usage for the heat sinks could also help saving the energy consumption during the manufacturing.

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Graphene-Based Thermal Interface Materials (TIM)

Because the density of electronic components in integrated circuits (ICs) has increased tremendously during the past few decades with a trend of miniaturization of individual electronic components, the density of dissipated power has also increased significantly. This has led to degradation of device performance. Therefore, thermal management in ICs or high-power electronics becomes a crucial issue to maintain device performance.
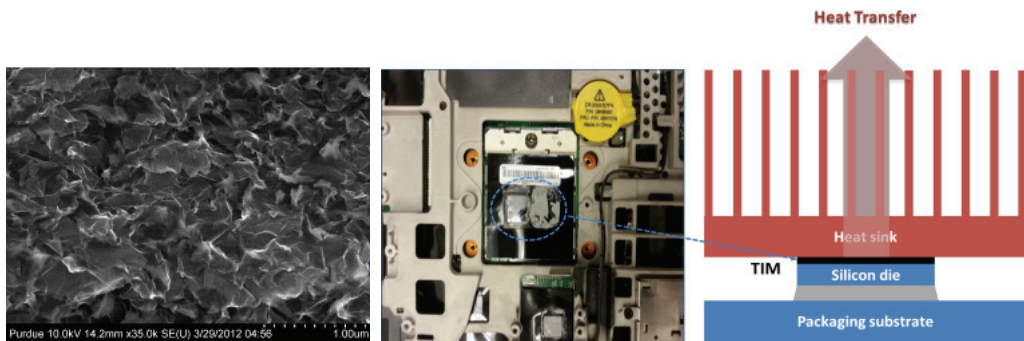
Scanning electron microscopy (SEM) image of graphene/polymer composites (left) and thermal interface materials (TIMs) applied to the interface between silicon die/metal heat sink in the laptop to enhance the efficiency of heat transfer (right).

Thermal interface materials (TIMs) between dissimilar thermal junctions (e.g., between CPU/heat sink) are necessary for efficient heat dissipation because microscale gaps or voids are unavoidable. These prevent efficient heat transfer. By filling out those thermal junctions with appropriate TIMs, the heat transfer efficiency across interfaces can be dramatically enhanced.

Graphene is a single planar sheet carbon atom with a honeycomb lattice structure. It has the highest thermal conductivity (~5000W/mK), and it is a thermally and mechanically stable material. By using these excellent properties, CTRC researchers have developed graphene/polymer composites for TIM applications based on "few-layer" graphene, which is prepared by a new and simple exfoliation technique. Unlike most previous conventional preparation methods, the new technique can be readily applied to mass production. Moreover, the measured thermal interface resistance between copper heat sinks and composites is comparable to current state-of-the-art TIMs. This indicates that graphene-based TIMs are good candidates for future thermal management applications.

Currently, the TIMs industry mainly focuses on ceramic/metallic particle-based TIMs (e.g., silver particles). One of the common problems is that these require high production costs compared with graphene-based TIMs. One of the most significant virtues of the graphene-based TIMs developed by CTRC researchers is their low-cost of production and their high performance characteristics (high thermal conductivity and low thermal interface resistance of graphene-based TIMs).

Economic Impact: The global market for TIMs is expected to increase to ~ $760 million by 2017. Polymer-based and metal-based TIMs still occupy the largest portion of the market. With increasing demands of thermal management applications, it is likely that the market will expand even more significantly than the current prediction. The TIMs market will be extended from conventional applications such as PCs or laptops to many types of consumer electronics applications including high-power light-emitting diodes (LEDs), display applications, and flexible and wearable electronics. By replacing conventional filler materials with graphene, we can develop high-performance TIMs with much lower production costs. Therefore, this work can open a new chapter in thermal management industries.

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Miniature Piezofan Arrays for Cooling Electronics

Innovative, miniature piezo-electric fans have been developed by the CTRC project into a viable technology for meeting a variety of cooling needs in portable and small-scale electronic devices, as well as in larger scale thermal systems that reject heat to ambient air. A piezofan cools a surface by oscillating a single fan blade, similar to a hand-held folding fan, but is instead driven by a highly efficient piezo-electric element that wafts the blade in response to an electric signal. Analytical

A piezofan cools a surface by oscillating a single fan blade, similar to a hand-held folding fan, but is instead driven by a highly efficient piezoelectric element that wafts the blade in response to an electric signal. The cooling capability is demonstrated by placing the fans into a laptop device, and observing a drop in the temperature with an infrared camera.

tools have been developed for modeling the flow field, heat transfer, and fan structure to allow the design of optimal cooling systems. Studies have been completed to test and characterize the thermal, electromechanical, fluid dynamic, and acoustic performance of piezoelectric fans. Interactions between multiple fans have been studied; coupling effects between the fans can cause the amplitude to increase by up to 40% over that of a single fan.

In smaller devices, where rotary fans are not practical and electronics are pushed to the limits of their heat dissipation capacities, piezoelectric fans offer the only realistic cooling solution while meeting the noise and power constraints of portable devices. Piezofans have no bearings or wearing parts that cause cyclic breakdown or noise-producing concerns. They are small, silent, and very low-power devices. They present no electromagnetic interference, nor will they affect magnetic fields. They produce negligible heat and are reliable over a high temperature range. The piezofans are cost-effective, use simple circuitry, and are highly efficient and lightweight. In order to realize the potential of piezoelectric fans in industry, CTRC optimized the design of fan blades based on robust electromechanical and flow-structure modeling. They are now

better suited to providing supplemental cooling in hot spots and in other stagnant areas in devices where rotary fan action is ineffective. Applications are in wireless devices, video game systems, automotive systems, data centers, telecommunication base stations, and multimedia systems where heat is typically rejected to air, and efficiency and durability are paramount.

Economic Impact: Piezofans are the solution to many problems in various industries where the traditional rotary fan failed. They result in lower cost, lower noise, lower power consumption, better size capability, and higher reliability. Since the original development of piezofans within CTRC, numerous piezofan-based thermal management products have been introduced to the market, most notably CTRC member company GE's highly publicized Dual Piezoelectric Cooling Jets (DCJ). The wealth of piezoelectric thermal management devices is a result of the burgeoning light-emitting diode (LED) light bulb market. Consumption of LED lamps in the United States totaled $891M in 2012 and is expect to grow to $2.77B by 2017 (ElectroniCast Consultants). While LED lights may have a significantly longer lifespan and lower energy consumption than incandescent alternatives, the devices produce significant amount of heat. Unlike conventional light bulbs, the solid-state devices at the heart of LEDs must be kept cool to retain efficiency. Energy consumption of a traditional rotary fan would offset any potential energy efficiency gains, making piezoelectric fans a viable alternative. Multiple piezoelectric-based LED thermal management devices have reached the market, such as the Nuventex SynJet.

The combined worldwide electricity consumption of data centers has increased from 71 billion kWh per year (in 2000) to 152 billion kWh per year (in 2005) to approximately 238 billion kWh per year (in 2010), representing a growth of roughly 11% per year over the last decade. As a fraction of the worldwide total electricity usage for all sectors, the contribution of data centers has increased from 0.53% in 2000 and 0.97% in 2005 to 1.31% in 2010. The growing IT demand is outpacing technological developments in sustainable energy management for these systems. Between 2003 and 2008, the total energy consumption of servers has doubled. Such growth levels are unsustainable and are especially worrying because IT equipment already contributes significantly to global energy use and carbon emissions. The main advantages of piezofans are low cost, low power consumption, low noise, good reliability, and good thermal performance in the low to moderate heat flux range. Piezofans can be used to replace or augment traditional air flow movers like axial fans. These devices can be combined with existing speed-controlled axial fans to achieve significant gains in heat transfer performance when the fans are operated at lower speeds. Even with marginal improvements to air cooling technologies, there is potential to save greatly on electricity consumption cost in current IT equipment for CTRC companies such as Huawei, IBM, and Intel.

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Two-Phase Transport in Microchannels

Researchers at the Cooling Technologies Research Center (CTRC) are exploring boiling and two-phase (liquid and vapor) flow in microchannels. Researchers have completed numerous studies on the direct cooling of silicon chips using microchannel heat sinks with dielectric (non-conducting) fluids. This CTRC work has resulted in better understandings of transport in microchannels and hence in rendering microchannel heat sinks more implementable in electronics cooling applications. Several novel experimental and modeling tools have been developed.

Cooling Technologies Research Center (CTRC)

This breakthrough technology was awarded the Alexander Schwarzkopf Prize for Technological Innovation by the I/UCRC Association in 2011.

Microchannels are very small channels that increase the total area of contact between the cooling fluid and the test chip. The large surface area allows for effective dissipation of heat from high power electronics commonly found in electric and hybrid vehicles. Transport through microchannels that range in width from 100 to 1,000 micrometers in copper, silicon, and acrylic substrates has been characterized.

Total heat dissipation and the local chip temperatures have been measured under a variety of flow

Heat is removed from high-power electronics by boiling liquid that flows through a microchannel heat sink.

conditions. Several heating configurations that range from a uniform distribution of heat input over the entire chip to a local hotspot have been tested. Additionally, the flow structure, including the shape and amount of gas flowing through the channels, has been experimentally measured. A predictive model has also been formulated that aids in the design and optimization of microchannel heat sinks.

Laser-induced fluorescence thermography is used to measure the liquid temperature during flow boiling heat transfer within microchannels. Infrared Particle Image Velocimetry (IR-PIV) is being developed as a tool to make measurements inside silicon microstructures (with no optical access), capitalizing on the transparency of silicon to infrared light. System-level analysis of microchannel cooling systems, with an emphasis on design for energy efficiency and manufacturability, is now possible through a software tool developed in the CTRC.

The effects of hotspot heating on the overall performance of microchannel heat sinks have been studied. CTRC research has developed models to use this technology in cost sensitive, very high-power electronic applications. Liquid cooling techniques using microchannels enables high-power electronics in hybrid vehicles, avionics, and spacecraft.

Economic Impact: Delphi Corp. (Kokomo, Ind.) helped commercialize this technology for electronic components in hybrid and electric cars. The new system will be used to prevent devices called insulated gate bipolar transistors that are used in hybrid and electric vehicles from overheating. The chips are required to drive electric motors, switching large amounts of power from the battery pack to electrical coils needed to accelerate a vehicle, perform regenerative braking, generating power to recharge the battery pack, and to convert alternating current to direct current to charge the battery from a plug-in line. The high-power devices produce about four times as much heat as a conventional computer chip and require novel cooling technologies. Delphi
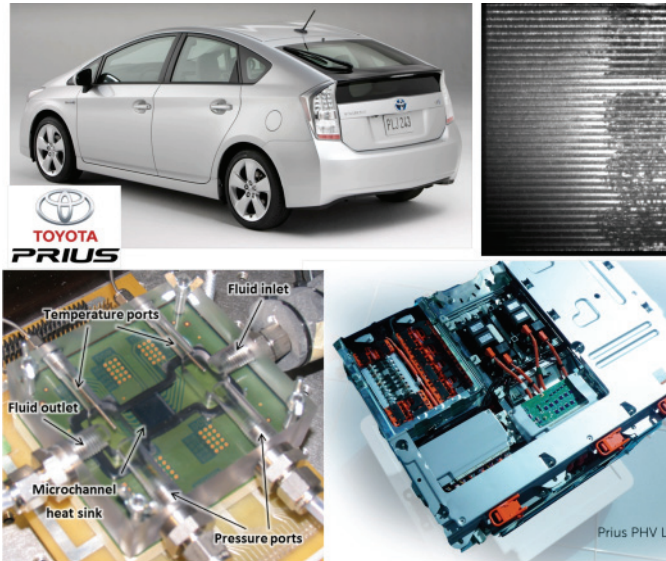
has created working prototypes and is commercializing this cooling technology. Other CTRC member companies are using this research, including Honeywell and Raytheon (aircraft avionics), HTRI (heat exchangers for the petroleum industry), Intel and Oracle (high-performance computing), and Eaton (power electronic systems - uninterruptible power supplies and motor soft starters). A patent titled "Microchannel heat sink" (#7,277,284) has been issued to Purdue University as a result of the work and 14 additional US and European patents, and patent applications were filed by Delphi as a result of the collaboration with CTRC. Additionally, correlations developed from this research have been implemented in Honeywell's in-house evaporator design code.

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Enhancement of Heat Pipe Transport Properties and Thin Film Evaporation

One of the key limiting factors in electronics technology today is the need to remove heat from the processor inside nearly every device. Because of their ability to move large amounts of heat over reasonable distances with limited electronics chip temperature rise, heat pipes are commonly used in electronics cooling applications. This efficient heat transport is due to the phase change of an internal working fluid from liquid to vapor and porous structures imbedded inside that passively drive the working fluid. Efficiency increases would allow devices to operate with less temperature drop across heat pipes, therefore keeping electronic components relatively cooler at the same heat load. While typical devices in industry use randomly packed particles as porous wicks, designing the wick structure at microscale levels has shown how device performance may be dramatically improved. These advances affect a wide range of applications, from increasing the range and resolution of military air and missile defense radar systems, to operation of laptops and mobile phones at cooler temperatures, all with extended battery life.

