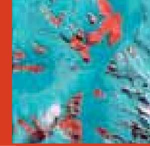
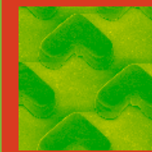
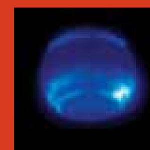
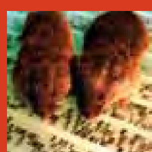
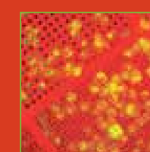





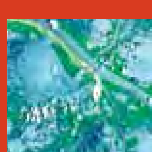
PROFILES IN TEAM SCIENCE

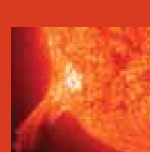
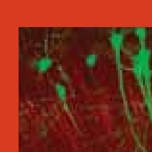
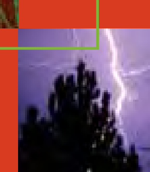
2012 EDITION



TEAM SCIENCE

2012



CENTERS

NSF SCIENCE AND TECHNOLOGY CENTERS

LEGACY CENTERS

ABOUT PROFILES IN TEAM SCIENCE...

Science and Technology Centers (STCs) have been established by the National Science Foundation (NSF) to support innovative and potentially transformative research and education projects that require large-scale, long-term awards.

The STCs provide a means to undertake significant and complex investigations at the interfaces of disciplines and/or fresh approaches within disciplines. An STC typically involves several partner universities, dozens of faculty and postdoctoral researchers from different departments, scores of graduate and undergraduate students, and dozens of industrial and community affiliates. A center has the staff, resources, and time to make a much larger and far-reaching impact than usually is possible with smaller grants.

Topics addressed by the STCs run the gamut from understanding what's happening to the Earth's ice sheets to innovations in cybersecurity. One center is developing plastic electronics, while another develops novel water disinfection strategies. Although the STCs are working on different topics, they all are organized following a similar pattern: an integrated, 10-year program of research, education, diversity enhancement, knowledge transfer, and public outreach.

Yet, research shows that the outcomes of this kind of "team" science may not be easily covered within the constraints of the news media. There's a news gap, and many members of the general public may not make the connection between the center mode of operation and the results produced. What is different about team science? How is it working? What can it accomplish that couldn't be done otherwise? Why is it important for people to know about centers?

This booklet explores those questions. It is aimed at increasing awareness about the STCs in order for policymakers, the scientific community, members of industry, educators, and taxpayers to better understand the role that the team mode of research funding plays in solving critical problems facing society.

— DEBORAH L. ILLMAN, Ph.D.
Editor, Profiles in Team Science
NSF Discovery Corps Senior Fellow 2006-09

ABOUT THE 2012 EDITION...

The first edition of Profiles in Team Science focused on how team science and "centeredness" enabled cutting-edge research at each of the 17 STCs that were funded in FY 2000, 2002 and 2005/2006.

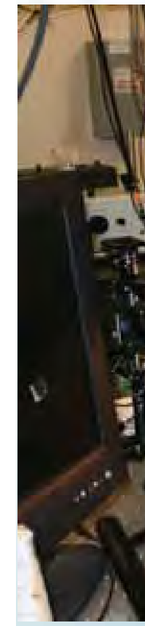
This new edition updates the findings from the earlier edition, examines the legacy of the recently "graduated" FY 2000 cohort, and includes descriptions of the five new STCs funded in FY 2010.

In these pages, we showcase some of the key research results from the STCs and how they are being applied to a wide-range of important technological problems in our society. At the same time, we explore how the centers are providing a unique educational experience for the development of the next generation of U.S. scientists and engineers grounded in interdisciplinary research and international settings.

We hope you are inspired and excited by the grand research challenges these centers are addressing.

— CLIFFORD J. GABRIEL, Ph.D.
Acting Director
Office of Integrative Activities
National Science Foundation

HISTORY AND OUTCOMES OF THE NSF SCIENCE AND TECHNOLOGY CENTERS



In 1987, in his State of the Union address, President Ronald Reagan proposed the establishment of Science and Technology Centers (STCs) by federal agencies in order to enhance U.S. economic competitiveness. The National Science Foundation responded with plans to run a competition and fund a series of new STCs in FY 1988.

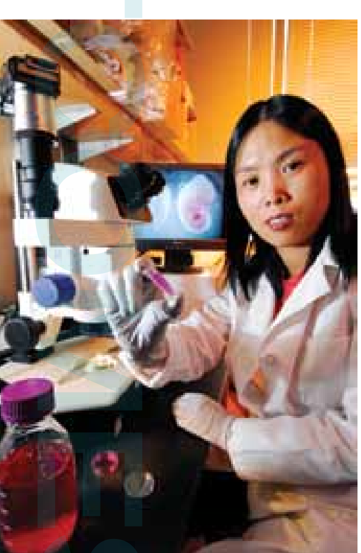
The NSF director at that time, Erich Bloch, sought advice from the National Academy of Sciences (NAS) on how to implement such a program. The NAS panel, chaired by Richard N. Zare, professor of chemistry at Stanford University, recommended that the STCs focus primarily on basic science in areas supported by NSF and that NSF should not constrain those areas in any one competition. The quality of the research and the need for a center mode of funding should be key criteria for funding.

The first solicitation, published in 1987, challenged investigators to propose research problems requiring significant resources in terms of equipment or facilities, or problems of great enough complexity, that the research could only be supported by a center. The expectation was that the STCs would be based in academic institutions; would provide education and research opportunities for students, postdoctoral fellows, faculty members and industrial fellows; would emphasize knowledge transfer to facilitate applications of scientific discoveries and thus address economic competitiveness of the United States; and would establish partnerships with other institutions.

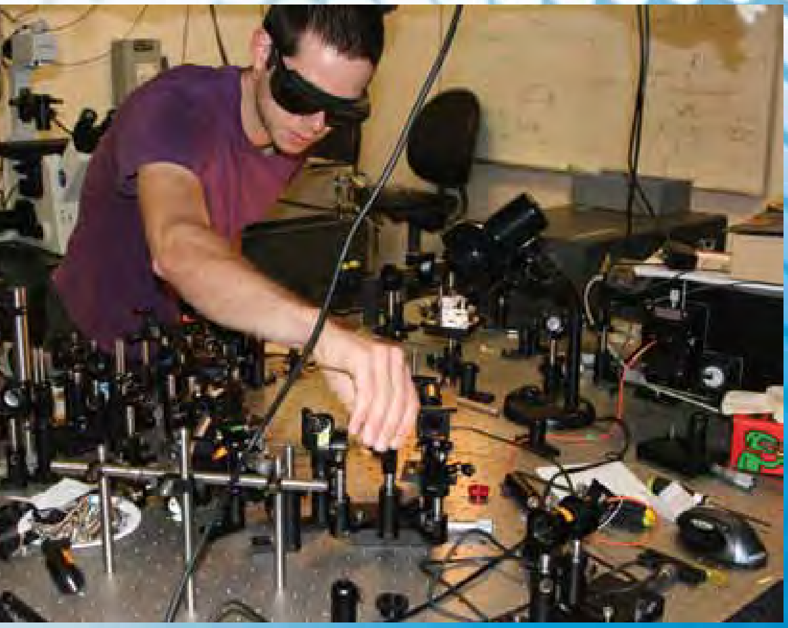
To date, there have been six competitions resulting in 47 centers: FY 1989 (11), FY 1991 (14), FY 2000 (5), FY 2002 (6), FY 2005/2006 (6) and FY 2010 (5). The program is administered by the NSF Office of Integrative Activities (OIA) (http://www.nsf.gov/dir/index.jsp?org=OIA).

Evaluations and assessment of the overall STC program, of STC centers and their impact or legacy, and of NSF management of the program have been carried out by the National Academy of Public Administration in 1995; the Committee on Science, Engineering and Public Policy (COSEPuP) of the National Research Council in 1996 (http://www.nap.edu/catalog.php?record_id=5401); and Abt Associates, also in 1996.

More recently, in 2010, the American Association for the Advancement of Science (AAAS) assessed the impact of the STC program in terms of the research, education, knowledge transfer, diversity, and partnerships goals and how well the program addresses important grand challenges and emerging opportunities. The AAAS report is available on the web at http://www.aaas.org/news/releases/2011/0301stc.shtml.



Yuhong Fan of EBICS.
Photo: Gary Meek, Georgia Tech



PROFILES IN TEAM SCIENCE

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation

2012 EDITION
Funding provided by the National Science Foundation under Grant No. CHE-0937434.

EDITOR: Deborah L. Illman, Ph.D., illman@u.washington.edu
WEB: http://depts.washington.edu/teamsci
DESIGN: Sarah Conradt Design (www.sarahconradt.com)
PRODUCTION: Maggie Keech, University of Washington Creative + Communications
WEB SITE: Brian Vogt
PRINTING: Litho Craft

For more information on the STC Program and NSF Office of Integrative Activities:
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http://www.nsf.gov/dir/index.jsp?org=OIA

2007 EDITION
Originally published in 2007 with support from NSF Grant CHE-0609451, a Discovery Corps Senior Fellowship from the NSF Chemistry Division.

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CONTRIBUTORS: Karen Gran, Marita Graube, Kris Ludwig, Amy Pletcher, Ben Raker, Jennifer Schripsema

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Photos courtesy of:
Top: CBST
Middle: CReSIS (left); CENS (right)
Bottom: C-MORE

CENTER FOR THE STUDY OF EVOLUTION IN ACTION (BEACON)

EVOLUTION IN ACTION

The word "evolution" may conjure up images of dinosaurs and fossils, but in fact evolution is currently happening all around us. A well-known example is the way that bacteria are constantly evolving resistance to antibiotics, but even larger, longer-lived plants and animals are continually responding to changes in their environments. At the BEACON Center for the Study of Evolution in Action, researchers are examining evolution in real time in biological and digital systems, and even applying these ideas to engineering design problems.

Designs under development for a museum exhibit about BEACON research on Evolution in Action.