As a follow-on collaboration to pre-completive heat pipe research performed in CTRC, Raytheon acquired external funding totaling $2.5M in partnership with Purdue University to develop a "Radio Frequency Thermal Ground Plane" (RFTGP). This provides significantly improved performance relative to state-of-the-art commercial heat spreaders. As part of this work, Raytheon was provided an experimentally validated model for transport in vapor chambers. This resulted in a direct increase in the technology readiness, which, in turn, led to additional funding of work at Raytheon for further technical demonstration.

Heat pipes may be used to keep electronic processors cool in next-generation radar defense systems and mobile phones alike.

Economic Impact: The heat spreading efficiency of heat pipes reduces the overall power consumption of the cooling solution because auxiliary cooling components, such as axial fans, which

dump heat to the ambient atmosphere, do not have to work as hard. While these are conventionally employed in larger-scale laptop and desktop computers, recent efforts within the CTRC have focused on heat pipes that may be used in mobile platforms such as cell phones and tablets (worldwide smartphone shipments are expected to surpass 2.3 billion units per year in 2017). A CTRC member has recently launched a $1.5M "platform thermals" research program through their University Research Office, targeted at thermal management in this market. Faculty in the CTRC have been awarded funding through this program to investigate transformational advancement of heat pipe technologies for ultra-thin mobile platforms.

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Transport in Porous Structures and Metal Foams
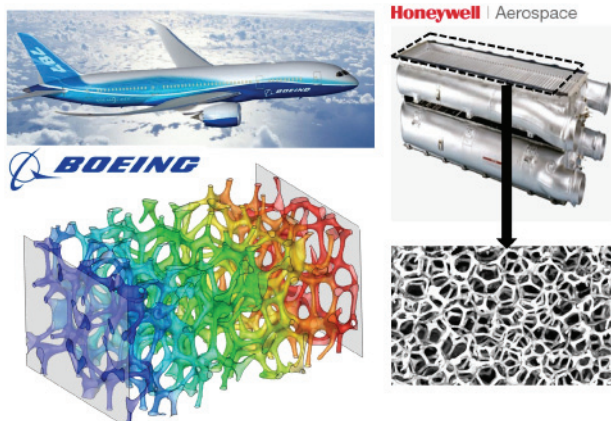
Heat transfer is simulated using a high-resolution x-ray microtomography scan of porous metal foams that are used in aerospace heat exchanger components and as heat sinks for other electronic devices.

Metal foams are novel heat transfer surfaces with potential use as heat sinks and heat exchangers. Their inherently high surface area allows extremely effective dissipation of heat to passing air stream. As a result, they have been recently come to be used in the heat exchanger industry, particularly by aerospace and power electronics companies. Naturally occurring and engineered porous materials are used in a wide range of other mechanical, biological scaffolding, energy storage, and thermal management applications. They have central functions in desalination, filtration, and in battery technologies.

The characterization and design of porous structures is critical for many industries, but generalized prediction of their properties is extremely difficult due to their random nature and geometric complexity. A novel computational methodology for detailed modeling of open-cell foams and other porous structures using microtomography imaging techniques (commonly known as CT scanning) has been developed at the CTRC. X-ray microtomography can visualize the intricate details of porous materials at extremely high resolutions, higher than would otherwise be possible with traditional destructive methods that rely on physical sectioning of the material. This approach has been used to generate geometrically faithful models to simulate heat transfer in porous metal foams.

Economic Impact: The heat exchanger market in the chemical, petrochemical, oil and gas, HVAC, and refrigeration industries is expected to have a compound annual growth rate (CAGR) of 11.5% that is expected to reach $19.5 million by 2018 (*Markets and Markets*, July 2013). Heat exchange applications will benefit from advantages such as cooler electronic components and smaller heat sinks, thereby increasing the life of the equipment as well as shrinking the overall

dimensions. The technology can be used to cut down heat exchanger equipment size by half or more, thereby cutting down significantly on material costs. Other savings will be in terms of decreased power consumption. The novel porous foam structures are able to transfer more heat at a far lower pumping power (energy cost) compared to their conventional alternatives. Researchers in CTRC have collaborated on internally-funded, proprietary research projects with Eaton Corporation and Honeywell Aerospace to commercialize heat exchangers that leverage these advanced structures and design methodologies.

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Ultra Wideband Multi-Port Antenna for Full Duplex Wireless Communication Systems

Researchers at the Connection One have developed a multi-port antenna with very high port-to-port isolation that should be useful for full-duplex indoor base stations of wireless communications in several GSM, LTE, and WiFi bands. Simultaneous transmission and reception of data can double the spectrum efficiency. However, any full-duplex transceiver with collocated transmit (TX) and receive (RX) antennas has leakage from high power TX signals into sensitive RX components, via antenna coupling.
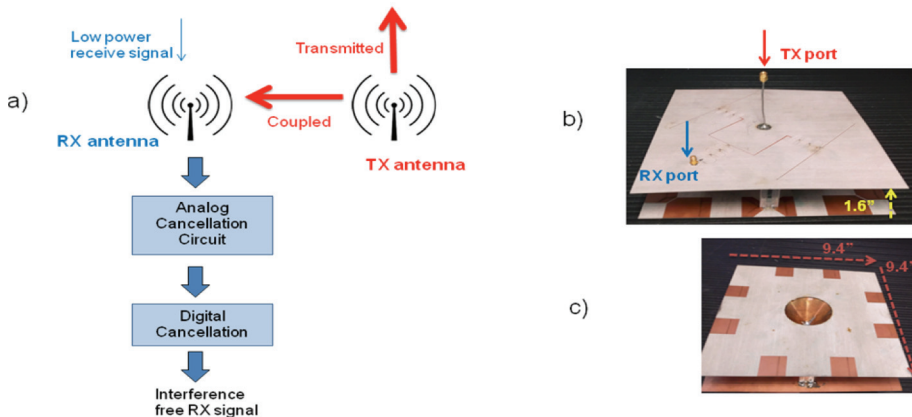
Above (a), a schematic view of the isolation problem between receive and transmit RF front ends; (b) Bottom view of the fabricated antenna and matching showing the RX and TX ports with integrated feed network; (c) Top view of the fabricated prototype.

To cancel this leakage, sophisticated RF circuits and digital algorithms are required in the receivers. Increasing the isolation between RX-TX antennas can ease the design constraints in these RF circuits and digital algorithms (even eliminate some of them). The designed ultra wideband multi-port antenna has about 40dB isolation between TX-RX ports over 800-2700 MHz frequency range. It allows for full-duplex operation

in several commercial communication bands. The antenna fits in a 9.4"x 9.4" x 1.6" volume and has an omni-directional radiation pattern (suitable for ceiling mounting).

Overall, the design is wideband, low profile (1.6"), and has high efficiency and +40 dB isolation across the entire band of interest (800 MHz-2700 MHz), which makes it unique compared to other commercial multi-antenna designs. Specifically, all of the available multi-port antennas lack at least one of the following feature: wide bandwidth, high-isolation, low profile, and/or omni-directional radiation pattern.

> **Economic Impact**: This antenna is a transformational technology as it provides for extremely wide bandwidths and MIMO capabilities for data rate wireless applications and for long distance communications in a very small size antenna. It will be marketed by Commscope Corp: http://www.commscope.com/. Its economic impact could be significant as it can be employed as a transceiver component for all indoor wireless communication systems, either being placed inconspicuously on ceilings or vertical walls. The advantage of the device is its broad bandwidth covering LTE, GSM, PCS, and WiFi among other bands using a single small aperture. Its low RX/TX isolation implies larger data rates with the potential to replace interior building cellular and WiFi wiring thus enabling uninterrupted high data transfers, including video connectivity. That is, the developed antenna transceiver is a breakthrough technology with high impact in all aspects of communications for commercial and defense applications.

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Universal RF Transceiver and Sensors

The goal of communication and computing systems is ubiquity; wireless devices that can be used seamlessly in many applications ranging from biomedical sensors, environmental sensors and wireless mobile phones. Connection One researchers have developed a multi-mode transceiver that is completely integrated on one chip.

The ultimate goal of communication and computing systems is ubiquity; wireless devices that can be used in many applications ranging from biomedical sensors, environmental sensors, wireless mobile phones, and radio frequency identification (RFID)s tags. For example, in order to develop an RF wireless system that can be used as an implanted bio-sensor inside the body, transceivers must be small (less than few millimeters) and capable of staying inside the body for 5-10 years without changing batteries. These needs also apply to mobile systems like multi-mode universal mobile and smart phones. Such systems require multiple standards (like GSM, CDMA, and UMTS) and must adhere to stringent power and size requirements; the entire transceiver, including the antenna, has to be integrated into very small areas. Current smart phones require integration of RF, antenna, signal processing, video and image processing, and microprocessors all on the same system. Accomplishing this has been a major roadblock with this technology.

In terms of power, two major components in transmitter architecture are the power amplifier (PA) and the PA modulator. PAs accounts for over 70% of power consumption in handsets and consume a significant portion of the handset's volume. Therefore, altering the power amplifier topology to lower the demand on their bulky passive filters while simultaneously increasing the efficiency and linearity is essential when realizing high-efficiency monolithic transmitter architectures. A new method using a noise shaping technique to modulate the controller integrated circuits in switched-mode converters and power amplifiers reduces the demand on the output filters of the structures.

Economic Impact: This breakthrough technology has impacted communications generally and multi-mode phones specifically. As a result of this Connection One work, it is now possible to reduce the overall size of communications transmitters and products. The new architectures are more efficient than other techniques. This research has resulted in over 50% overall improvement in efficiency (improved battery life by 30-40% reduced transmitter power by over 40%). The overall complexity and size of transceivers, PAs, antenna and power management components have been reduced by 30-50%. This has been very important to a number of center sponsors, including Qualcomm, Texas Instruments, Broadcom, and to the communications industry generally as new efficient topologies for transceiver chip sets are developed.

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Data Center Waste Energy Recovery and Re-Use

Data centers are a growing source of "waste energy." In fact, recent figures show that data centers alone are responsible for more than 2% of the United States' total electricity usage. With the steadily increasing demand for computing services in all sectors of the economy, and the rapid adoption and transition to cloud-based computation and storage, electricity demands will continue to soar over the next few years.

With these increases in computing demands, the processing load on the data center servers escalates. Increased load leads to increased chip power and possible overheating of the electronics. To maintain reliability and prevent system failure excess heat must be removed from the server. The heat is typically removed using either extensive air conditioning systems or using a liquid coolant stream. As the air or liquid removes the heat from the electronics, the coolant stream itself heats up, generating what is referred to as "waste heat." This waste heat is then often discharged directly to the environment though cooling towers.

This breakthrough research has focused on identifying the most promising methods and technologies for using the energy transferred to this coolant stream, rather than discharging it to the surroundings. This project's goals have been to: 1) comprehensively analyze and optimize two key methods of waste heat recovery; and, 2) produce validated computer models for use in analyzing the potential benefits to facilities of being able to choose the best system and then to calculate and optimize the return on investment.

Data centers produce large amounts of waste heat, but it is at relatively low temperatures (80 °C/176 °F). Most existing waste heat recovery systems are optimized for performance at temperatures closer to 300 °C/572 °F. Lower temperature waste heat recovery is challenging because fewer options exist for its industrial re-use. Thus to date, it has been difficult for organizations to justify the investment required to recover the waste heat. The low value of this waste heat compared with the value of the business and the potentially large capital investment required for waste heat recovery equipment means that from a business point of view it remains difficult to justify the long and sometimes uncertain return on investment.

Up to this point none but the largest organizations have been able to investigate the possibility of waste heat recovery and consequently there are very few global examples of such schemes being applied to data centers. The traditional concepts for re-use of low temperature heat include localized hot water heating, or public heat distribution such as district heating systems. These applications are of limited appeal and provide a tenuous justification at best for organizations to invest in energy recovery. In contrast, this research demonstrates realistically how companies can recover waste heat and re-use it on-site for electrical power production and/or by operating a waste heat powered refrigeration cooling cycle, both of which reduce overall energy consumption and cost.