The process of evolution involves three major components: variation, selection, and inheritance. First, variation exists in a population as a result of mutations at the genetic level. Second, some variants can outcompete others for resources, and these individuals survive and reproduce more successfully. Finally, if the traits are heritable, they are passed on to the offspring of the survivors, making those traits more common in the population. In this way, evolution can occur in every generation.

This process happens not only in biological systems, like animals and plants and bacteria, but in digital "organisms" that "live" inside a computing platform. Evolutionary dynamics can also be applied in engineering, allowing a selection process to find and evolve the best solution to a problem like software security or facial recognition or automotive part geometry.

Researchers at the BEACON Center for the Study of Evolution in Action work across these three fields, focusing on evolution in genes, in behavior, and even in communities of species. The Center is headquartered at Michigan State University, with partners at North Carolina A&T State University, University of Idaho, University of Texas at Austin, and University of Washington,

BEACON research covers a wide range of evolutionary phenomena, but much of it addresses grand challenges in evolutionary studies. Several scientists are focusing on the process of speciation: how organisms evolve from one species to another.

Richard Lenski's Long-Term Evolution Experiment, in which 50,000 generations of E. coli have been evolving in the laboratory, is a rich source of information about the process of evolution. Twelve lines of *E. coli* have been evolving in flasks for nearly 25 years, and every 500 generations, bacteria from each line are frozen so that they can be compared with their later descendants. This project has already produced several important results, most recently demonstrating that over time, long-term adaptability outcompetes short-term advantages, bringing to mind the fable of the tortoise and the hare.

Computational work plays a very important role in these studies, not just in providing the power needed to decode genetic information that can give clues to the evolutionary process, but also in replicating the process in digital organisms.

Many BEACON projects rely on digital evolution software platforms like Avida, developed by Charles Ofria, Chris Adami, and C. Titus Brown. In Avida, a population of self-replicating computer programs is subjected to external pressures, such as mutations and limited resources, and allowed to evolve subject to natural selection. This is not a mere simulation of evolution; digital organisms in Avida evolve to survive in a complex computational environment and will adapt to exhibit entirely new behaviors in ways never expected by the researchers, some of which seem highly creative. This process happens much faster than evolution in biological organisms, so that a million generations can pass by in a matter of weeks. The "genetic code" of these organisms–basically the set of instructions that the Avidians use–can then be explored to understand what genes or instructions were adaptive in this set of conditions.

Another major focus of research is the evolution of complex behavior, such as cooperation, which is observed in species as diverse as bacteria and hyenas. For example, many lethal diseases are caused by biofilms formed by cooperating bacteria. Spotted hyenas cooperate to hunt much larger animals. The evolution of cooperation can be difficult to understand, since it may seem counterintuitive that helping another individual can be beneficial to the helper. BEACON researchers are working in both biological and digital domains to understand this process. For example, biologist Kay Holekamp's long-term study of spotted hyena behavior in Kenya provides important information about behavior and environmental conditions related to cooperation, information that computer scientists like Risto Miikkulainen are using to replicate the evolution of cooperation in digital organisms.

An understanding of how cooperation evolves is also being applied to develop such behavior in robots. Engineers Xiaobo Tan and Philip McKinley are developing robotic fish, which have real-world applications such as monitoring water quality, and are finding ways to "evolve" cooperative behavior in these robotic fish so that they will be able to school together and coordinate their movements on their own. Biologist Jenny Boughman is collaborating with Tan and McKinley and plans to conduct behavioral studies in which the robotic fish interact with live fish in order to test hypotheses about fish behavior.

Evolutionary engineering is another important focus. Evolution is itself an algorithm, in which the best or fittest types are selected from a range of variation, and the process is repeated generation after generation. This algorithm can be applied to solve engineering problems. For example, Gerry Dozier is applying these principles to create better and more efficient facial recognition software. Rather than using an entire photograph of a face, evolutionary principles enable researchers to determine which few aspects of a photograph contain the most information about individual identity, making the process faster and perhaps allowing the use of a wider range of photographs. □

High school students test the performance of toy cars designed with evolutionary computation.

Designs under development for a museum exhibit about BEACON research on Evolution in Action.

A CONVERSATION WITH THE DIRECTOR

Erik Goodman

Why does BEACON need team science?

In contrast to much of the traditional study of evolution by examining the fossil record, BEACON is studying evolution in action, meaning things that we can observe as they proceed in the world today. However, even experiments in bacterial evolution can take years to conduct, so we need other ways to explore the subtle mechanisms of evolution. Happily, the invention of digital organisms—essentially self-reproducing computer programs evolving in a computer—allows us to formulate and conduct some relevant experiments in days or weeks, confirming or rejecting hypotheses about mechanisms observed in nature or suggesting carefully structured experiments to conduct in the lab. Thus, BEACON needs researchers with skills in both biology and computer science.

What is the job of the center director?

For team science to work, the director must work to spur scientists from different disciplines to collaborate. This means cross-disciplinary training for our graduate students, as well as all-BEACON meetings focused on research problems requiring multidisciplinary teams and a competition for seed projects that rewards multidisciplinary research. Since I've spent most of my career in collaborations between biologists and engineers, in modeling of evolutionary processes, and in study of multidisciplinary teaming, BEACON has been a great fit.

As we learn more about evolutionary mechanisms, we look for applications of these ideas in areas ranging from medicine, such as control of infection, to engineering, including design and control of robotics, electronics, transportation, and agricultural machinery. The interactions among BEACON researchers help to create a fertile landscape for identifying new problems to address with team science.

Above: Terrrestrial robot swarm.

At right: Students with 3D printer used to produce evolved robotic components.

EDUCATION AND OUTREACH: CRITICAL COMPONENTS OF BEACON'S MISSION

Through K-12 programs, teacher training, online software and computer games, podcasts, and museum exhibits, BEACON educators are demonstrating to the public that evolution is a process that can be observed and applied.

BEACON's artist-in-residence Adam Brown is developing three-dimensional glowing, sensing, and audio-producing robots called biolumes that will be installed in a display in MSU's new Broad Art Museum. The robots will evolve in response to museum visitors as attractive lights and sounds draw people closer, while less attractive patterns may drive them away. This exhibit will function as a living laboratory, showing evolution in action as art.

The center is training a new generation of interdisciplinary researchers. Collaborative courses taught by faculty in the biological and computer sciences are requisites for BEACON graduate students. A program called Avida-ED, an educational version of AVIDA, provides undergraduate students an opportunity to do experiments on evolution. And a one-week residential program launched in July 2011 introduces high school students to inquiry-based field opportunities focused on evolutionary science.

DARK ENERGY

CENTER FOR DARK ENERGY BIOSPHERE INVESTIGATIONS C-DEBI

EXPLORING THE EARTH'S DEEP BIOSPHERE

The notion of a "deep, hot biosphere" supported by geological energy sources was put forth by Thomas Gold in a 1992 essay in the Proceedings of the National Academy of Sciences (PNAS). It was a provocative idea at the time.

Top: Ocean drilling locations.

Bottom: Students explore environmental microbiology at C-DEBI summer course.

By 1998, William B. Whitman and colleagues had expanded the concept, analyzing available data on aquatic, soil, and sub-seafloor microbes. In their PNAS paper, "Prokaryotes: the unseen majority," they concluded that a significant portion of the biomass on Earth may be harbored in sediments and rock below the surface in a massive, buried biosphere of "intraterrestrial microbes."

Deep biosphere habitats exist in the dark, removed from the photosynthetic activity that fuels the surface biosphere. Energy and carbon cycling in the deep biosphere are potentially important issues in solving global energy and carbon budgets. However, studying the dark biosphere and its organic versus inorganic energy and carbon sources is very difficult, and there have been few data available about these deep ecosystems.

Compounding the challenge is the fact that most of the Earth's surface is covered by oceans, making the majority of intraterrestrial microbes only accessible by deep ocean drilling. Given the difficulty and expense of conducting such operations, little information exists about the identity of these microbial communities or the processes within the biosphere under the oceans—information that is critical to understanding the role of intraterrestrial microbes in global processes including the development and evolution of life.

Researchers at the Center for Dark Energy Biosphere Investigations (C-DEBI) have set out to tackle fundamental questions that have far reaching consequences. What is the nature and extent of life on Earth? What are the physico-chemical limits of life? How are microbes dispersed in the deep sub-seafloor biosphere? How does life evolve in deeply buried geological deposits beneath the ocean floor?

Headquartered at the University of Southern California and led by director Katrina Edwards, the center has assembled an interdisciplinary team with expertise in microbiology, molecular biology, geology, geochemistry, engineering, hydrology, among other fields, to address these questions. Partner institutions include the University of Alaska, Fairbanks, University of California, Santa Cruz, University of Hawaii, and the University of Rhode Island.

One of the roles of the center is to provide a sort of portal to the drilling activities conducted by the The Integrated Ocean Drilling Program (IODP), an international program that explores Earth's history and structure recorded in seafloor sediments and rocks. IODP is funded by six international partners, with the U.S. and Japan leading the program. The center aims to facilitate access for researchers to these drilling activities, explains James Cowen, a co-investigator of the center based at the University of Hawaii. Cowen is a member of the center's executive committee and serves as instrument and technology director for the center.

"We are at a crossroad in our quest to resolve the major questions in deep sub-seafloor biosphere research. Three new U.S.-led IODP projects for deep sub-seafloor biosphere research are poised for drilling before 2013, headed by our executive committee members and involving many of our science participants," note Edwards and colleagues."These projects developed independently, with specific sites and scientific objectives. C-DEBI will seize a unique opportunity to bundle these diverse projects to accomplish an integrated, global scientific mission. Our first major science objective is to coordinate, integrate, support, and extend the science associated with these three projects, establishing a new model for conducting internationally coordinated collaborative research in the deep sub-seafloor biosphere. C-DEBI will establish the technological, collaborative, and distributed infrastructure that is needed to effectively plan, execute, and maximize returns for deep sub-seafloor biosphere research—now and into the future."

The center aims to foster an interdisciplinary community of researchers in deep sub-seafloor biosphere research, with a focus on students and junior researchers. C-DEBI will nurture new projects through collaboration and networking between newcomers and researchers with experience in the logistical and technological know-how for mounting and executing IODP projects. In this way, the center hopes to optimize use of scarce resources and to enhance the design and development of projects that address critical global science questions.