Using the optimized designs and operational models developed here, organizations will be able to easily consider all options for energy re-use from their data center facilities, and the organizations can expect reduced overall energy consumption and lower energy costs. In addition, the contribution to global warming will be significantly reduced. If applied globally, the industry will not only recognize significant financial savings, but will also avoid the potential negative public image associated with the rapidly growing energy consumption of IT facilities and their environmental impact.
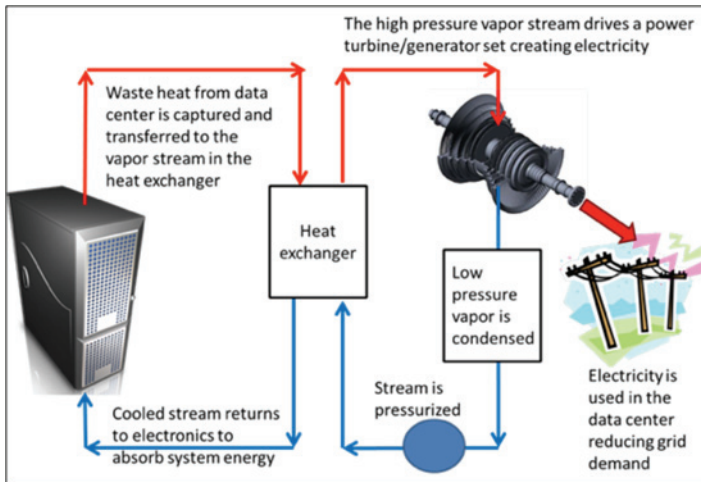
An example of a waste heat power-producing cycle. The waste heat is captured from the data center and used as the heat source to boil an organic liquid. The high pressure vapor that forms when boiled spins a turbine, generating electricity. The low pressure vapor exiting the turbine is condensed, re-pressurized and the cycle begins again.

Economic Impact: The high cost of energy and the depletion of limited resources are two of several issues driving significant interest in the capture and reuse of waste energy. If energy that is typically "wasted" can be reused, significant economic and environmental impacts can result. Given the significant energy consumption in data centers, the ability to capture and reuse energy offers the potential for massive reductions in energy consumption globally. A "typical" data center may contain 250 server racks, with each rack containing 42 to 64 servers. A single data center may therefore dissipate as much as 3-6 MW of power in the form of waste heat. Assuming that 90% of this waste heat can be captured and converted to electricity in a low temperature vapor power cycle at 10% efficiency, the data center can produce 300-600 kW of power from waste heat. Over the course of year, with 85% online operational time and considering a purchased electricity cost of $0.08/kWh, a company can save $175,000-$350,000 in annual power costs alone. However, when one also considers that the servers providing the waste heat to the power cycle may now be removed from the data center cooling system, the savings increase substantially. If a data center is dissipating 3-6 MW of power as waste heat, and the data center no longer needs to provide cooling to these systems, the savings can easily exceed $1,000,000 - $3,000,000 per year in electricity and operational costs, with subsequent reduction in load on the national power grid. Thus investing in capital equipment to recover and reuse waste heat will result in significant and positive impacts on the user's bottom lines and on the environment.

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GRid-Connected Advanced Power Electronic Systems (GRAPES)

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Smart Green Power Node
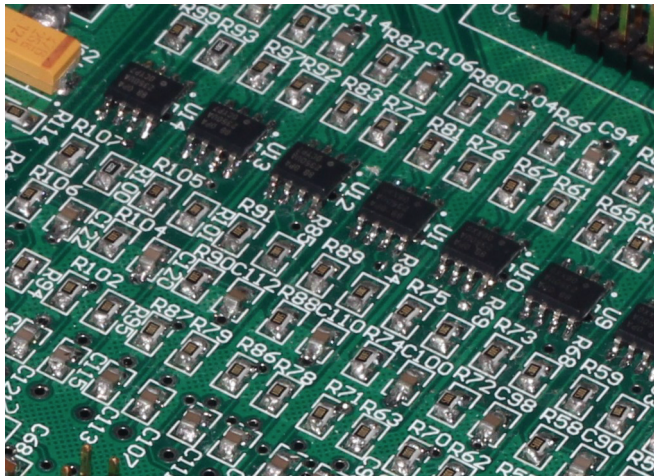
The many control channels of the Smart Green Power Node control module evoke notions of the larger power control channels that route electric power between sources, loads, energy storage systems and the grid. Such optimal power routing minimizes energy costs for the consumer.

GRAPES researchers have developed a "smart green power node," a combination of electronic power converters, power routers, and control algorithms that put the "smart" into residential power systems. "Dumb" power systems have been the standard for the past 100 years, with power cables running to everything that needs power and everything using power whenever we or it wants to. But emerging electronic and information capabilities, new energy resources and new environmental priorities have created a need for better ways to integrate renewable energy systems, energy storage, and time-of-use power management into simple-to-use systems that will consume energy more wisely while minimizing the cost and environmental impacts of our energy consumption.

The Smart Green Power Node does this by directing the flow of electric power from resources such as solar photovoltaic or wind to storage batteries or to the house wiring, and it coordinates the operation of various smart appliances on the home's power network. The thermostats of heating or air conditioning systems and of water heaters and of the on/off status of deferrable appliances such as clothes washers or dish washers are managed by the Smart Green Power Node so as to optimize system efficiency, minimize energy cost, and maximize comfort and convenience of the homeowner. Maximizing essential consumption (by running appliances or storing energy in the battery) when power is cheap or readily available (e.g., the sun is shining), and minimizing grid consumption (by turning appliances off or by powering essential appliances

from the battery) when power is expensive (e.g., during load peaks) or not available (e.g., nighttime or no wind), minimizes the total cost of power for a homeowner.

The Smart Green Power Node contains electronic devices that convert dc power from batteries or photovoltaic panels to the 120 V or 240 V ac power that is used in homes. And it contains computing hardware and software that collect information from the internet - things such as weather forecasts and current or future (e.g., next hour, next day) prices for electric power - and information from a home's occupants - things like patterns of electric power use and comfort settings - which inform the node's decisions on when and where to send power. The demonstration unit is rated at 2 kW. Although this is less power than a typical home often uses, this size maximizes the "bang for the buck" in terms of return on investment. But the system is modular so a homeowner who wants greater power capability can simply plug in more power modules. Likewise, the storage battery can be sized to maximize the return on investment when considering the local prices of electric power, the lifestyle and energy use habits of the homeowner, and the availability of renewable energy sources. At less than $1/W now, and perhaps far less when produced at commercial scale, the Smart Green Power Node is a low-cost mechanism for maximizing energy utility.

The Smart Green Power Node has been an exemplary study in cooperative work between the two sites of the GRAPES center. More than 15 students in total have played a role in its development, with various aspects of the research and development done at each site. From business case analyses, to power circuit design, from network connectivity to decision-making algorithms, from simulation-based analyses to cost-conscious design of power converters, the many parts of this puzzle could only be completed by relying on the broad intellectual and human resources of the two institutions. Furthermore, this project has had the most consistent support from a broad base of center members - from electric utilities to equipment manufacturers to semiconductor manufacturers - everyone understands and appreciates the tremendous promise of this system.

The SGPN will change the way that residential power customers use electricity. It will simplify the integration of renewable resources such as solar and wind, and it will make smart energy use more feasible for the average power consumer. It will also enable more effective use of the existing power grid by incorporating battery energy storage through one simple off-the-shelf solution.

> **Economic Impact:** The potential economic impact of the Smart Green Power Node is enormous. In the US alone, residential electric power consumption totals roughly 1000 kW hours per month per home which costs the 125 million residential energy consumers $160 billion per year. If the Smart Green Power Node reduces power bills by only 10%, that would amount to $16 billion of energy savings per year. Not just savings in dollars would result, but also there would be savings in the offset costs of building new power generating facilities and in reduced CO_2 emissions overall. While in the U.S, the average residential price for electricity ranges from $0.10/kW hour to $0.36/kW hour, global prices tend to be much higher and therefore payback will be even more rapid in these other regions of the world. And then there is the land beyond the edge of the grid; in undeveloped regions the Smart Green Power Node can serve as a stand-alone micro-grid, being the one and only source of reliable power. The actual cost savings that homeowners will be able to realize from this system varies widely and depends on the pricing structure for electric power, the lifestyle and habits of the homeowner and the local climate. Case studies indicate that payback periods will range from several years to a decade or more. Outcomes will be strongly affected by decisions of governmental regulatory commissions. While there is great uncertainty in many of the essential circumstances, two trends are virtually certain: future prices of electric

power will be higher than today's prices and prices will become more volatile, changing on seasonal, daily and hourly schedules. Both of these trends will make this system become more and more valuable.

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Superior Relief From Dry Eye and Dry Mouth Problems

Many people suffer from both "dry eye" and "dry mouth" problems. They experience a "gritty" sensation when blinking or when trying to swallow. Researchers at SUNY Buffalo's Center for Biosurfaces have developed a new and improved tissue-on-tissue measurement technology that provides information that correlates better with what really goes on in the eye and in the mouth. The new methodology is leading to the development of products that result in user benefits more quickly than was possible with earlier techniques that used only synthetic materials. Using this new tissue-on-tissue testing protocol researchers demonstrated the superior reduction of "blinking" friction and swallowing difficulties associated with addition of novel solutions compared to saline-wetted tissue surfaces. Significant improvements in the lubricity of in-the-eye and in-the-mouth comfort formulations have been achieved by selecting the polymer products of nature rather than synthetics made in the laboratory. More importantly, the research has shown how to formulate these polymer products for safety and effectiveness in over-the-counter products. Previously available test methods did not reveal the clinically relevant superior lubricity for the natural polymer solutions.

This photo shows the simple placement of a drop of lubricating solution, after which significant and long-lasting comfort is obtained. This effect is demonstrated well in the unique tissue-on-tissue test developed at the Industry/University Center for Biosurfaces (IUCB), and is now being explored for in-the-mouth lubrication as well.

Economic Impact: Expensive doctor's visits and costly time off work can now be more frequently avoided because of the availability of in-the-eye lubricants that allow more hours of comfort and function. Soon, it is expected that research will reveal the even more-needed solution to problems of "dry mouth" that plague our aging population and often render swallowing of needed medications difficult or impossible. Annual commercial sales of the SYSTANE artificial tears solutions now exceed $200 million.

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Allergy Friendly Room Program

A new industrial partnership now combines a recently patented allergy-friendly room-treatment process, with a line of novel air purifiers capable of maintaining high air quality for long periods. A new Corporation, PURE-HealthWay Global of Pulaski, NY is marketing the new process and equipment worldwide. The company provides pre-packaged allergy friendly rooms to the hospitality market.

The process substantially reduces particles, bacteria, mold spores, and fungi in indoor environments. An added benefit is energy savings of 25% or more through the cleaning and sanitization of heating and cooling coils in an air-handling unit. An intrinsic part of this breakthrough technology is a special line of HeathWay air purifiers that can maintain the room environment at fewer than 600,000 respirable

The new PURE HealthWay Global process keeps hospitality rooms, as shown above, clean and crisp and tolerable for allergy-prone guests. The process of cleaning and maintaining the air quality is so good that the PURE process has now been adopted for health clubs and related facilities worldwide.

particles, regardless of how dirty the outside air really is. Within the past year, IUCB has tested an expanded line of HeathWay filters and ascertained that they are able to remove 99.99% of all respirable particulate matter, even when deliberately introduced.

Economic Impact: Ongoing research with PUE HealthWay partners is resulting in substantial new business opportunities across the nation and around the world. The new PURE HealthWay International Division has developed a worldwide licensing program. It has partnered with firms in Canada, Dutch Caribbean, Barbados, United Arab Emirates, Singapore, Scandinavia, Malaysia, and China. The Hyatt national hotel chain agreed to convert 2,800 rooms over the next year. The contract, valued at over $10.0 million U.S is generating substantial royalty fees for the company.

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Institute for Next Generation IT Systems (ITng)

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Software Rejuvenation

Researchers led by Kishor Trivedi at Duke University and the Center for Advanced Computing and Engineering (CACC) developed a method to detect problems of memory leak, data corruption, and fragmentation that have plagued a wide range of computer systems and networking components. Problems build up over time and lead to performance degradation, hanging up or freezing, and other failures of computing systems. Such system failures and resulting downtime cost billions of dollars in banking, telecommunications, military and

Memory leak and data corruption problems build up over time and lead to performance degradation, hanging up or freezing, and other failures of computing systems.

other sectors. Such failures may also cause a loss of life in life-critical systems. Memory leak is a phenomenon in which memory resources in computing systems decrease over time and eventually cause system problems. The problem occurs because software programs request memory but sometimes don't release it. This unreleased memory accumulates over time.

The researchers collected empirical data on these problems and developed a way to monitor the course of the deterioration and to predict when future problems would occur so that preventive measures could be taken. This software rejuvenation method has been adopted by IBM in their X-series servers, and subsequently other companies including Oracle and Microsoft have adopted this technology. This technology has also been adopted in telecommunications sector. The use of software rejuvenation is known postpone or prevent disrupting system failures and hence reduce the cost of downtime. It has also been implemented in NASA's space-based software systems.

Economic Impact: Ramifications of computer system failures and associated downtime, cost the banking, telecommunications, healthcare, armed forces, and other like organizations billions of dollars each year. Several studies have analyzed the economic cost of IT systems' downtime. In large systems, direct associated downtime cost has been calculated to average around $125,000 per hour (in data center environments this value can reach $335,000 per hour). However, there is a missing gap in terms of the economic impact of software rejuvenation strategies specifically. Even so, we can extract interesting remarks from these studies. According to the Aberdeen Group

Institute for Next Generation IT Systems (ITng)

Research Report on June 2010, based on the analysis of 125 organizations, the "best in class" companies (top 20%) in terms of time to recover, number of downtimes and percentage of data availability are able to recover their systems 6.5-times faster than the laggard companies (bottom 30%). In absolute economic terms, "best in class" companies were losing 40-times less revenue than laggard organizations. Simply improving from laggard to average (middle 50%) organization, this CACC work will increase the revenue to the company by about $1.3 million per year. So, any recovery mechanism (i.e., software rejuvenation) able to reduce the outages and its consequences is reducing significantly the outage invoice while increasing the revenue and productivity of the organizations.

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Intelligent Maintenance Systems (IMS)

A CISE-funded Center

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Platform for Prognostics and Health Management (PHM) System Development

In the field of industrial equipment health monitoring and maintenance logistics optimization, new predictive health equipment algorithms and methodologies are emerging from academia and industry. In today's industry and academia, much work focuses on either a physical health monitoring approach or a pattern recognition health monitoring approach. Both have advantages and limitations.

Application of Watchdog Agent® in monitoring ballscrews for precision machining.

With data driven technologies, predictions of maintenance needs are made from comparing actual sensory data collected from assets to historical reference patterns. With model based technologies, sensory data are compared with a physical model of the equipment to determine deviations from expected performance.

When the two approaches are combined, both accuracy of equipment degradation measures and accuracy of predictions are greatly improved. Building on the 2012 nominated works, as listed at "Assessing Equipment Performance with the Watchdog Agent®" on page 179. The University of Cincinnati has completed an important phase of model-based prognostics. Both the physical model-based and data driven prognostic approaches work together to tune each other as new sensory data arrives from monitored equipment.

The Coupled Model for prognostics and health management investigates physi-

cal model development for common mechanical components in order not only update the physical models over time but also to fuse the health monitoring result from both aspects. Effectively, the Coupled Platform combines the model-based approach with a data driven approach to bring forth the best of both methods into a single application.

National Instruments offers several products for equipment health monitoring applications. These products are influenced by the University of Cincinnati's work in the area of PHM. They benefit National Instruments' customers in that they optimize logistics of maintenance, increase revenue, and improve the reliability of operations. With the incorporation of the Intelligent Maintenance Systems (IMS) work in the areas of PHM, National Instruments' health monitoring now includes a new dimension beyond basic sensory measurements.

> **Economic Impacts**: With this breakthrough National Instruments is becoming more competitive in the equipment monitoring market. National Instruments can rely on the validation of algorithms and techniques developed by IMS to avoid more costly efforts and the need to have prognostics experts on staff to perform this work. For National Instruments to develop this Intellectual Property, they would need to employ 3 to 5 researchers full time. Beyond the monetary savings with respect to R&D cost avoidance, there is significant potential for increasing data acquisition hardware sales that are related to asset monitoring. In addition to the increased hardware sales that National Instruments will receive from these installations, end-customers should also reap the benefits of having better productivity, less unplanned downtime and outages, and more reliable power production. There will be even more widespread impacts to the economy and society by having more reliable power generation, which is one of the potential benefits from these predictive monitoring systems.

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Prediction and Prevention of Hydraulic Hose Failure

The University of Cincinnati researchers from the NSF I/UCRC for Intelligent Maintenance Systems (IMS) and the NSF ERC for Revolutionizing Metallic Biomaterials (RMB) collaborated in the research and development of a smart sensor that can be utilized for flexible tube fittings (such as a hose), as well as the advanced analytics-based monitoring solution, in order to predict and prevent expensive and catastrophic hydraulic hose system failures.
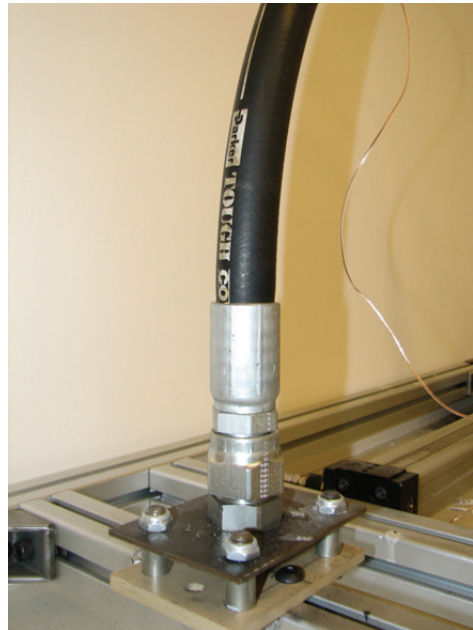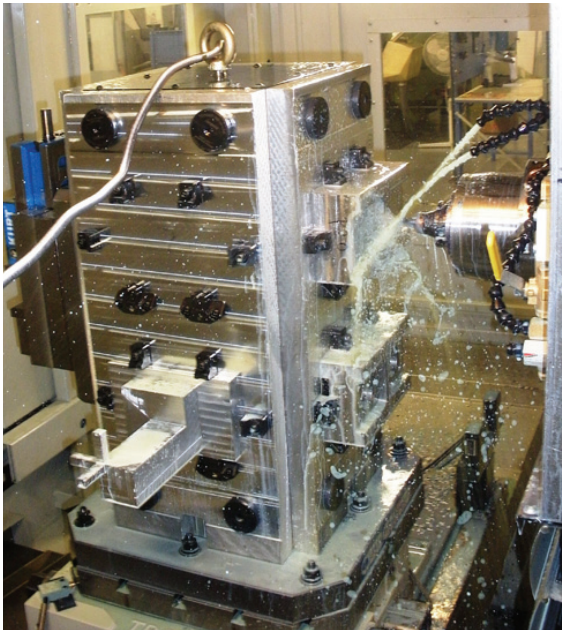
IMS researchers have developed a smart sensor that has an embedded prognostics algorithms can easily attach to hydraulic hoses. The sensor monitors the degradation of hoses and automatically sends alerts when potential failures are predicted to occur.

There have been a limited number of studies involving hose prognostics, owing to the lack of an appropriate and effective sensor, both in the research and industrial communities, that can be used with hydraulic hose systems. The previous state-or-the-art inspection method was very time-consuming and costly. It was associated with the risk of catastrophic accidents most especially in high-pressure applications. As a result, there was a dire need for an intelligent hydraulic hose sensing and analysis method.

Parker Hannifin helped support the research and development of the novel sensing method and hydraulic hose health monitoring analysis methods. Parker Hannifin is one of the largest manufacturers of motion and control technologies and systems, including hydraulic systems and hoses.

Intelligent Maintenance Systems (IMS)

The hydraulic hose health monitoring technology can be adapted for a variety of customer segments, including oil, gas, and mining applications. For customers in the oil and gas industry, having a hydraulic hose with this health monitoring capability could prevent many hose failures that could cause serious economic or environmental impacts.

> **Economic Impact:** Because the previous hydraulic hose inspection state-of-the-art method was inconvenient, time-consuming, and costly, having an intelligent sensing and analysis method can provide significant time and cost savings. This breakthrough technology has many critically important industrial applications. Significant reductions of environmental and human safety consequences related to hose failure are now possible. Across-the-board, end-users of systems that rely on hydraulic hoses will be able to realize dramatic improvements in productivity and in safer working environments. With the new technology the sensor sleeve is designed to change electrical impedance (resistance) due to fluid pressure initiating a hole through the sensor itself. The sensor sleeve will detect the earliest fluid leak when the hole penetrates the sensor and brings the two elastic electrodes in contact with each other and/or the fluid. This creates a signal path between the first electrode layer and the second electrode layer. It also changes the impedance as measured across the electrode layers. Smarter, stronger, and safer hydraulic hose systems will provide significant economic benefits to customers across many applications. Due to its predictable potential economic potential, the inventors and sponsors of this technology applied for a patent. The patent focuses on a sensor sleeve for use in detecting a failure in an article (e.g., a hydraulic hose). Patent number EP2569620 A1 was granted on March 20, 2013.

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Assessing Equipment Performance with the Watchdog Agent®

The goal of every machine user is to reap the maximum return on investment for their assets. This can be achieved with optimal equipment utilization that is characterized by high usage reliability and safer working environments for system operators.

Since 2001, and continuing through 2014 the Center for Intelligent Maintenance Systems has been pioneering research on the Watchdog Agent®, a suite of predictive analytic tools, that can be deployed to industrial equipment. Unplanned machine or process breakdowns and non-sustainable production throughputs can severely limit equipment effectiveness. Systematic methods utilizing advanced analytic tools, such as those found in the Watchdog Agent®, are needed in order to predict equipment performance over time so that failure events can be detected at their onset and avoid them altogether.

The Watchdog Agent® is a toolbox of advanced analytic tools that can be reconfigured and customized for any products or systems for which it would be beneficial to predict when and how they fail. It can be applied from a system-level (an entire equipment) down to component level (such as a valve). The Watchdog Agent®-based monitoring solutions assess and predict the performance of processes or equipment based on inputs from sensors mounted on them. System health indicators are extracted from the signals recorded from the aforementioned sensors and they are intelligently fused to generate health information, also known as confidence value (CV).

By referencing historical machine behavior degradation patterns, performance on future usage can be inferred to estimate when the next maintenance event should occur. The Watchdog Agent® toolbox covers a broad range of analysis tools so that it can be applied for a wide variety of applications including, but not limited to, wind turbines, industrial robots, machine tools, EV batteries, locomotives, and mining and construction trucks. The IMS consortium has provided necessary test-beds and domain expertise to validate the tools. Among the participants are: Siemens, Nissan, Harley-Davidson, Caterpillar, Toyota, Metron Hong Kong Limited, Bosch, BorgWarner, Tongtai, Komatsu, Daimler Chrysler, Kone, Woodward, TechSolve, P&G, Precision Machinery and Research Development, Parker Hannifin, Omron, National Instruments, Industrial Technology Research Institute, Institute for Information Industry, Hiwin, Goodyear, General Motors, Boeing, Flanders Mechatronics Technology Center, etc.

Economic Impact: The Watchdog Agent® toolbox is now available as a commercial technology through the National Instrument's LabVIEW platform. This commercialization allows users to rapidly design and develop predictive monitoring solutions for their critical assets. Industry practi-

tioners have benefitted from the Watchdog Agent® technology by having more in depth understandings of their equipment's reliability and process stability. Since its inception, the IMS Center has grown and validated the Watchdog Agent®, conducted research on innovative approaches and techniques in order to apply these new analytic tools more appropriately. The early adopters were machine end-users, but after seeing the benefits and providing reliable and therefore convincing early successes, more and more machine original equipment manufacturers are now incorporating these advanced predictive solutions into their products as built-in capabilities. In an independent study sponsored by the National Science Foundation, it was determined that the IMS Center has generated over $855 million of economic impact to its members for a year in the form of severe and catastrophic failure avoidance, productivity improvements, higher efficiency, and lower scrap rates, among others. These benefits are documented via an objective evaluation of machine performance using advanced analytics so that future failure events can be predicted and avoided.

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Membrane Science, Engineering and Technology Center (MAST)

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Single Molecule Protein Interactions with Surfaces
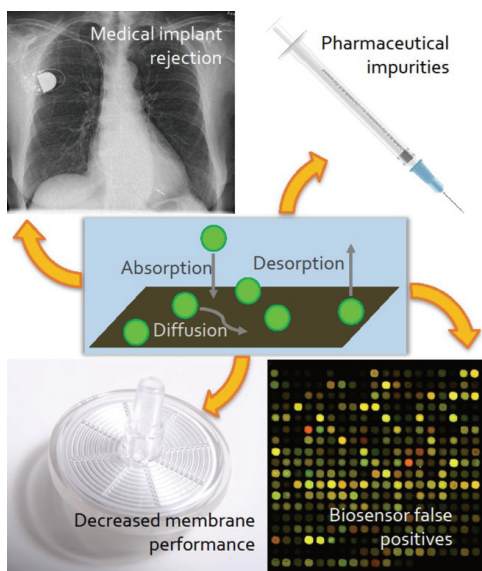
The ability to observe individual protein molecules attach to (adsorb), detach from (desorb), and move around (diffuse) on material surfaces will allow industry to develop improved materials that are not readily fouled by protein layers. This will decrease production costs and improve performance, product quality, and safety in a variety of industries where proteins are critical components.

The understanding of what occurs when protein molecules approach surfaces has many practical applications for the biopharmaceutical industry and for therapeutics for more that half a million Americans annually. As one important example, associated advances in knowledge guide the development of materials that do not foul (or that are easily cleaned) when filtering, transporting, or storing pharmaceuticals, foods, and beverages. These advances increase patient safety, reduce the production costs of numerous pharmaceutical products, and increase product quality and shelf life. In other industries it helps in the development of packaging materials that do not alter the effectiveness or taste of the package contents.