Cowen points out there are also many opportunities for research in the center on deep biosphere studies that do not involve drilling at sea, such as studying the fluids discharged by hydrothermal vents on the seafloor. Other researchers may be involved in developing new kinds of sensors and instrumentation that can function in conjunction with drilling operations: devices to recover samples from boreholes and to perform in-situ incubation of samples, sensors such as electrochemical devices to look at fluids, and microbial scanners that can help identify and catalog organisms in drilling operations.

The Deep Exploration Biosphere Investigative Tool, for example, will provide a quick means for characterizing the distribution of microbes in subsurface matrices. This scanning capability will allow for a near in-situ assessment of biological organisms along a transect of a borehole wall. Center researchers have been testing the optical design and detection capabilities with a laboratory mock-up. Recent modeling and lab work suggests detection limit of the device may be 105 to 106 cells per cm^2.

A portable microbial scanning tool under development acts as a triage tool for spatially locating microbes that are distributed over the surface of a core. It can non-destructively locate "hotspots" of biological activity to guide prioritization, sampling, and analysis and extends the capability from borehole logging to core imaging.

C-DEBI's education and diversity objectives are to educate, inform, and translate knowledge of the deep sub-seafloor biosphere via a coordinated program across primary, secondary, and higher education programs. In the process, C-DEBI scientific participants are learning how to be more effective in communicating scientific and technical results to broader audiences. C-DEBI provides a gateway for researchers and students who originally may have been focused on biological or microbiological science to study the deep biosphere and even to cross into the disciplines of geology, physics, hydrology, genomics and more, says Cynthia Joseph, director of education and diversity for the center. □

DIRECTOR'S VIEWPOINT

VIEWPOINT

Katrina Edwards

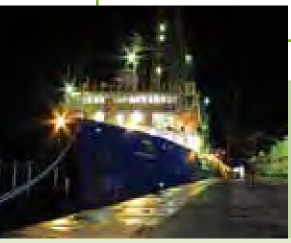
Director, C-DEBI
Professor of Biological Sciences, Earth Sciences and Environmental Studies, University of Southern California

Why drill on the sea floor?

"I think it's a tremendous opportunity for science and I think it's a tremendous boon for science exploration, which has been just really underplayed in recent years. It's really been very difficult to fund exploratory research as opposed to hypothesis-driven research. And that really goes against the human grain, you know–we're here to use our eyes and our senses every single day to explore the world around us, and it's really in our make-up to continue doing that.

The scientific future for ocean drilling has been uncertain and it's still uncertain today. Many activities that I've been involved in have been basically to promote the science of exploration. Drilling is a tool that is critical to keep in our array of exploration methods in order to further scientific research and knowledge of the world around us.

The reason to drill on the sea floor is because it represents the largest potential biome on this planet. The oceans cover seventy percent of the planet, and below that is the sub-seafloor biosphere, which is virtually unexplored. If we should ignore that, and presume that we can just focus on continental drilling, I think that would be a great leap of faith. The environments are quite different, their chemistries are quite different. The mechanism of how fluid gets into those environments is entirely different. And so I think we need to explore the largest biome on Earth for the sake of understanding it."



IODP EXPEDITION 336: "RETURN TO NORTH POND"

C-DEBI director Katrina Edwards and University of Bremen's Wolfgang Bach led this expedition during fall of 2011 to conduct experiments within the seafloor at North Pond on the western flank of the Mid-Atlantic Ridge.

Researchers and land-lubbers alike were able to follow along and learn about the expedition with Edward's blog, excerpted here. The blog was posted to the C-DEBI web site and linked to Scientific American's page on "Expeditions: Field notes from the far reaches of exploration."

About the Expedition

"... Expedition 336 takes the Integrated Ocean Drilling Program's (IODP) flagship, the Joides Resolution, to a site known as "North Pond," located the very middle of the Atlantic ocean. North Pond (22°N, Western flank) is a famous site for Ocean Drilling; originally drilled in 1975/1976 for the purposes of examining the geology of the ocean crust, this location has been studied nearly continuously for its geological, geophysical, and hydrological characteristics since first drilled.

"Now, we start a new chapter for North Pond, as well as for scientific ocean drilling: microbiological research. This expedition will be the first dedicated to study of the microbiological characteristics of the igneous ocean crust—the rocky realm that lies beneath the sediment—and will establish a long-term presence at the seafloor through the creation of subseafloor laboratories. These subseafloor laboratories are called "CORKed observatories," and are used to monitor temporal changes in the geophysical, geochemical, hydrological properties of a system and now–microbiological properties.

"CORK stands for circulation obviation retrofit kit. This is basically an acronym that was dreamed up to fit the term "CORK" because these devices effectively create a seal at the seafloor, enabling researchers to deploy instruments, experiments, and sampling devices down inside the cored borehole, that can communicate with the surface through specialized sensors and fluid umbilical lines. Deployments are designed for collection up to five years after deployment, and the physical structure that maintains the open hole may be used for decades to come. That technology now exists to permit active experiments to be conducted below the bottom of the ocean is really quite amazing, and relatively new to ocean drilling. Microbiological experiments that can be conducted include colonization experiments, perturbation experiments, isotopic experiments, and more. Only a few experiments have been deployed in CORKed observatories, and again, never before associated with a program that is dedicated to microbiological research.

"Exp. 336 is not only intending to establish CORKed observatories, but also will collect rock and sediments from below the bottom of the ocean. From these samples, scientists are planning to analyze them for their microbiological content using genetic, genomic, proteomic, biogeochemical and cultivation techniques. From analyses on these recovered materials, as well as similar analyses to be performed on recovered experimental materials from CORKs, scientists hope to learn about the what kind of microbes reside in the ocean crust and sediments, what they might be doing, and how active they are in biogeochemically important processes such as in the transformation of iron, sulfur, and carbon.

"This work, focused one of largest nearly unexplored territory on Earth, will forever change our understanding of microbial populations, their function and activities and ultimately, the consequences of their existence in the oceanic crust."

READY TO ADOPT A MICROBE?

Members of the public can get to know a microbe–up close and personal. Virtually, that is. This interactive project was designed to help raise awareness among school kids and life-long learners about the wonders of microbes living in the deep biosphere of the Earth.

Led by Beth Orcutt and sponsored by the National Science Foundation and C-DEBI, this project allows anybody to sign up to virtually “adopt” a microbe and follow along as a deep ocean project is carried out.

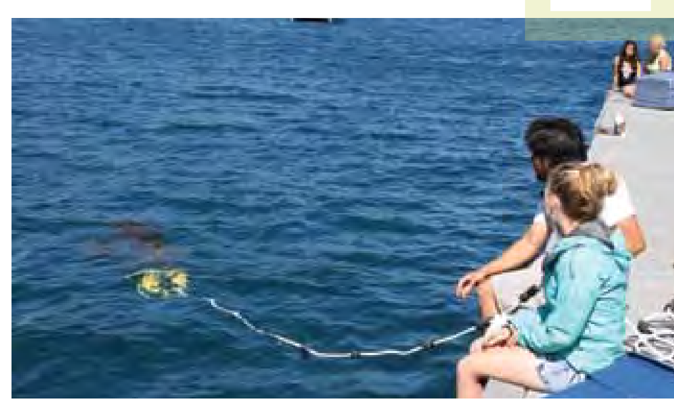
Adopters can take part in weekly activities and read regular posts on the project web site to learn more about microbial life Activities are designed with young kids in mind, but C-DEBI researchers hope that even adults will find them entertaining. Periodically, microbe adopters are invited to share their creative projects, such as their drawings of microbe life. Participants can watch videos, read blogs about life in the deep biosphere, and giggle at the researchers daily shenanigans while sailing the high seas, according to the project web site.

C-DEBI SUMMER COURSE FOR UNDERGRADUATES ON GLOBAL ENVIRONMENTAL MICROBIOLOGY

Undergraduate students had the chance to get their feet wet” in the field of microbial ecology and learn what bacteria are, how they work, and what they do in a four-week course sponsored by C-DEBI at the University of Southern California during summer 2011.

Lectures and labs, held at USC and at the Wrigley Marine Science Center on Santa Catalina Island, were combined with field trips to La Brea tar pits and Long Beach Aquariums.

Taught by John Heidelberg and Eric Webb of USC, this field-based, hands-on experience in microbiology and microbial ecology gave students the chance to explore DNA, genetics, and genomics and their roles in environmental systems.



RESEARCHERS TACKLE A GRAND CHALLENGE: REDUCING POWER CONSUMPTION OF ELECTRONIC SYSTEMS

Readers who grew up in the 1950s and 60s may remember the sense of excitement and modernity that the terms "transistor" and "solid state" evoked at that time. Transistors were the key to new electronic products that were transforming people's lives. To a teenager in the 1960s, a transistor radio was definitely "cool."

The advent of the integrated circuit, which put many tiny transistors onto a single computer chip, eventually propelled an explosion of personal computing and communications technologies that continue to shape our society.

Fast-forward to 2010, and our appetite for electronic products had grown to the point that information-processing devices of all kinds—including consumer electronics, computers, office equipment, network equipment, data centers, servers, and supercomputers—were using a growing fraction of the total electricity production in the U.S.

Researchers at the Center for Energy Efficient Electronics Science (E^{3}S) are concerned that the inexorable expansion in the role of information in society will place an increasing burden on the U.S. energy economy and ultimately will limit functionality. But reducing power consumption will mean rethinking the very component that has been the iconic mainstay of electronics since the middle of the 20th century.

Current electronic systems are dependent on the transistor, which requires a powering voltage close to 1 volt. But the wires of an electronic circuit can function adequately even at voltages as low as a few millivolts. If a transistor also could be made to operate in that range, that is, if its operating voltage could be reduced by a factor of about one thousand, then the power consumed by the transistor would be reduced by a factor of one million, since power scales as the square of the voltage.

E^{3}S researchers aim to reach this target. They are working to develop the fundamental and conceptual breakthroughs in the underlying physics, chemistry, and materials science that form the foundation of information-processing technologies in order to make novel electronic components with dramatically lower power consumption.