Researchers at the University of Colorado Boulder have refined a way to monitor individual protein molecules as they attach to and detach from solid surfaces. This work represents a major advance over the previous state of the art because it facilitates a detailed mechanistic understanding of how individual molecules interact with surfaces rather than simply measuring overall rates of fouling or cleaning in an empirical, trial-and-error manner. It also enables researchers to better study how proteins interact with a fouled surface after attempted surface cleaning; something that is very difficult to achieve with other methods.

In this breakthrough approach, surfaces of interest are irradiated with lasers during exposure to solutions of proteins that are tagged so that they glow (i.e., fluoresce) when they become attached to surfaces. The proteins stop glowing when they detach from surfaces. The appearances and disappearances of each glowing protein molecule are recorded with a sensitive camera through a microscope so that millions of individual molecules may be separately observed in a given experiment. Specialized custom-written software computes the rates of attachment and detachment of different proteins from the surfaces studied.

Membrane Science, Engineering and Technology Center (MAST)

This work literally provides improved pictures of the mechanisms of surface fouling and the nature of the surfaces after cleaning compared to what had previously been available. The information obtained aids in the design of materials and coatings that are not readily fouled and can be quickly and repeatedly cleaned for re-use. The method impacts the design of filters, packaging, drugs, foods, medical devices, and biomedical implants.

The research that began in the IUCRC is now completed and is being expanded through a private contract from industry to further extend the capabilities. The work has already led to a follow-on private research contract with the Principal Investigator to further develop the technique. Future work will likely bring this kind of work in-house.

> **Economic Impact**: Biopharmaceutical therapies are becoming increasingly important for treating a variety of diseases including cystic fibrosis, skin and breast cancers, tuberculosis, and leukemia. Biopharmaceutical purification (e.g., filtration) accounts for 50-80% of all manufacturing costs. The ability to rationally design non-fouling and cleanable filtration materials will lead to safer, more efficient product purification. Reducing the cost of filtration will also help grow new business in cost-sensitive applications where good filtration is currently considered too expensive to be economical. Similarly, the rational design of protein-resistant materials for shipping, storage, and delivery will lead to greater product stability and efficacy. The implications of this work for medical therapies are major and many of these will have significant economic ramifications. For example, anticoagulation therapies that accompany implanted stents or heart valve procedures are often costly and dangerous (e.g., can result in excessive bleeding).
>
> Each year more than half a million Americans receive coronary stent implants. Designing smarter materials that prevent pathological material-blood interactions can reduce the need for such treatments, thereby reducing the economic burden on the health care system. Biosensors have wide applications in medical (e.g., detecting disease markers, sugar or insulin levels in the blood of diabetics) as well as important environmental applications (e.g., identifying toxins or organic compounds in groundwater). Non-specific protein adsorption presents major challenges in biosensing applications. These can lead to poor detection limits and false positives in state-of-the-art medical diagnostic devices, all of which have major economic impacts, most of which are almost impossible to estimate. Understanding and reducing non-specific binding can greatly increase the speed and sensitivity of such analyses, allowing more information to be collected with fewer sensors and enabling portable devices for use in the field.

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High-Recovery Desalination Process for Brackish Groundwater

The first-generation desalination pilot plant.

Many regions of the world including the Middle East are plagued by a severe scarcity of fresh water sources. As a result, seawater has been the most commonly used raw water source for desalination. Desalination is a well-established process that uses reverse osmosis (RO) for the removal of salt from seawater or other brackish (salt-containing) water sources. RO is a pressure-driven process in which water is forced through a polymeric membrane while salts are retained. A major barrier to efficient desalination processes is the potential for the precipitation by sparingly soluble salts on the surface of the membrane, a process termed scaling. Scaling is of immense practical importance since it significantly degrades membrane performance and/or water quality and hence increases the cost of desalination.

Current approaches for control of scaling include addition of antiscalants, base softening, or adjusting the pH. These approaches, however, involve relatively high chemical costs and/or increase the complexity of the overall desalination process. The innovation in this work is that it delays the onset of scaling through a unique combination of the flow-reversal technology developed at Ben Gurion University and the ultrasonic sensor technology developed by the NSF Center for Membrane Science, Engineering and Technology (MAST) at the University of Colorado Boulder. This new sensor-based separation process could significantly lower the cost of brackish water desalination. Since its inception, the project has received support from the NATO Science for Peace (SfP) Program, the Middle East Desalination Research Center (MEDRC), and ROTEC, a small start-up company specifically formed to commercialize this technology.

The Middle East is plagued by a severe scarcity of fresh water sources. There, seawater has been the most commonly used raw water source for desalination. However, for those countries of the region that are mostly or completely landlocked, such as Jordan, brackish water is a potential major resource. This project enabled the design and fabrication of a pilot demonstration desalination plant based on RO using brackish groundwater that is configured for this new technology. The ability to exploit brackish groundwater for the successful operation of a demonstration plant would encourage development of these marginal water sources in countries in the region as well as globally in those countries with similar water characteristics. In addition, sensor-based flow reversal has significant potential for increasing recovery from RO for boron reduction in seawater desalination for direct or indirect agricultural use.

Economic Impact: This new sensor-based separation process has the potential to significantly reduce costs associated with brackish water (BW) desalination, which is expected to have a global market value of $30 billion by 2015 with a growth rate of 10%/year. This technology enables higher recovery so that there is more fresh water and less salt produced per unit of feed water.

For example, adding the technology to a 1200 m^3/day BW-RO plant (80% fresh water recovery) would enable operation at 92% recovery thus generating 1380 m3/day of fresh water. The total cost for adding the technology would be about $11,000/year. The additional water produced is valued at about $31,000/year, a significant economic benefit. This cost reduction becomes quite

significant given that the expected annual investment in desalination in the United States is currently estimated at $4.5 billion. In addition to the favorable economics, implementation of the technology will relieve pressure on existing water sources thereby reducing friction and facilitating cooperation between affected countries as they attempt to cope with dwindling freshwater supplies. This technology should help make it possible for water scarcity to become less of a driver of future conflict. It is difficult to overestimate impacts of avoiding the economic and human costs that would be associated with diminishing such future conflicts.

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Net-Centric Software & Systems Center (NCSS)

A CISE-funded Center

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Die-Stacked 3D DRAM Processor-Associated Large Memory Technology
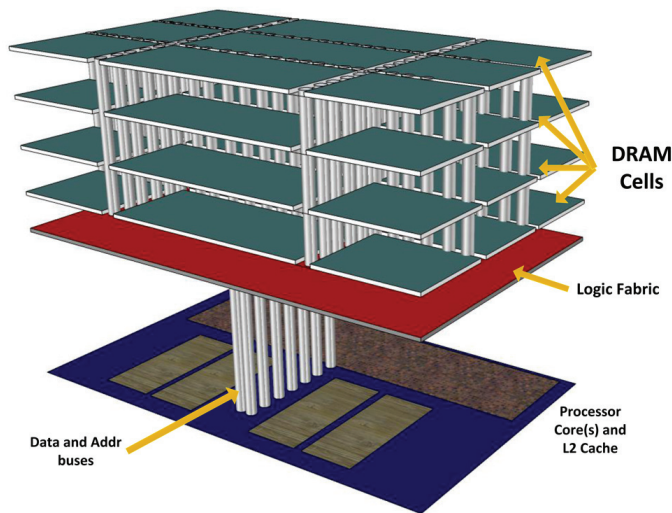
The figure shows how 3D DRAM may be manufactured. While some advocate placing 3D DRAM on top of processor cores, the heat dissipation presents challenges.

An emerging DRAM technology, die-stacked 3D DRAM, reduces access latencies for large amounts of memory placed close to processor cores. In addition, very large non-volatile memory technologies such as Flash and Phase-Change Memories (PCM) can be used in place of magnetic disks. These new memory technologies have several advantages over current systems. They present very fast accesses, very large capacities, and potentially lower power requirements.

Before these new memory systems could become commonplace in computer systems, it was necessary to investigate design alternatives on how they can be integrated within a processor memory hierarchy. The low memory latencies and transfer delays required changes to how virtual-to-physical address translation is implemented.

In this breakthrough, NCSS project researchers explored the use of cache-like set-associative indexing to speedup virtual-to-physical address translation and limited the number of page tables needed for address translation.

Researchers evaluated three design alternatives for using 3D DRAM and PCM in memory hierarchy: 3D DRAM as main memory, 3D DRAM as last level cache (LLC) with PCM as main memory, and both 3D DRAM and PCM as main memories. Each of these organizations used cache-like addressing for main memory. In other words, main memory was assumed to behave both as a cache and as a traditional main memory; researchers refer to this organization as Cache Main Memory. The three alternatives presented different benefits: 3D DRAM as LLC provided best performance but consumed more energy, while 3D DRAM as main memory required lower power but executed slower than the other organizations. Using both 3D DRAM and PCM as main memory offered a large design space for exploration.

Current computer systems use hierarchical page tables for virtual to physical address translations, sometimes requiring the system to consult four to seven tables before obtaining the physical address in DRAM. With very low latency 3D DRAMs this approach is unacceptable. Future computer systems, particularly in the server systems, will consist of several 3D DRAM stacks to support the memory requirements of processing cores. The new NCSS approach is leading to more efficient utilization of the new memory technologies. This will result in higher performance and lower power requirements for applications running in Cloud-based computing systems.

> **Economic Impact**: Energy budgets of large data centers are a major factor in the overall cost of supporting "Big Data" applications. This work will positively impact the development of exa-scale computers as well as Big Data applications. The Department of Energy is looking to build next generation super-computers with very tight energy budgets, and is requiring innovative and radical changes to processor and memory systems. It is anticipated that service providers such as Google, Amazon, Microsoft, Hewlett-Packard will realize significant cost savings and efficiencies because they must support very large amounts of data with extremely fast access. The NCSS approach to address translation will aid in reducing execution times and in the process reduce energy requirements. For this reason the die-stacked 3D DRAM technology can be expected to play a significant role in reducing what can only be characterized as major costs associated with addressing data in large data centers.

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Photopolymerizations Center (PC)

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Ultra-Rapid Photopolymerization Method

Fiber optic coatings are one potential use for this technology.

Novel (meth)acrylate monomers for ultra-rapid photopolymerization have been developed by researchers at the Photopolymerizations Center (PC). This program has identified and characterized several new monomers that provide highly photosensitive acrylate compositions with excellent physical and mechanical properties. These materials have potential for the design of improved structural adhesives in engineering applications. One application noted by UCB Chemicals is that of inks used in printing on food packages. Fast-reacting monomers can reduce both cost and food contamination. The fast-reacting monomers result in inks that dry faster and in packaging that is not as slippery, thereby improving the ability to stack packages. These two effects help reduce packaging costs. These materials have also been demonstrated to improve properties when used as dental restorative materials.

An added benefit to the fast-drying ink is that it does not seep through the packaging and therefore does not contaminate food contained in the package with chemicals.

Economic Impact: The economic impact of this project is significant in several respects. First, the enhanced understanding of the formation-structure-property relationships in monomers has been critical in designing formulations. This approach dramatically reduces the experimental evaluation necessary to develop photopolymerizable formulations for new applications, enhancing their penetration into new markets. Further, the existence of new monomers developed by this project that have enhanced characteristics will improve coating performance. Through improved performance, the solventless photopolymerization process, which has improved economics and environmental compatibility, will be able to penetrate markets that could not be reached otherwise, particularly in automotive or other outdoor applications.

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Covalent Adaptable Networks (CANS)

PC researchers have developed Covalent Adaptable Networks (CANS), which are polymer networks that are adaptable and have reversible structures with concomitant abilities to reduce stress and change shape after polymerization. These networks have the unique combination of being covalently bonded polymer networks that maintain an ability to change their bonded state. This capability enables materials to alleviate stress, change their shape, become adhesive (or debond), or even to heal fractures and cracks.

Two different classes of CANs exist, those that utilize radical-mediated addition fragmentation and those that utilize thermoreversible Diels-Alder reactions as the activatable bond. In a series of papers, we have demonstrated that the addition-fragmentation based CANs enable three critical advantages: reduction of polymerization shrinkage stress, photoactuation and light induced shape changes, and a novel mechanically assisted photolithographic process that enables a single light exposure to achieve complex topography. The thermoreversible CANs have also been demonstrated to be of significant value through three key developments as well: the ability to heal cracks, the

Dental companies benefits from this technology.

ability to be remotely actuated and manipulated through radiofrequency exposure, and an ability to form complex, custom 3D objects simply through a thiol-ene based photofixation process.