Headquartered at the University of California Berkeley and led by Eli Yablonovitch, the Center for E^{3}S brings together an interdisciplinary team from UC Berkeley, MIT, Stanford University, and Tuskegee University, to tackle the grand challenge of reinventing the transistor. They are focusing on four interrelated themes: nanoelectronics for solid-state millivolt switching; nanomechanics methods of zero-leakage switching; nanomagnetic logic; and nanophotonics for optical communication in support of new energy-efficient devices.

Hit the Wall? Go Through It

To understand how conventional transistor technology has "hit the wall" in terms of power reduction requires a refresher on some of the fundamentals of computer processors.

Today's consumers likely are familiar with microprocessor chips, the "brain" of electronic products. "Information is stored in computers in binary form, in other words there are two states, high or low voltage, representing a 1 or 0," explains E^{3}S researcher Tsu-Jae King Liu, professor of electrical engineering and computer sciences at UC Berkeley. "Basically, a microprocessor chip is largely comprised of transistors that simply act as switches. There are a bunch of 1s and 0s–that is, high and low voltages–being routed through logic gates throughout the chip to perform some computation.

"So a state-of-the-art microprocessor chip today might contain multiple billions of these transistors, most of them simply acting as switches. They either make or break a connection. And we do this in a solid-state transistor by raising or lowering a barrier to current flow.

"The problem is that as the transistors are scaled down to really small dimensions, the two terminals are coming so close together that it's really hard to turn off the current; there's always some leakage. That leakage leads to power consumption. We could raise the switching voltage of the transistor to stem this leakage; however, if the switching voltage is high, then it's actually hard to get a lot of current to flow freely when the transistor is on, and to compensate for that, then you have to apply an even higher voltage.

"So this is the fundamental issue: when you scale transistors down in size, you can't really scale down their operating voltage and still get low leakage. You can't scale the switching voltage down for a transistor, otherwise the leakage will go up, and also the operating voltage of the transistor cannot scale down, simply because otherwise the transistor won't conduct a lot of current when it's turned on."

What's the solution? One approach under development at the center is based on the quantum mechanical phenomenon of tunneling. Instead of raising and lowering a "wall" as the switching mechanism, researchers are controlling the energy levels of the materials, aligning them to allow electrons to tunnel through the wall to start the flow of current and then misaligning the levels to stop the current.

"This is a switching principle that's completely different from the principle that's used in all conventional transistors," says Yablonovitch. "To turn the tunnel transistors on and off, we'll simply move the energy levels from being in coincidence to being misaligned. That shift is done with voltage, so if the energy levels are very sharp, then a small voltage will misalign the energy levels, and that's the secret," he says. "The energy levels have to be very sharp, and if they are not very sharp, then we won't get the full benefit." More fundamental research will be needed to develop materials and systems to make the tunnel transistor a reality.

On another front, Center researchers are focusing on the design of nanoelectromechanical switches that will have zero off-state leakage current. With a tiny mechanical switch, "you don't have any material in between the two electrodes when it switches off, so really, no current can leak. And then to turn on the switch, you just bring two electrodes into physical contact. So the challenge is how to make devices with very small gaps, so that they can operate with very low actuation voltages," explains King Liu.

However, opening and closing a physical structure is slower than having electrons flow through a material. "The speed of the mechanical devices is about a thousand times slower than electrical devices," says King Liu. "But our research in the Center is also looking at how to design the circuits quite differently for mechanical switches to overcome this disadvantage. Even though the switches are switching at a lower speed, the overall system can be operating with the same performance by taking advantage of parallel processing.

"A lot of the computers you've seen nowadays have multiple cores–dual core or quad core–and in the future, you may have thousands of cores working in parallel, so

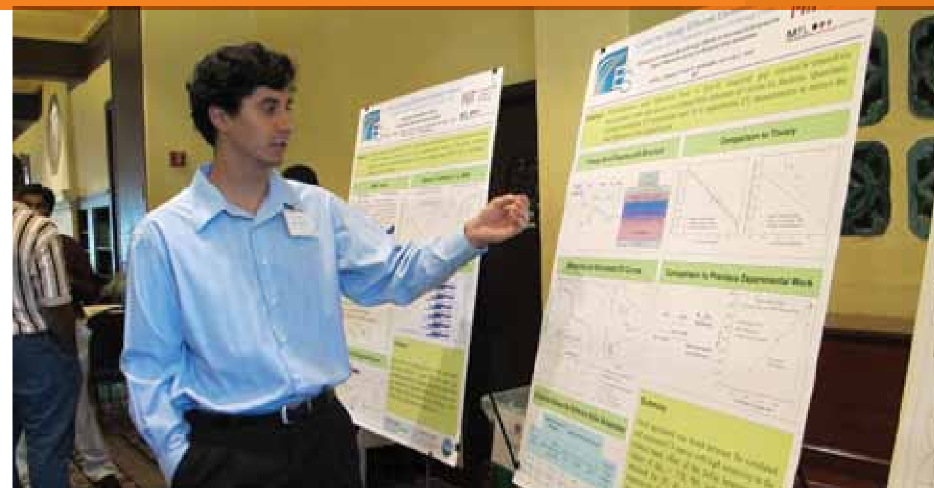
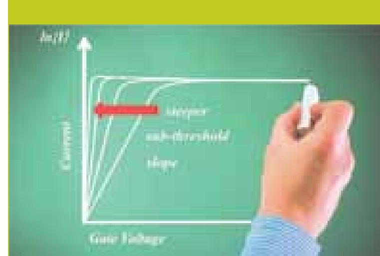


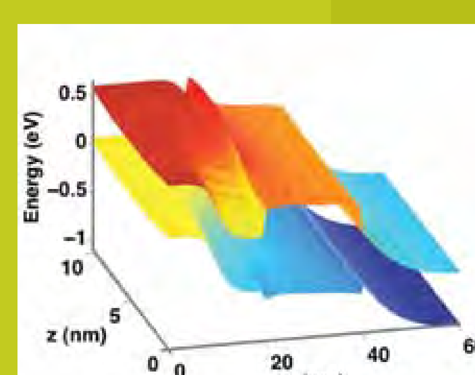
Photo: J. Peng, E³S

the switches can be permitted to switch a thousand times slower. The key is that if each switch can operate at lower energy, the energy efficiency can be orders of magnitude better. The prototype devices we've made so far are on the order of tens of microns long," says King Liu. A micron is a thousandth of a millimeter in length, or about 0.00004 inch. "The gaps are on the order of tenths of microns. We're aiming now in the Center for the next few years to really aggressively scale down the lateral dimensions to be sub-microns and the vertical dimension approaching 10 nanometers or less, permitting lower energy operation."

Another research thrust of the Center is focusing on optical connections for computer chips rather than conventional wiring. "If we look at the current energy consumption in a chip, a large portion of that is spent on communication between transistors, the so called 'interconnect.' So we cannot solve the entire problem without tackling the interconnect energy consumption," explains Ming Wu, professor of electrical engineering and computer sciences at UC Berkeley. Today, a bit of information is represented by 20,000 photons per bit. This needs to be reduced to 20 photons per bit in nanotechnology systems, he says.

This goal will require new kinds of ultra tiny light sources and receivers that can be integrated into microprocessor chips. "So that's our step one: making miniature lasers. Step two is to look at whether we can accomplish the mission without lasers. We are looking at light emitters that are much more efficient than traditional LEDs and we have some theoretical framework on how to achieve that. And so that is part of the center research."□





Above: In search of millivolt switch.
Image: M.J. Yuen, E³S
Right: Tunneling transistor simulation.
Image: K. Ganapathi, UC Berkeley

A CONVERSATION WITH THE DIRECTOR

Eli Yablonovitch

Why did you seek to create a Center focused on this particular theme?

There was a real need to address the most pressing question, which is: what will replace the transistor? We need to have a replacement that operates at much lower voltage. How could we resist a challenge like that?

When I investigated it, I learned surprisingly that there is no reason why transistors should be operating at the high voltage that they're operating at today. They operate at around 1 volt, but they could operate at a few millivolts and still perform the required digital functions.

We are creating of a new field of electronics which I think will eventually be regarded as an important avenue, aimed toward reducing the energy per bit-function–I'm trying to get people to accept that as a figure of merit.

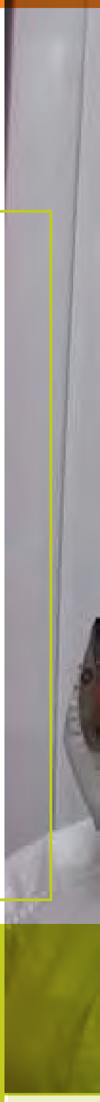
And that's why it's irresistible: it's very much a grand challenge. And it's going to take a while. I knew the only way to achieve something like that would be with a Center.

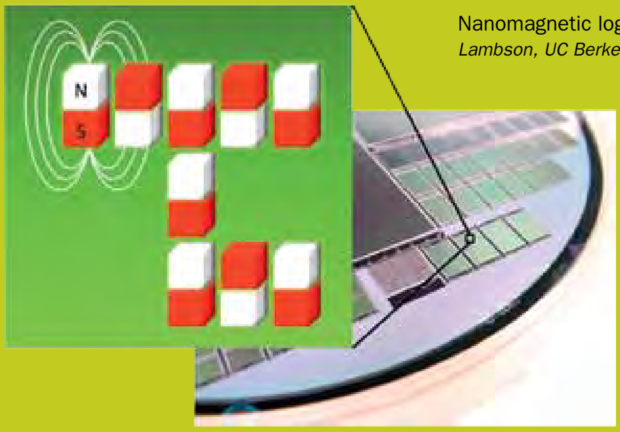
How does industry get involved?

We have a relationship with industry. They came to the site visit and expressed their need for this type of research, and they're participating very strongly. This is very long-range for them. They're monitoring it very carefully.

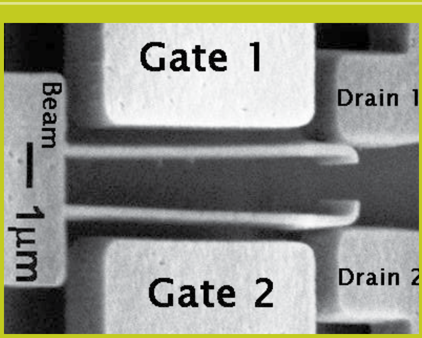
How do you view the role of director?

In a complex task like this, one that involves collaboration with industry, I'm drawing upon all of my life experiences. For example I worked for fifteen years in industry for three different companies. I'm also the founder of four startup companies, and that was a good preparation. Research like this is more long range, so it will develop a little more slowly. I do my part, but I have to encourage my co-principal investigators to dig deep and to do fantastic things. I've had a little bit of experience with that at the startup companies.





Nanomagnetic logic. *Image: B. Lambson, UC Berkeley*



Nanomechanical device.
Image: Daesung Li, Stanford U

FACULTY VIEWPOINT

VIEWPOINT

Ming Wu

Professor of Electrical Engineering and Computer Sciences
University of California Berkeley

"The center really brings people together. Without a center, if I'm interested in a subject, I will be working on that, trying to find support, but it will be very difficult to find long-term support like that of the NSF center so support these long-range ideas. And it will be difficult for me to get industry support because they like to see more evidence in place before they invest in research in this area.

Right now, we have several companies that are watching the project, they are highly interested. They say 'as soon as you have some demonstration,' they would like to be involved. So a Center makes such kind of communication possible.

There are definitely more interactions. Without the Center we wouldn't be meeting as often, talking as much. I'm enjoying the interaction with Center members and still enjoying the scientific intellectual portion of our own subproject.

There is a sense of the Center, a sense of community—we are learning together."

E³S PROGRAM FOR COMMUNITY COLLEGE STUDENTS

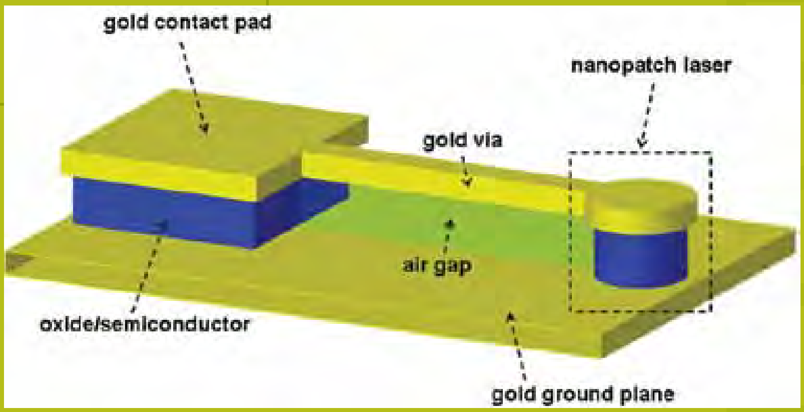
TRANSFER-TO-EXCELLENCE

Transfer-to-Excellence (TTE) is intended to inspire California community college students to ultimately transfer and complete a Bachelor's degree in science and engineering. The program consists of two components. A cross-enrollment program enables community college students to take a science, math or engineering course at UC Berkeley, and a residential summer research program brings community college students to undertake a research project hosted by a Berkeley professor.

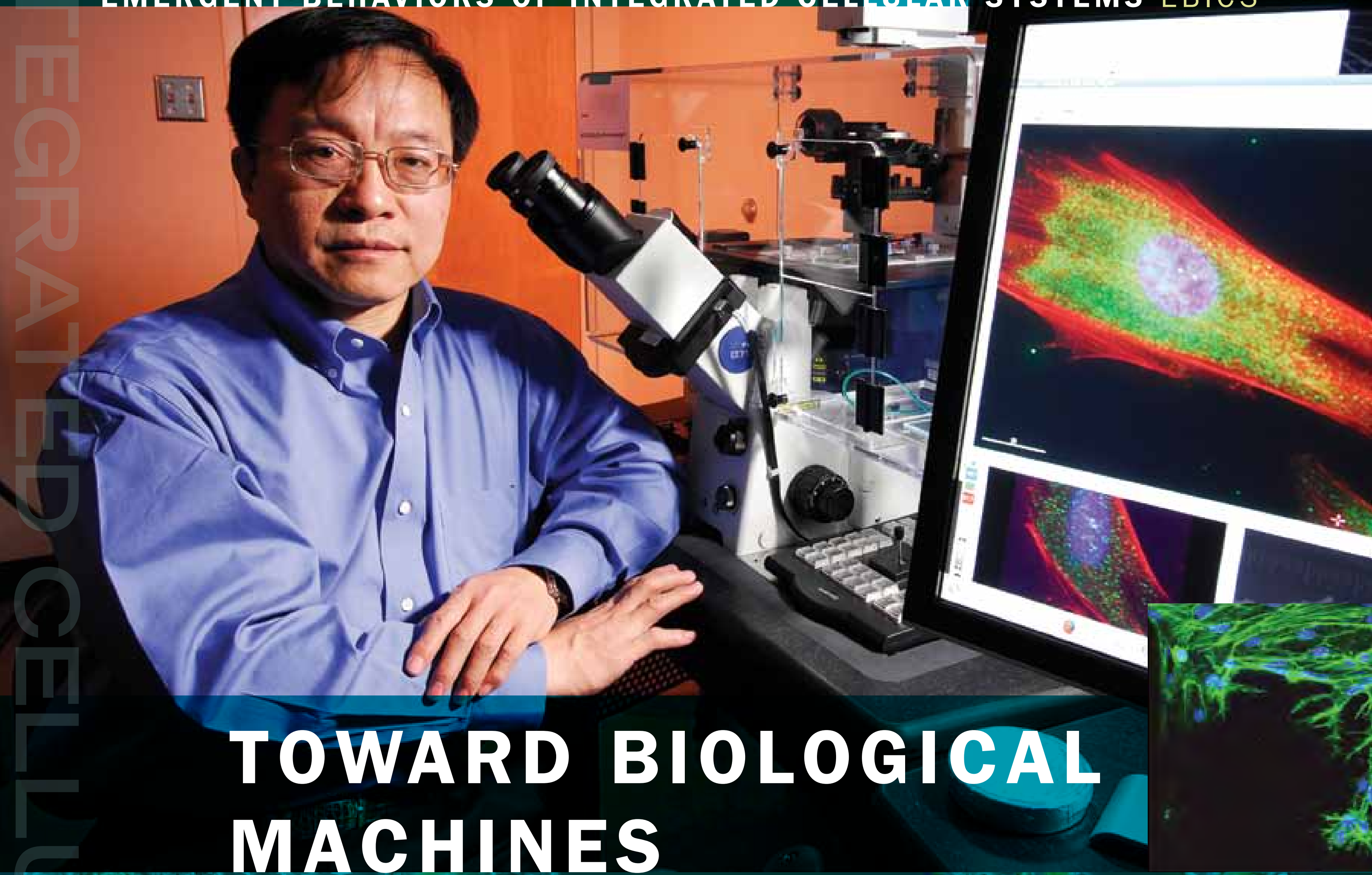
While at UC Berkeley, TTE participants have access to academic, professional, and personal development seminars to enhance the overall preparation and confidence to pursue studies in science and engineering and, eventually, a career in the field. For the academic year following the completion of one component, participants continue to receive advising and support in their efforts to transfer to a science and engineering baccalaureate program.

TTE graduated its first cohort on August 12, 2011. Two students from the E³S partner institutions, Contra Costa College and LA Trade-Technical College, spent eight weeks doing engineering research, and one student from Chabot College completed a 4 credit lower division math course at UC Berkeley.

Undergraduate researchers in clean room at Stanford University. *Photo: S. Artis, E³S*



Schematic of tiny laser for optical interconnects. *A. Lakhani, UC Berkeley*



TOWARD BIOLOGICAL MACHINES

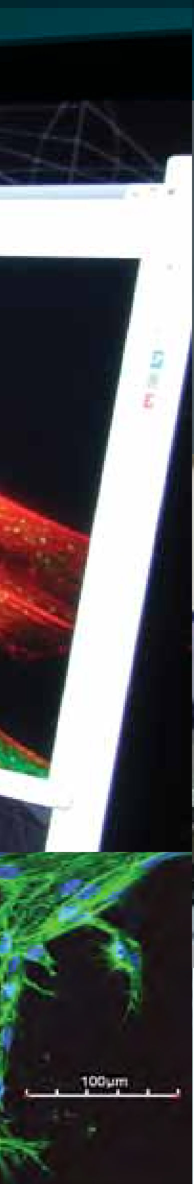
The mission of the center for Emergent Behaviors of Integrated Cellular Systems, or EBICS, is to create a new scientific discipline for building living, multicellular machines that can be applied to solving problems in health, security, and the environment.

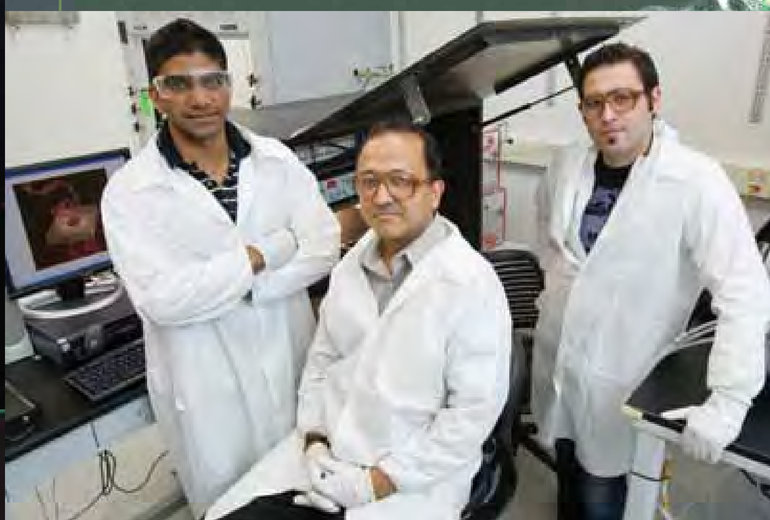
EBICS brings together scientists and engineers from the Massachusetts Institute of Technology, the Georgia Institute of Technology, the University of Illinois at Urbana-Champaign (UIUC), and seven other institutions to focus on developing biomachines that ultimately could, for example, clean up toxins in the environment or deliver life-saving therapies in the clinical setting. The center is led by professor Roger D. Kamm of MIT.