Economic Impact: These materials present an entirely new and functional class of thermosets. Thermosets resins represent a multi-billion dollar market that has exclusively focused on polymer networks that are permanent and unalterable. Here, for many applications, nearly all of the same advantages can be achieved with this CANs approach, with the added benefit of numerous additional and desirable properties such as reduced stress, the ability to heal and mend cracks and defects, and the ability to be recycled more easily. Because the technology has such broad reaches across industries from adhesives to composites to 3D prototyping and photolithography, there has been significant interest from companies. Several invention disclosures have already been submitted spanning applications from conventional composites to dental material to 3D prototyping, to photolithography and adhesives. Dental companies involved in 3D prototyping and adhesive companies have expressed interest or have already optioned the technology in these fields.

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Improvement in Photo-Cured Acrylate Coatings
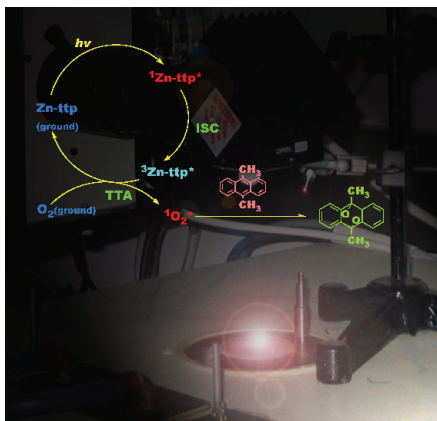
Increasing the polymerization rate in air environments.

At the University of Iowa's Photopolymerizations Center, (PC) a novel photochemical method to eliminate oxygen inhibition in free-radical photopolymerizations has been developed. This work provides a unique and practical solution to a major problem involving photo cured acrylate coatings, namely, inhibition by air at the coating surface. The advance involves the inclusion of two specially selected components in the reactive formulation: 1) a light-absorbing molecule which interacts with the ground state (triplet) oxygen to produce an excited (singlet) state of oxygen (Zn-ttp in the figure), and 2) a second compound which reacts with the singlet oxygen thereby removing from the system (dimethyl anthracene in the figure). By introducing the near infrared illumination before ultraviolet curing, the combination of singlet oxygen generator and trapper can effectively remove the molecular oxygen dissolved in the system. It therefore significantly increases the polymerization rate in air environments. Unlike the traditional methods to mitigate oxygen inhibition, this new method decouples the oxygen consumption and the polymerization process. The peroxide products formed from the oxidation of trapper have the potential to create new reactive centers upon UV illumination or heating.

Economic Impact: Oxygen inhibition is widely regarded as the most important unsolved problem in acrylate polymerization. Methods to mitigate the problem are generally expensive, ineffective, or undermine the properties of the resulting polymer coating. This breakthrough provides an attractive new alternative for solving this important problem. Because the method is based upon the addition of trace quantities of specially selected additives, it can be applied to any acrylate system with no other modifications to the reactive formulation. Henkel Loctite Corporation expects this technology to be of significant commercial value.

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Improved Understanding of Photopolymerization Using Photobleachable Dyes

Understanding the mechanism of this chemistry helps provide the basis for essential irreversible loss of color in a variety of consumer products. Research at the Photopolymerizations Center (PC) has examined brightly colored photopolymerizable compositions. Research at PC is providing improved fundamental understandings of the photo-induced electron transfer processes that determine the retention or loss of color, as well as the formation of active centers that lead to polymer formation. The work provides direct evidence for conditions required to achieve simultaneous photopolymerization and mechanistic understanding of both reversible and irreversible photobleaching of colored compositions. The work is important for photocurable adhesives in dental and orthodontic materials that provide easy visualization during placement (due to color), then upon light exposure, polymerize and become colorless.

> **Economic Impact:** A fundamental understanding of photopolymerizable systems that possess color has important economic implications for a variety of products. The work has played a key role in the dental industry by in the form of photo-bleachable sealants, orthodontic bracket adhesives, as well as electronic adhesives. It will have significant economic impact in industries that use photopolymers for an array of coatings, dental/orthodontic materials, electronic adhesives, and encapsulants. It has already impacted dental material including photocurable composite fillings, sealants, and orthodontic bracket adhesives.

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Real Time Methods to Examine Photopolymerization Conversion

Researcher have developed real time instrumentation and methodologies to examine and correlate photopolymerization degree of conversion versus shrinkage stress and key mechanical properties. This work at the Photopolymerizations Center has provided results that improve upon 25 years of previously unsuccessful attempts to understand critical relationships involving dental materials and other photocurable, cross linkable systems. Key critical questions relating to shrinkage, stress, degree of conversion, and associated mechanical properties have finally been definitively addressed. These advances have provided definitive proof concerning the polymerization, shrinkage stress, and mechanical properties. Previous efforts failed to address all three relevant aspects resulting in extensive speculation and hand waving arguments.

> **Economic Impact:** A more thorough understanding the relationships among the degree of conversion, the shrinkage stress, and the mechanical properties could impact any product that is based upon crosslinked polymer networks. This advance will have significant impacts in any industries that use photopolymers for a coatings arrays, dental/orthodontic materials, electronic adhesives, and encapsulants. It has already impacted the development of dental material including photocurable composite fillings, sealants, and orthodontic bracket adhesives.

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SuperCalibrator: Expanding Real-Time Information for Power System Operators

Significant penetration of renewable resources, demand response, and distributed generation cause rapid increases in the level of uncertainty in control of electric power systems. This requires a completely new approach to the design of a control system for the future power grid. Current centralized approaches to providing power system operators with the information they need to be aware of their power system's situation (or state) have become highly inefficient and, for all practical purposes, are now considered obsolete. To address this problem, researchers at the Georgia Institute of Technology have developed a game-changing technology called "SuperCalibrator." System visibility to operators has been identified as an important component for power grid reliability. The SuperCalibrator provides unprecedented visibility update rates of 60 times per second thereby reducing the risk of blackouts.

System visibility to operators has been identified as an important component for power grid reliability. The SuperCalibrator provides unprecedented visibility update rates of 60 times per second thereby reducing the risk of blackouts.

The SuperCalibrator is a distributed state estimator that uses a detailed model of a substation and measurements from all devices in the substation (such as meters and protection relays) for the purpose of extracting a real time model of the substation, identifying and rejecting bad data, identifying and correcting topology errors, and verifying the model parameters. In the presence of at least one valid Global Positioning System (GPS) synchronized measure-

ment, the real time model of the substation is valid for a specific time instant with precision one microsecond. Subsequently, results from each substation (that is, the state of each substation) are transmitted to the control center where all substation real time models are combined to synthesize the real time model (operating state) of the entire system for that instant in time. Synthesis of the entire system model requires minimal computations. The most significant advantages of the SuperCalibrator are: a) high update rates of the system-wide state estimation and solutions (with a demonstrated operation of 60 times per second); b) the accuracy of the real time model; c) scalability that enables high update rates independent of system size; and, d) the model's ability to extract real time model during disturbance conditions.
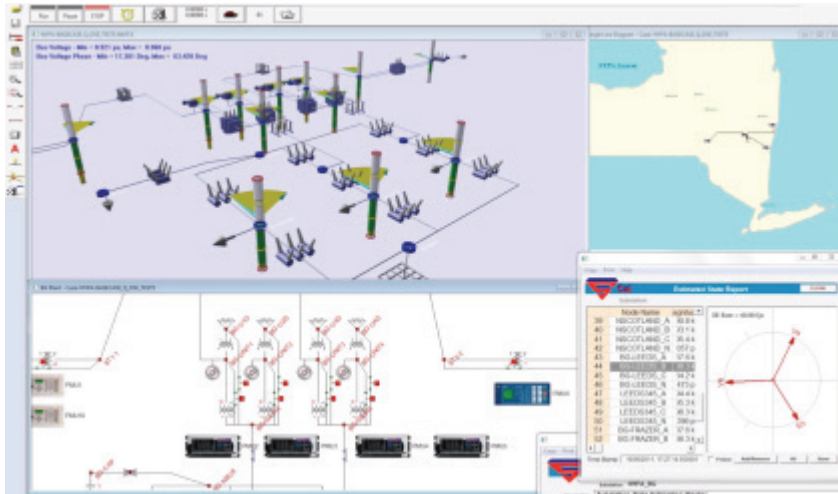
The SuperCalibrator is a distributed state estimator that uses detailed models of substations and measurements from all substation devices to provide power operators with real-time information that can help them avoid blackouts and improve the efficiency of the grid.

When these characteristics are compared to the present state-of the-art in state estimations, it is clear that the SuperCalibrator is a breakthrough that enables unprecedented speeds for achieving improved system visibility.

The SuperCalibrator has been implemented and demonstrated at several substations (in US Virgin Islands, New York Power Authority, and Pacific Gas and Electric). With the expected massive phasor measurement unit installations across the US, SuperCalibrator will play an important role in the future for both control center applications and substation protection and control.

> **Economic Impact:** The potential economic impacts of SuperCalibrator will result from: 1) elimination of the costly centralized state estimator; 2) operational savings resulting from the accurate real time model that enables avoidance of overly conservative or wrong decisions; and, 3) early (and fast) detection of the danger of cascading power outages (saving on the costs of blackouts). At the individual utility level, this technology can replace the costly centralized state estimator resulting in a savings of several million dollars for each utility. Since the nation's power grid oper-

ational procedures and optimization are based on the system model, a more accurate real time model provided by the SuperCalibrator will favorably impact practically all operations of its power grid. A conservative 0.1% reduction in operating losses will translate in $200 million annual savings for the nation's power grid. That said, the true economic impact of a more visible power grid will remain a topic for speculation. The impacts are believed to be very high because avoidance of just one widespread blackout could result in difficult to document savings of billions of dollars.

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Advanced Power System Visualization Tools

Researchers at PSERC have integrated new visualization techniques with power system modeling methods to create visual insights for the user into the condition of power systems. Using visualization tools, industry can "see" what is happening without disruption of the actual energy production. Using two- and three-dimensional plotting capabilities coupled with power system animation, the technology gives the user a picture of the power system that synthesizes thousands of pieces of information.

The visualization technology shortens the time between observing power system problems and identifying appropriate corrective actions, thereby making power systems more reliable. It integrates visualiza-

With advanced visualization tools, power system operators can be better aware of current operating conditions and prepared to take decisive actions needed to avoid blackouts. The tools are also useful in power system planning, policy analysis, and education of the next generation of electric power engineers.

tion of economic and engineering data, thereby informing decision-making for economic and reliable power system operation. It is widely used on operational and long-term planning analyses in the electric power industry, allowing engineers to efficiently run and analyze the reliability and economic effects of alternative scenarios. It also enables power systems engineers and operators to better communicate with non-technical audiences that often include business and regulatory policy-makers. It serves as a training tool for technical and non-technical audiences. From either a free download or as run from a CD inserted in a popular power system education book, the tool is improving university education by giving students simulation experiences that give insights into the operation of real power systems so that students can learn about the very complex technology of power systems through simulations. This technology was awarded the Alexander Schwarzkopf Prize for Technological Innovation by the I/UCRC Association in 2005.

Economic Impact: Problems with situational awareness can lead to blackouts, such as the Blackout of 2003 that cost over ten billion dollars. The cost of outages and transmission constraints

Power Systems Engineering Research Center (PSERC)

leads to some $100 billion in costs nationwide every year, so this tool is directly addressing the need for improved power system reliability. This technology has been successfully commercialized via a new small business. It is being incorporated into software that is sold worldwide. The visualization tool is a spin-off from university research that demonstrably improved power system monitoring, control, analysis, and education in the electric power industry. A small business has installed the tool in some 20 control centers across the US to improve situational awareness for control room operators. It is being used by over 700 engineers and policy-makers worldwide. The technology will be used by the National Electric Reliability Corporation for nationwide reliability monitoring.

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Safety, Security, and Rescue Research Center (SSR-RC)

A CISE-funded Center

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Distributed Decision Making for Large Scale Disaster Management (DDM-LSDM)

Disaster management is becoming increasingly complex, due to uncertainty, limitations in resources, difficulty of coordination among teams, the existence of multiple and at times conflicting objectives, the need to adapt continuously to changing situations, and the scale of the operations. During disasters, traffic blocks, fires, floods, and collapsed structures hamper their movements. Assessing situations is difficult. Too often, loss of communication prevents effective team coordination. DDM-LSDM is an exciting area of work that deals with disaster management for homeland security applications.

SSR-RC researchers model disaster management scenarios involving multiple autonomous agents that can sense, act, and make

This tool simulates civilians, traffic blocks, fires, and building collapse. Police, emergency, and fire agents need to rescue civilians and extinguish fires before the civilians die and the fires spread.

decisions at different time scales using realistic information and communication channels. The work builds on a simulation tool developed by the Robocup Rescue Project after the 1995 Kobe earthquake. The tool simulates civilians, traffic blocks, fires, and building collapse. Police, emergency, and fire agents need to rescue civilians and extinguish fires before the civilians die and the fires spread. We focus on the decision processes and communication needs of the agents, addressing specifically the need to rapidly adapt to changing situations. We study: 1) distributed decision making algorithms that make the best use of available information; and, 2) multi-agent systems approaches to manage interactions and cooperation among large numbers of individual agents and teams of agents.