Center researchers are pursuing an array of programs to move this nascent field forward and provide educational opportunities to students. "To effectively carry out EBICS-STC's mission, we need not only to produce innovative research results and develop new technologies, but also to train the next generation of research and education leaders," notes Kamm and members of the leadership team Robert M. Nerem, and K. Jimmy Hsia in the November 2010 issue of the journal *Mechanical Engineering.*

"The leaders of this new field should be knowledgeable in engineering and physical sciences, and in biology," note the authors. "They should be not only competent in these scientific disciplines, but also familiar with other big-picture issues such as public policies, intellectual property and patent law, entrepreneurship, and ethics. They should possess strong communication skills and leadership qualities. Furthermore, the new generation of research and education leaders should be a diverse group including women and underrepresented minorities."

Pictured above: Gang Bao, EBICS researcher at the Georgia Institute of Technology.
Photo: Gary Meek, Georgia Tech





Rashid Bashir (center) is a professor of electrical and computer engineering and of bioengineering at the University of Illinois at Urbana-Champaign. He is flanked by graduate students Murali Venkatesan (left), and Sukru Yemenicioglu (right). *Photo: L. Brian Stauffer, ScienceDaily.*

BIOBOTS ON THE MOVE

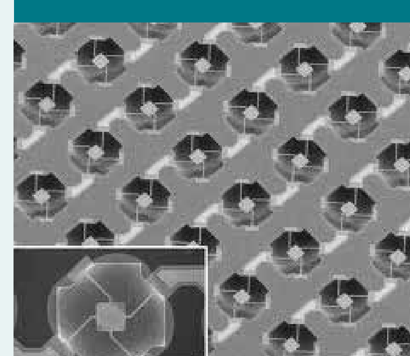
"I became fascinated about 15 years ago with the notion that we could program cells," says Ron Weiss, a biological engineering professor at MIT. "I started getting into synthetic biology. I'm a computer scientist by training, so I like to program stuff," he laughs. "I think biology is now the coolest thing that you can program, so that's my particular interest."

Weiss co-leads an EBICS research project with UIUC researcher Rashid Bashir working on so-called "biobots"–biological "robots" ultimately capable of moving, sensing, and carrying out actions of interest. These are assemblages made of groups of cells of different kinds, such as muscle cells to produce movement, cells to sense substances in the environment, and neurons to control the biobot's actions and motion. The long term goal is to develop biobots using muscle cells and neurons that can achieve net motion towards a chemical toxin and subsequently release chemicals to neutralize the toxins.

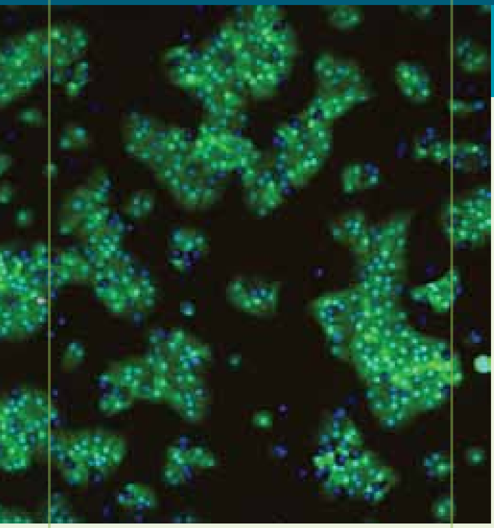
It's a field in its infancy: scientists currently are working on the most fundamental strategies for assembling the basic building blocks that would make up such biological machines. Weiss, Bashir and colleagues have outlined an ambitious 10-year plan to develop biobots of increasingly greater sophistication and capabilities.

They envision four basic levels. "The first would be what we're calling flapbot; it would just flap muscle cantilevers or muscle-actuated cantilevers. It would move around in one direction," Weiss explains. "Stopbot would move until its neuronal sensors detected a particular analyte–could be a toxin or other chemical in the environment--and then it would stop. Even if the analyte went away, it would still be stopped." In contrast, something at least for now he's calling "scaredy-bot" would move around randomly, and then when it sensed a toxin, it would move away forever in a particular direction. A "follow-bot" would move up a gradient toward increasing concentrations of a substance in the environment, such as a pheromone, a chemical substance produced by an animal, often as an attractant. □

Ron Weiss of MIT



Microsensors can measure cell mass like tiny scales. Bottom: A scanning electron microscope image of a microsensor array. Inset: an individual sensor. Courtesy of Rashid Bashir. *Photos: www.pnas.org/cgi/doi/10.1073/pnas.1011365107*



Pancreatic beta cells.
Photo: Richard Lee

Georgia Tech researcher Manu Platt. *Photo: Rob Felt, Georgia Tech*

CELLULAR MACHINES FOR GLUCOSE BIOSENSING AND INSULIN RELEASE

EBICS researcher Richard Lee and colleagues are developing a cell-based system for monitoring glucose levels. The project targets "a big clinical problem that's been unsolved for a long time," says Lee, a Harvard professor of medicine in Cambridge, Mass.

"We have this problem in glucose monitoring," Lee explains. "A person with type I diabetes that's hard to control has very little insulin, and the reason that you can't give them enough insulin to keep their glucose in a normal range is because they'll have periods of hypoglycemia–low blood sugar. It's actually the high blood sugar levels that cause the organ damage, like to the eyes and kidneys–but it's the low blood levels that prevent you from giving enough insulin to prevent the high levels. So if we had ways of continuously monitoring glucose--particularly for the low blood sugar levels–we would be able to be more aggressive with insulin."

The strategy in this EBICS project is to take some of the patient's own cells, and make them able to sense and report out the glucose level. A small wearable device about the size of a large earring or a wristwatch would pick up that signal. In turn, the wristwatch would wirelessly transmit that information to an insulin pump, an existing technology in routine clinical use. Insulin pumps usually are worn on the belt, and a small needle near the belt administers the insulin.

"If one could actually monitor glucose incredibly accurately and in near-continuous fashion, one could get nearly perfect glucose levels in these patients," notes Lee. "That part has been proven. In effect, a big advance in Type I diabetes therapy is figuring out how to do the monitoring."

Researchers from a half dozen labs have participated in the work, both within and outside of the STC. "This has been an interesting experience because it's a real team effort," says Lee. "The funding from NSF is a small fraction of the project, but we were able to interest other labs because they were so excited about it. This is not just a 'cool' science project--this is a real life issue, and to remind myself of what patients are doing, I keep a glucose monitor on my desk and prick my finger to make a measurement a few times a week. For us, this is taking a bioengineering concept and putting it into an 'every minute counts' situation."

Pictured opposite right: Andres Garcia (right) and a student. *Photo: Georgia Tech*

"By emergent behavior we mean the characteristics and self assembly that occurs naturally for a population of cells due to their microenvironment and genetic programming–an order, structure, and complexity that arises due to the cues provided. Through the research of EBICS, our goal is to understand how this occurs and how we might control these processes so as to use this in the creation of biological machines."

— **ROBERT NEREM, EBICS Associate Director**
Parker H. Petit Distinguished Chair for Engineering in Medicine and Institute Professor Emeritus, Georgia Institute of Technology

INTEGRATED CELLULAR SYSTEMS

EDUCATIONAL PROGRAMS AT EBICS PREPARE STUDENTS FOR RESEARCH ON CELLULAR SYSTEMS

Graduate Teaching Consortium

In Fall 2011, EBICS launched its first full-scale Graduate Teaching Consortium (GTC) courses exploring the field of engineered biological systems. The classes are Internet-based and include asynchronous and synchronous lectures, live Q & A sessions, and discussion forums.

One of the offerings, entitled "Cell as a Machine," was taught by professor Michael Sheetz of Columbia University and Hanry Yu of the National University of Singapore. The other, on "Principles of Synthetic Biology," was taught by professors Ron Weiss of MIT and Adam Arkin of the University of California-Berkeley.

"The exciting thing about the Graduate Teaching Consortium is that it creates the opportunity for students at a fairly wide array of universities to have access to cutting-edge content taught by the leading researchers in the field around the new biology," says Lizanne DeStefano, EBICS education co-director located at University of Illinois at Urbana - Champaign.

"Our students gain an advantage through the Graduate Teaching Consortium because they're getting a course from the person in the field who's doing the leading work in that area. And for our students at our minority serving institutions, we find that it really enhances the level of graduate coursework that they're able to take, because they may not have people at their university who are doing work on that particular topic."

In Their Own Words...

"As one can imagine, whenever the issue of creating living systems with new functionalities is raised, caution must be exercised. Indeed, a number of ethical issues will need to be addressed. Will these machines be endowed with the capability to self-repair, adapt, and self-replicate? If so, they become indistinguishable from natural organisms and need to be considered in a similar light. If stem cells are used, from what source may they be taken? What protections and regulations need to be in place? These and many other questions will be openly debated within EBICS and with the larger community in parallel with the development of advancing technologies."

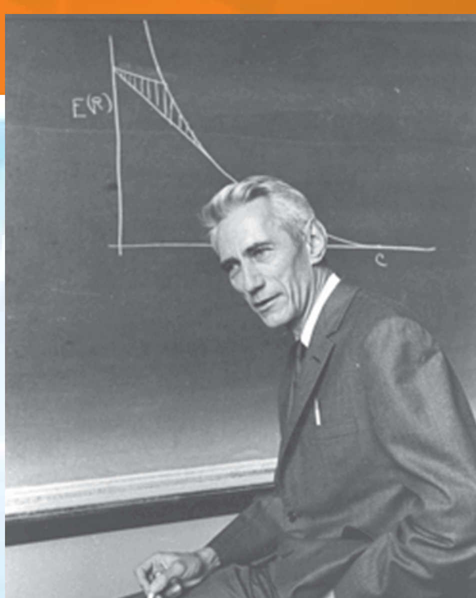
— ROGER D. KAMM, ROBERT M. NEREM, AND K. JIMMY HSIA
in "Cells into Systems," ***Mechanical Engineering,*** November 2010
http://memagazine.asme.org/Articles/2010/November/Cells_Into_Systems.cfm

Roger Kamm

CENTER FOR SCIENCE OF INFORMATION CSoI

TOWARD A NEW SCIENCE OF INFORMATION

It's often said we live in the information age. With our mobile phones, iPods, iPads, DVDs, wireless networks, and the Internet, we are awash in information. What people may not realize is that the foundations for transmission of information in today's technologies were laid back in the 1940s by Claude Shannon in his seminal paper on "A Mathematical Theory of Information."