Using the agent-based DDM-LSDM simulation tool, researchers model large cities with large populations and a variety of emergency responders. They are able to study how each decision made by each agent affects the global outcome of the disaster. The simulation tool works on real maps of real cities, giving the

decision makers ways of assessing how well their emergency plans will work under different circumstances and providing a training tool for emergency responders.

> **Economic Impact:** In the opinion of SSR-RC sponsors, this simulation tool facilitates disaster management operations by providing emergency responders and citizens with a tool that can be used not only to train emergency workers, but more importantly to better understand how disasters can affect them, to locate escape routes and to become better prepared when a disaster strikes. The long-term plan is to connect the simulator with software systems such as Eden (Emergency Development Environment), an open software system for rapid deployment humanitarian response management (from the Sahana Software Foundation), so that the information used by the simulator can be updated with real-time data provided by citizens in the affected areas.

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Scout Robot Platform: Urban Search and Rescue

The Scout Robot Platform currently being used by the US Army and several police departments for search and rescue missions.

The development of large-scale robot teams has been prohibitive for a number of reasons. The complexity of such systems has been hard to simulate, especially in the case of a many to one relationship between a marsupial robot and the robots it can deploy. Additionally, the construction of physical systems can be expensive to implement and maintain. However, there is a number of scenarios in which large scale distributed teams are advantageous such as urban search and rescue, biological or chemical release monitoring, or distributed surveillance and reconnaissance. Distributed robot teams are often able to leverage the power, computational, and locomotive capabilities of a larger system to transport, coordinate, and control miniature robots which may carry more specialized capabilities into areas that are spatially restrictive. Research at the Safety, Security, Rescue Research Center has resulted in the development of the Scout Robot Platform currently being used by the US Army and several police departments for search and rescue missions. The above robot has a cylindrical shape that allows it to be deployed by launching it from an appropriate barreled device. Once deployed, these robots move using a unique combination of locomotion types. Each Scout is provided with a sensor suite, which may vary with the Scout's mission. Scouts may contain some combination of a Complementary Metal Oxide Silicon (CMOS) camera, a passive infrared sensor, a microphone, and other sensors.

> **Economic Impact:** The Scout Project has resulted in a start-up (ReconRobotics Inc.) that has sales of more than $20 million annually. The Scout is projected to achieve sales of $100 million in sales within a few years. More than 4,000 robots have been deployed worldwide by the US Army and Navy, the FBI, and various police forces in more than 50 countries.

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Security & Software Engineering Research Center (S^{2}ERC)

A CISE-funded Center

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Design Metrics Technology

Improvements in the software development process depend on the ability to collect and analyze data drawn from the various phases of the development life cycle. Stress points are defined as critical components in software; points where errors in coding and programming logic are likely to occur. The Security and Software Engineering Research Center (S^{2}ERC) Design Metrics Team has developed a metrics-guided methodology for maximizing and maintaining software reliability. The technology provides an unbiased framework that efficiently makes cost-effective determinations for design improvements, code-modifications, and related testing and management strategies. Applying this methodology to software designs identifies and highlights stress points within software. It helps improve overall design quality.

Satellite-related projects are one type of technology benefiting from design metrics.

Identifying stress points in advance and applying mitigating approaches results in improved resource allocation. In the coding phase, the technology can identify stressful components and provide change impact analyses. In testing, metrics can assist in determining where testing efforts should be focused and the types of test strategies that are needed. In twenty years of metrics validation on a wide variety of projects ranging from missile defense, satellite, accounting, and telecommunications systems to interactive games, the design metrics have identified at least 75 percent of error-prone components with very few false positives. Applying this design metrics technology is assisting developers engineer higher quality software products. In 2007, this technology was awarded the Alexander Schwarzkopf Prize for Technological Innovation by the NSF I/UCRC Association. The S^{2}ERC Design Metrics Team continues to learn more about enhancing reliability and dependability of critical software systems.

Economic Impact: Software unreliability often is due to design faults. While software can fail for reasons other than faulty design, these design mistakes occur in various forms, including design inconsistencies and semantic errors. Historically, identifying error-prone components early in the life cycle reduces software failures and their associated costs.

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Visual Intrusion Detection System (VIDS)

Network-based attacks have become more sophisticated and visualization can increase the speed at which security issues are identified. Losing control of network nodes even for the shortest period of time can generate unpredictable consequences. Loss of connectivity can provide an adversary with unexpected advantages that may lead to life threatening adverse events, injury, extended power outages, water contamination, and subsequent losses of confidence in large portions of the economy.

The destructive potential of cyber-attacks is all too real. Those who wish others harm are no longer necessarily geographically distant, but can be just behind the firewall. As more high technology products are designed to communi-

The screenshot depicts a VIDS three-dimensional view of alerts with various priorities, shown in the graph as spheres of different colors.

cate directly without human involvement, the attacks can cascade unpredictably. It is crucial, therefore, to mitigate network threats. Monitoring can be an effective deterrent against misbehavior from both insiders and intruders.

Efficient security monitoring has always been complex, involving collecting, correlating, and storing information from many sources, firewalls, and intrusion detection systems. S²ERC researchers aim to provide security analysts with a tool to discover patterns, detect anomalies, identify correlations, and communicate findings. The VIDS project combines the research efforts of visualization and network security to create a practical tool for network security analysis/monitoring. The visual approach offers a number of benefits over the traditional textual analysis of security data.

Complex relationships can be hidden within the large amount of data produced by security tools. Visualization can help analyze millions of log entries. Often, patterns that were not anticipated are revealed when the data are graphed. Visualization requires the distillation of large amounts of data into meaningful displays. These can assist security personnel decide which areas to investigate.

> **Economic Impact:** It is estimated that $1 trillion was lost in 2010 to cybercrime; a figure that is considered low due to unreported incidents. Assisted by VIDS, analysts protect our essential digital infrastructure, identified by President Obama, as "the backbone that underpins a prosperous economy and a strong military and an open and efficient government. Without that foundation we can't get the job done." If analysts using a system such as VIDS can avoid just 1/1000 of the value of these cybercrimes, then the savings could amount to $1 billion. [May 2009 remarks by the US President on Securing our Nation's Cyber Infrastructure.]

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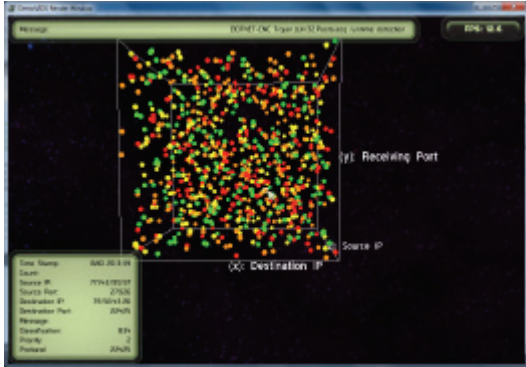
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New Silicon Growth Techniques Lowers Costs of Solar Photovoltaics

Cast monocrystalline Si holds the potential to decrease the cost of photovoltaic solar electricity.

Crystalline silicon continues to dominate the photovoltaics (PV) industry in the renewable energy market. Within silicon based solar, cast multicrystalline (mc-Si) and Czochralski (Cz) grown material account for the majority (~80%) of photovoltaic (PV) devices made. Each type has advantages and disadvantages when considering the total cost of production.

Traditionally much of the performance disadvantage incurred in mc-Si materials is a derivative of the growth methodology. Due to the nature of the solidification of the Si melt, the crystal segregates into smaller randomly oriented crystals and suffers from many planar dislocations. These regions serve as sinks for impurities, along with crystallographic stress defects that reduce photo-diode quality. This limitation of traditional as-grown mc-Si can only be overcome through advanced gettering techniques and supplemental processing which are currently not conducive to commercial application.

SiSoC researchers at the Georgia Institute of Technology (GIT), along with commercial partners have also produced >19% conventional cells through study of growth methodology and commercial process optimization. Collaborations with researchers at multiple companies have explored new growth techniques that seed the mc-Si casting crucible with a (100)-oriented Si crystal. With careful growth rate and temperature control they are able to grow a nearly single crystalline material over a large vertical and horizontal area of a casting which maintains the seed orientation. This material is called quasi-mono, cast-mono, or monocast (mcast-Si). Due to the crystal orientation of mcast-Si, anisotropic texturing methods normally used for Cz-Si can be applied to the wafers during cell processing. The net result is a >1% absolute boost in efficiency over isotropically textured mc-Si wafers (non-encapsulated). This type of material when commercially processed has obtained >18% efficiency which is on par with Cz-Si material.

If processes can be optimized to increase the area of monocrystalline material and if the material quality can be maintained with reduced costs, then the advantages of the mcast-Si material would be multi-faceted. One advantage would be the packing factor for wafers in a module. Mcast-Si wafers are 6x6 inches (~244 cm^2) square like mc-Si wafers. Cz-Si wafers are 6x6 inches (~239 cm^2) pseudo square in most cases with rounded corners due to growth constraints. A module can hold the same amount of mcast-Si cells as

Cz-Si cells. Hence the mcast-Si material provides additional power due to maximizing the active area of the PV module. A second advantage is that the material retains the flexibility of Cz-Si for advanced cell structures needed to make the PV industry more competitive. Under application of one of GIT's more advanced structures, mcast-Si material has achieved >19% conversion efficiency on a full 244 cm^2 substrate. This is a significant efficiency for full-scale cells based on materials grown using a casting methodology.

> **Economic Impact:** A key cost of production metric for the PV industry is the total cost of production in terms of the power produced ($/Watt). If module efficiency is fixed at 16% and the wafer cost considered, mc-Si material is significantly cheaper to produce (~0.35¢/Watt) when compared to Cz-Si (~0.50¢/Watt). The potential impact of this collaboratively developed mcast-Si material on the PV industry is clear. In addition to cost advantages to consumers of solar electricity, research performed by SiSoC researchers has lead to significant cost avoidance by member companies and stimulation of research activity. In 2010, ten industry members reported starting 18 new research projects valued at $1 million as a result of SiSoC research activity. In 2011, the value of SiSoC-stimulated research at member firms was valued at $2.5 million. Also, in 2012, member companies reported $5.5 million in cost avoidances and savings through SiSoC research interactions as well as $1 million in new project initiation within member companies.

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Smart Vehicle Concepts (SVC) Center

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Design Concept for Smart, Adaptive Seat Belts

Current seat belt systems use a compromise design for the median sized individual in an average collision. These systems rely on mechanisms that have a limited capacity to adapt to varying conditions and are massive and complex. Under the direction of Marcelo Dapino at the Ohio State University Researchers at the Smart Vehicle Concepts (SVC) Center have developed an innovative design concept for a new generation of automotive seat belts.

The research is focused on the enabling technologies for the adaptive seat concept: friction reduction via piezoelectrically-induced ultrasonic vibrations next-generation flexible sensors. By using "smart" materials these adaptive seat belts promise enhanced crash safety along with a reduction in the mass and complexity of the seat belt system. Smart materials rely on externally applied stimuli such as magnetic fields, electric fields, heat, or light.
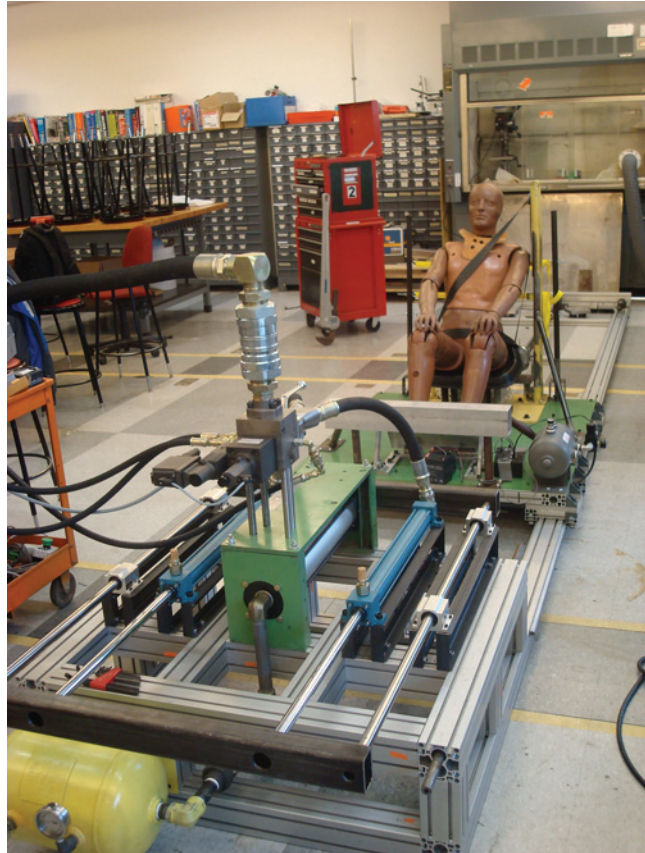
Testing an adaptive seat belt.

Smart Vehicle Concepts (SVC) Center
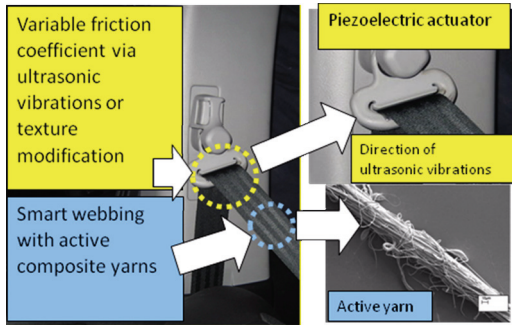
Concept for adaptive seat belt based on smart materials.

Crash data suggest that small changes in friction forces at the D-ring have a large effect on the chest force. Smart seat belts measure chest force by using flexible smart polymer sensors that are woven in the seat belt webbing. These sense ultrasonic vibrations, then small piezoelectric actuators embedded in the D-ring automatically adjust the friction force and maintain the desired constant chest force during a crash. The critical benefit over existing seat belts is that the system modulates the chest force independent of webbing displacement. The fundamental technologies investigated in this research, ultrasonic friction control and flexible polymer sensors, are directly applicable to adaptive seat belts and numerous vehicle components such as suspension links, steering, powertrains, and human-machine interfaces.
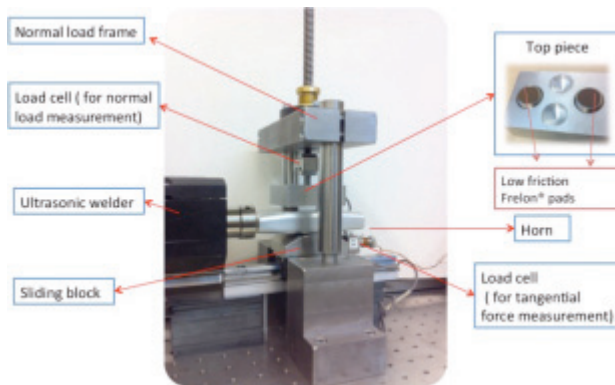
Experiment for fundamental characterization shows part of the experiment developed to quantify and understand the fundamental mechanisms of Poisson-effect ultrasonic lubrication.

Economic Impact: Adaptive seat belts can change the economics of vehicle safety by greatly increasing the effectiveness of seat belts and associated reduction in injury and insurance claims, while simultaneously facilitating fuel economy due to lower bulk and mass of the overall seat belt system. Use of solid-state lubrication can eliminate the need for lubricants that can be expensive. Economic gains can also be achieved in hydraulic systems in agricultural and construction equipment, commercial vehicles, ships and aircraft; thus greatly reducing the size of batteries needed for powering mobile devices.

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Water and Environmental Technology (WET) Center

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Advanced Oxidation Processes (AOPs) for Water and Wastewater Treatment

Advanced Oxidation Processes (AOPs) generate highly reactive species (e.g., hydroxyl radicals) for the oxidative destruction of target pollutants in water and wastewater. The WET Center has been researching a number of technologies that can be used to generate hydroxyl radicals. The Center AOPs (ozone, UV, ultrasound, hydrogen peroxide and their combinations) have been successfully applied for the removal of wide range of environmental contaminants including: steroid hormones, pesticide, pharmaceuticals, 1,4-dioxane, and BPA. Comparative life cycle analysis (LCA) and life cost analysis (LCC) is used to evaluate, optimize, and determine the environmental impacts of AOP technology. The best AOP is selected for a given application according to the efficiency of ECs removal, technical feasibility, energy consumption and costs.

A pilot-scale, skid mounted water treatment system has been acquired for testing at several global locations. This highly automated AOP pilot plant supplied by ITT (a Center member company) consists of an oxygen generator, ozone generator, low intensity UV lamps, and peroxide feed pump. This unit is also equipped with inline ozone monitors to measure ozone in air, water, and atmospheric phase, UV sensor, degassing unit, and catalytic ozone destructor. This system uses three proven treatment technologies (Ozone, UV, and hydrogen peroxide) in six different ways to eliminate organic pollutants. It has a capacity to treat 2,500 to 25,000 gallons per day of water and wastewater.

This unit is equipped with inline ozone monitors to measure ozone in air, water and atmospheric phase, a UV sensor, a degassing unit and a catalytic ozone destructor.

Economic Impact: The AOPs are gaining attention in the market and have tremendous application potential for drinking water, municipal wastewater, industrial wastewater, and groundwater treatment. A member company estimates revenue generation of $30 million in five years, as well

as the creation of new jobs from the application of this technology. The global water industry is estimated to be about $500 billion.

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Real-time Detection of Contaminants in Potable Water Distribution Systems

For 24-7 monitoring, Smart water distribution systems require a centrally located computerized data base.

The WET Center has developed a Real-Time Sensor Laboratory at the Water Village within the University of Arizona. Sensors in parallel allow for instantaneous detection of both chemical and microbial contaminants. Viable microbial contaminants can be detected via fluorescence from NADP and riboflavin. Chemical contamination can be detected through the use of multiple total organic carbon inline sensors. For continuous monitoring of distribution systems, multiple sensors must be employed as part of a supervisory control and data acquisition (SCADA) system. For 24-7 monitoring, management of simultaneously generated large data sets becomes critical. Smart water distribution systems require a centrally located computerized data base and appropriate software to integrate and correlate data with realistic alarm thresholds to protect consumers from drinking contaminated potable water.

Economic Impact: Since water is delivered to consumers via distribution systems in every town and city within the US, the economic impact of this proof of concept for the nation could involve billions of dollars annually.

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Survival of Infectious Prions during Wastewater Treatment

Prions are malformed proteins that can enter healthy organisms, affect their neural tissue, and result in untreatable disease that is usually if not universally fatal. Recently published research documented that prions can survive wastewater treatment.

Transmissible spongiform encephalopathies (TSE) are a group of neurological prion diseases of mammals. In humans these include Kuru, Creutzfeldt-Jakob disease (CJd), sporadic Creutzfeldt-Jakob disease (spCJd), and variant Creutzfeldt-Jakob disease (vCJd). In animals, TSE includes scrapie in sheep and goats, bone spongiform encephalopathy (BSE) in cattle, and chronic wasting disease (CWD) affecting deer, elk, and moose.

Normal prions found within humans have a tertiary structure involving the alpha helix. In contrast, infectious prions have a beta sheet structure. Of interest is the fact that when an infectious prion encounters a normal prion it converts the normal prion to the infectious mode, ultimately resulting in disease. One route of exposure to infectious prions is through raw, contaminated wastewater via animal rendering and meat processing operations due to prion-infected cattle or sheep. However, Western blot technology was used in this study which only looks at the amino acid sequence and does not distinguish between infectious and normal prions.

Researchers at WET developed a new assay that only detects infectious prions. They used this assay to study of the fate of prions during wastewater treatment. Data showed that prions are actually inactivated during mesophilic or thermophilic anaerobic digestion negating the possibility of prions surviving wastewater treatment. This is significant in that if prions had survived wastewater treatment, they could have been found in biosolids and subsequently land applied with a potential for infecting cattle.

Because one route of exposure to infectious prions is through contaminated wastewater via animal rendering and meat processing of prion-infected cattle and sheep, the risks to local and national economies can be substantial.

Economic Impact: The outbreak of "mad cow disease" in Britain in the 1990s resulted in the slaughter of hundreds of thousands of animals and many millions of dollars in damage. The toll on human life is incalculable. This breakthrough assay is making it possible for wastewater treatment plants to help to avoid or at least substantially reduce such losses in the future.

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Wood-Based Composites (WBC)

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Extending America's Timber Resources Through Advanced Composite Science

Wood composites, such as laminated veneer lumber (LVL) and oriented strand board (OSB), are common products used in the construction of homes, non-residential buildings, and many consumer products. There is a great diversity of wood composites, all of which depend on adhesives in order to bond veneer, strands, particles, and/or fibers for durable, strong, and economically viable applications.

Nearly all adhesives for wood products are derived from petroleum. Many incorporate formaldehyde. Surprisingly, we know very little about why some adhesives perform better than others when bonding very complex natural materials like wood. Consequently, the development of new adhesive systems, such as those based on bio-based materials, is a slow and tedious process. This WBC research has advanced the science of adhesive bonding by developing a breakthrough method for visualizing and analyzing adhesive bonds in wood products.
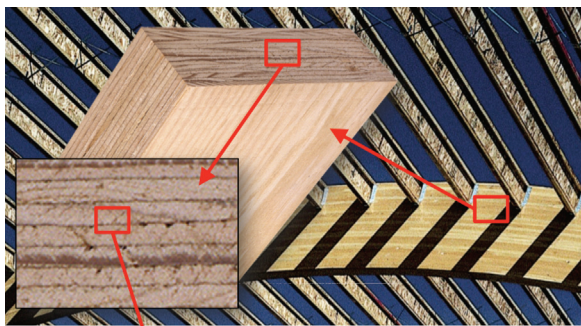
Micro computed x-ray tomography (XCT) and advanced numerical modeling tools were used to create a computer simulation model of mechanical forces associated with adhesive bonds in wood composites to assist in design of new composites and new adhesive products.

More than 90% of these homes are light-frame wood construction, of which essentially all include some structural wood composite products. For most homeowners their home is their single largest investment. The durability of the wood composites in these homes is critically important to millions of homeowners.

XCT of Adhesive Bond

Adhesive

Predicted Stress Distribution
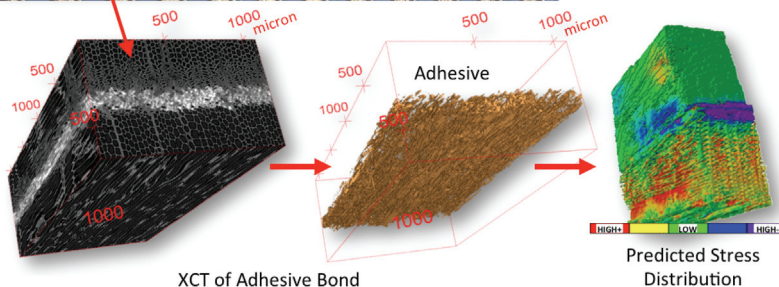
Wood-Based Composites (WBC)

Adhesive bonds have two functions: to hold the components together and to facilitate transfer of mechanical forces from one component to the next. The first function is the strength of the bond. In contrast, the second function, which is roughly-speaking the bond's stiffness, may affect all mechanical properties of the product. This breakthrough combines state-of-the-art imaging tools with emerging computer modeling methods that yields an integrated characterization of the fundamental behaviors of adhesive bonds. This work considers effects of adhesive penetration into the porous network of wood cells, complex loading applications, and the micron-level mechanics imposed on the bonded interface.

The long-term goal of this project has been to improve performance of wood composites and initiate innovation for the development of new adhesives. This work pushed the envelope of fundamental knowledge on the micro-mechanics of adhesive bonds in wood composites and developed a numerical model to simulate the mechanical behavior of bonded wood assemblies. Another valuable output was the creation of quantitative and visual three-dimensional (3D) data sets for the micro-structure of adhesive bonds.

3D visualization of adhesive bonds on a micron scale, in tandem with the ability to interactively rotate and dissect the virtual bonds using 3D imaging software, has created a paradigm shift in how scientists and engineers interpret the creation of adhesive bonds in wood and their resulting performance.

The project had three parts: 1) micro X-ray computed tomography (XCT) characterization of adhesive bonds; 2) micro-mechanics modeling of bonds; and, 3) macro wood-adhesive bond evaluations. The work leveraged collaborations involving scientists at Oregon State University, the US Forest Products Laboratory, the Argonne National Laboratory, and several major adhesive and composite manufacturing companies. The research was guided by close industry oversight from conception to completion; whereas, the interpretation and implementation of the results was made possible by the unique organizational structure provided by the NSF Industry/University Cooperative Research Center Program.

> **Economic Impact**: This work will positively impact the US wood products industry and the American consumer. Specific examples of markets that will benefit are: glue-laminated timber, LVL, plywood, OSB, engineered wood flooring, and component wood products, such as furniture, cabinets, windows, and doors that rely on adhesive bonding. These markets represent over $77 billion in annual sales to the US economy and manufacturing employment of nearly 500,000 (US Census Bureau). A typical wood composite manufacturing facility may spend $5 million annually on adhesives. Even a modest 2% reduction in adhesive consumption, would save approximately $100,000 for each facility. US housing construction has averaged 1.5 million new units annually since 1960. The insights gained from this research, and the model developed, provide several important benefits with implications for the bottom line. These include: 1) improved durability of glued wood products, resulting in fewer failures and longer service life; 2) optimization of wood utilization, resulting in lower demand on timber resources; 3) development of new adhesives and improved formulations for existing adhesives, resulting in improved product performance, lower cost, and less reliance on petrochemicals; and 4) reduced time and cost for future development of adhesives and new wood composites.

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