Claude Shannon

> **We need to focus more on how information is managed in living systems and how this brings about higher-level biological phenomena.... We need to describe the molecular interactions and biochemical transformations that take place in living organisms, and then translate these descriptions into the logic circuits that reveal how information is managed. This analysis should not be confined to the flow of information from gene to protein, but should also be applied to all functions operating in cells and organisms, including chemical interactions and transformations as well as physical phenomena, such as electrical signaling and mechanical processes.**
>
> — **PAUL NURSE, "Life, logic and information,"** *Nature 2008*

Published in 1948, Shannon's work established fundamental limits on the compression, transmission, and storage of information in simple communication systems—and we've been riding the Shannon "wave" ever since. These are the principles that govern, for example, how many songs you can fit in a 16 Gigabyte iPod and how well your streaming video works over your WiFi connection.

At the time, Shannon deliberately made many simplifying assumptions, acknowledging that in the future, other work would be needed to account for aspects not encompassed within the scope of the problem he defined. He ignored issues of time-critical transmission of data, multi-point communication, spatially structured information, and message content and context. Nevertheless, it was enough to help spur a trillion-dollar communications industry that has had profound personal, societal, and economic effects. Enough to make one ask: What wonders might be in store for us next?

"Shannon basically gave us fundamental modes for storage and communication point to point," says Wojciech Szpankowski, director of the Center for Science of Information (CSoI). "In today's applications, there isn't just point to point communication; everything is dynamic, from biological networks, to the Internet, to wireless. And this changes the situation completely."

Researchers at CSoI are working to advance the science of information to transcend the limits of Shannon's theory. Headquartered at Purdue University, the center brings together researchers at nine partner institutions from computer science, information theory, and applications areas such as natural sciences, economics, and social sciences to advance the field.

"We are part of the Shannon legacy," says Szpankowski. "The goal is to extend Shannon theory beyond its original objective to incorporate temporal, spatial, structural, semantic, and contextual features in order to better understand the flow of information in today's applications: in biology, modern communications, economics, and others."

In the mathematical definition of information that Shannon introduced, the main objective was the statistical reduction of uncertainty. In a broader sense, however, information is something that has to be related to the objectives of the recipient.

An example of time-critical information is an airline passenger waiting for a flight, explains CSoI associate director Ananth Grama of Purdue. "You need to find out what time your flight is leaving, and if you get a text message after the flight has already left, saying that you're flight is going to be on time, that information is worthless to you," he notes. Center researchers are working on ways to incorporate the "value" of information with respect to time, "overcoming the simplifying assumptions that Shannon imposed–time doesn't matter, delay doesn't matter--but we know very well that if the message arrives very late it might be completely useless," emphasizes Szpankowski.

Another of Shannon's simplifying assumptions was to ignore the content of messages. "If you study the traffic flow of trucks on the highway, you may not care what they carry. Whether they have bananas or jet fuel or whatever–in other words, the semantics doesn't matter. But in other applications, it does matter very much," says Szpankowski.

Other problems involve data structures that are not easily tractable in classical information theory. "We've gotten to a point where information is a lot more sophisticated that just bags of zeros and ones," says Grama. "Data may have structure—geometry, as in chemical structures, DNA, proteins. In biology, we're talking about very large networks of cellular interactions. In social sciences, we're talking about social networks. In economics we're talking about transactions. Data are higher order–it's not just simply bits anymore."

The mission of the Center for Science of Information is to advance science and technology through a new quantitative understanding of the representation, communication, and processing of information in biolog¬ical, physical, social, and engineered systems. In the process, the center aims to prepare a new generation of scientists equipped to develop and apply emerging theories.

This area of work is expected to have many applications for industry and government organizations. The center currently is interacting with a range of companies, large and small, in the retail, software, aerospace, and biotech sectors, in addition to federal agencies, says Grama, who serves as director of knowledge transfer for CSoI. "Each has a large amount of data, and they are trying to find effective and rigorous ways of extracting actionable information from their data sets."

A CONVERSATION WITH THE DIRECTOR

Wojciech Szpankowski

"I see myself as an enabler," says Wojciech Szpankowski, director of the Center for Science of Information and the Saul Rosen Professor of Computer Science at Purdue University.

"The team we have is incredible–the best researchers in information sciences in the world. This is a one-hundred member center with about fifty faculty, fifty students, and some collaborators. So it is huge. The people are top-notch. Of course you can't tell them to do anything," he laughs. "The only thing you can do is to motivate them, and when they become enthusiastic about something, they will do wonders.

"So that is why we are using a process of extended, one-day workshops, held at many regional sites. We sit for six to seven hours and we ask questions, and people pick up problems and begin to work on them. We need to establish natural collaborations–this is the hardest part because the center is big. And they are indeed being established."

EDUCATIONAL PROGRAMS AT CSOI

A new undergraduate course, titled "Introduction to the Science of Information," has been developed by CSoI to provide a new synthesis of this emerging discipline and to provide undergraduate students a foundation to pursue higher studies at Center institutions.

The course was launched during fall 2011 at Purdue University by CSoI associate director Mark Daniel Ward through the University Honors Program. A related course is scheduled to be given at Bryn Mawr College in spring or fall of 2012.

On another front, the Center's inaugural summer school brought students and faculty from ten universities together during summer 2011. Students gained a broad understanding of the emerging field of science of information while establishing connections with one another and the Center's faculty. The four-day intensive included ten surveys and tutorials spanning the breadth of the Center's research thrusts. Students learned new tools and applications in daily laboratory offerings.

"I learned what information really is, as it was a vague concept I took for granted before the summer school. Specifically, I learned about how information science should be studied from a multi-disciplinary approach," says one participant. "I also learned about graduate schools and different programs/departments that might be of interest to me in the future from talking to professors and students." Lectures with video/audio/slides and laboratory exercises are available at http://soihub.org/summer-school.php

In Their Own Words...

EDUCATION AND OUTREACH: TAKING THE SCIENCE OF INFORMATION FROM THE CLASSROOM TO THE COMMUNITY

Deepak Kumar

CSoI Associate Director for Education & Diversity
Professor of Computer Science, Bryn Mawr College

"Computing, for me, is very intimately related with the study of information. Even though the idea of information transcends computing and computation, I think computing is what makes it more interesting and makes it possible to apply the science of information.

Models of information or underlying principles of information ultimately come to life in computers, and so my goal, what's exciting to me, is I can take these ideas and introduce them to students in many different disciplines.

Here's a question we can actually ask and answer today. Were all the works we associate with Shakespeare today actually written by him? We can apply computational techniques and mathematical analyses to the texts, to the entire body of work that's claimed to be Shakespeare's, and we can analyze it within a matter of, if not minutes, then hours, and come up with metrics of evaluation that tell you yes, they're all in the same style.

Another example: we now have available the texts of all of the U.S. president's states of the union speeches over the years. Let's analyze it by various metrics. When did the word woman actually appear in those speeches? When did issues of race come up? How many times? We can plot the frequencies, and when you do that you actually see when cultural and social awareness of some of these issues came about.

There's this whole new field that's coming up now called digital humanities. Information theorists would be interested in the efficiency of language–how many words, how long a text needs to be to express the same set of ideas in different languages. We can look at translations of the same text and come up with some metrics about how efficient with respect to the size of the text a particular language might be. And actually Shannon sort of dropped some of these ideas way back when, because according to Shannon's theory, redundancy in language is actually a good thing, because there is loss of data over transmission, and so that's the key to error correction.

English, it turns out, is only about 50 percent efficient. You can see that when you text now–you don't send text messages with complete words and phrases. There are a whole bunch of these issues we didn't even know how to get a handle on, that we can now.

The science of information is one of these areas that brings many disciplines together. And so the idea of creating a new undergraduate course on science of information is founded on those ideas: how can we engage students who are in a college where everything is by department, right, and you have to take x courses in this discipline and y in that, and so forth–How can we break those boundaries?

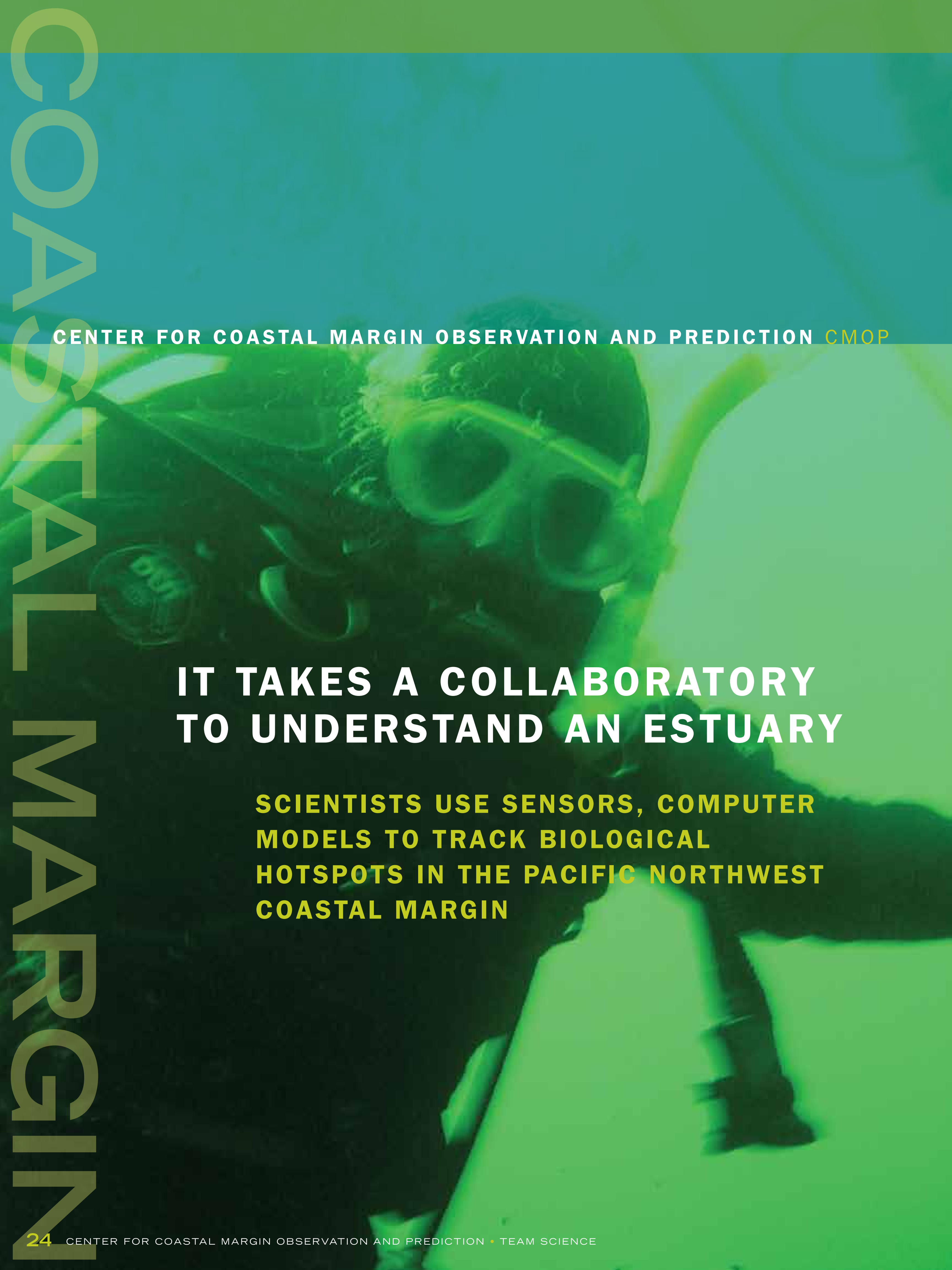
Science of information is a natural place–it combines computing, it combines information, and it brings all these other disciplines together. And so the new course we're creating has those goals. How can we engage students so that no matter what they're studying, they'll bring a lot more back into their own studies than they would have otherwise. So when an English major comes and takes a course like that, goes back to the English department, what is she bringing back to that? Some of the examples I've described are in that realm: suddenly the paradigm of computing, the way of thinking about information is relevant to their own disciplines in a new way. That's exciting to me.

As somebody responsible for education and diversity, I'm actually looking well beyond information in terms of outreach. For instance, in fall 2010, there was a movie that came out called *Top Secret Rosies,* and it's about women mathematicians at the University of Pennsylvania during World War II. Instead of Rosie the Riveter, during the war, these were their mathematical cousins. Nobody knew about their work because it was all classified. The filmmaker making the documentary interviewed these women, who were still alive.

It's about computing history, it's about women in computing history, it's about an important piece of that, so as part of the center, we actually rented the local theater in town, made it free to the public, invited the filmmaker, screened the movie, and had her do a question and answer session. We had 300 members of the public, and when the question and answers started, there were actually a few people who stood up and said they were one of these top secret Rosies, or their grandmother was one. One of the things we're trying to do is make sure that we organize and host events like these. We did this in March at Bryn Mawr Theater in Pennsylvania, and partners in Purdue also held a similar event."

EDUCATION AND OUTREACH

SCIENCE OF INFORMATION



COASTAL MARGIN

CENTER FOR COASTAL MARGIN OBSERVATION AND PREDICTION CMOP

IT TAKES A COLLABORATORY TO UNDERSTAND AN ESTUARY

SCIENTISTS USE SENSORS, COMPUTER MODELS TO TRACK BIOLOGICAL HOTSPOTS IN THE PACIFIC NORTHWEST COASTAL MARGIN

Like canaries in coal mines, biological hotspots in coastal margins are sensitive to the changing environment, such as changes in climate and increased demands on freshwater supplies. Scientists and engineers at the Center for Coastal Margin Observation and Prediction (CMOP) are improving the ability to monitor, understand, and anticipate changes in these hotspots, using the Columbia River as a natural laboratory. An expected outcome is to develop approaches and tools necessary to sustainably manage one of the largest rivers in the world.

Headquartered at Oregon Health & Science University (OHSU) in Beaverton, Ore., CMOP is one of three NSF supported Science and Technology Centers (STCs) that focus on the ocean. It is the first STC dedicated to studying coastal margins, the complex, productive and sensitive regions where rivers meet the sea. Participants include researchers at Oregon State University (OSU), University of Washington (UW), and several other academic, industrial, state, federal and tribal partners. CMOP's research is regionally focused on the Columbia River, but has global relevance for all coastal margins.

Famous for providing Lewis and Clark with a gateway to the Pacific, the "mighty Columbia" ranks first in freshwater input to the Pacific Ocean in the Western Hemisphere. It is the lifeblood for a dense population founded on a rich economy of trade, fishing, logging, recreation, and hydroelectric power industries in the Northwest. Of particular importance to the region is the balance between protection and recovery of species listed under the Endangered Species Act, and the economically vital activities of energy production and of fluvial and marine transportation.

Although Columbia River issues are specific to the region, the need to understand and manage coastal margins is not. Natural features such as estuaries, freshwater and sediment plumes, continental shelves, watersheds, and rivers are all part of coastal margins. These zones are found all over the world and mark unique and ever-changing environments where fluctuations in temperature and salinity–and human activity–affect populations at every level of the food chain.

Because of the importance of coastal margins, oceanographers have long studied the physical and chemical conditions within these dynamic environments. They have sought to quantify seasonal fluxes of sediment discharged by the river to the sea, changes in salinity as a result of melting snow, trends in ocean temperature as a result of El Niño events, and effects of these changes on seasonal salmon runs. They have also started realizing that microorganisms may hold clues to understanding and even predicting natural variability and trends. CMOP is using a systems approach to answer these complicated questions, and to place them in a context of evolving climate and human activities.

Central to CMOP's approach is a "collaboratory," a network designed to transcend disciplinary, logistical, institutional and societal barriers, allowing diverse user communities to interact freely and to have shared access to objective information.

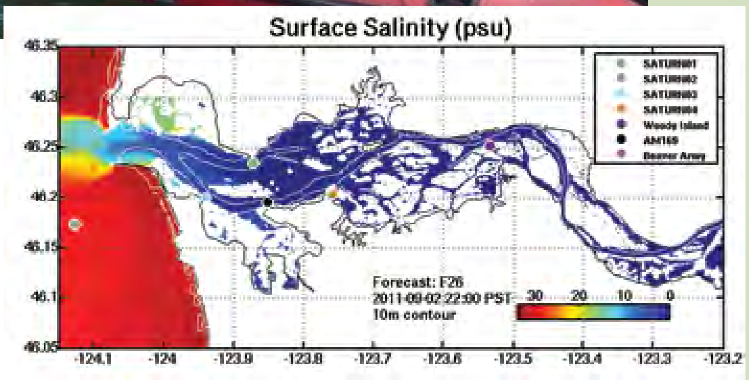
"In the first five years of CMOP we laid the foundation by building SATURN, from the sensors and models to the scientific and broad-impact partnerships," says CMOP director António Baptista. "We are now ready to advance the science in a very systematic way. Our immediate focus is understanding the estuary as a 'bioreactor' that integrates and transforms land, ocean and atmospheric influences."

CMOP scientists are focusing on three biological hotspots – high-turbidity events in rivers, lateral bays, and plankton blooms–which they believe are key. "If CMOP researchers can correlate microbial hotspots in the estuary to the response of the broader coastal margin relative to large-scale forcing, they will greatly advance the ability to anticipate future changes in the ecosystem," says Baptista. "CMOP stakeholders, including state, federal and tribal agencies, would then have a very powerful tool to steer ecosystem performance and sustainability accounting for climate changes and increasing pressures on natural resources. "

This integrated research program and broad societal impact would not be possible without an STC, says CMOP co-director David Martin of UW-APL. In the coastal zone, "everything is interconnected–the hydrosphere, the lithosphere, the chemosphere, the biosphere, the atmosphere," he observes. Trying to understand the entire ecosystem, and the diverse human influences on it, would be impossible through the narrow view of any one discipline. Equally important, the effective integration of scientific findings in regional management is uniquely facilitated by the broad view that the STC program takes of science as a catalyst for societal transformation. □

At top: The Pacific Ocean and Oregon Coast from Cape Lookout State Park. *Photo: Jeff Schilling, CMOP*

At left: Ninety feet below the surface of the Pacific, OHSU diver Michael Wilkin grasps a mooring cable that anchors an ocean observing buoy to the seafloor. *Photo: Jon Graves, OHSU*



Above: OHSU field staff members Michael Wilkin and Jon Graves rewire an ocean observing buoy on a calm day in the Pacific Ocean west of Seaside, Oregon. *Photo: Courtesy of CMOP*

At right: Model of surface salinity in the Columbia River estuary and near plume.

THE SATURN COLLABORATORY

http://www.stccmop.org/saturn

Central to CMOP's approach is the SATURN collaboratory, a network for interaction and data sharing. "SATURN offers a data-rich and model-supported environment, where information, tools and ideas flow freely, enabling team science to flourish," says center director António Baptista.

The SATURN collaboratory is anchored on an interdisciplinary, river-to-shelf observational network. The network includes endurance stations measuring everything from salinity and temperature to biogeochemistry and bacterial diversity on a 24/7 basis. Adding spatial coverage is an array of ocean gliders that roam the Washington shelf and autonomous underwater vehicles (AUVs) that capture the small-scale details of the structure of the Columbia River estuary and plume.

The data collected from the observation network are essential to assessing the skill of SATURN's modern modeling system, the Virtual Columbia River. At the heart of the system are various types of numerical models, each run with realistic bathymetry and river, ocean, and atmospheric forcing to produce daily forecasts, decade-scale historical simulations, and scenarios of change in the future due to climate or anthropogenic activity.

SATURN's observations and the simulations are products used and influenced by a number of communities of practice: individuals and groups who conduct science or make decisions incorporating the information and insight generated by these collaboratory components.

The observations, models, and communities of practice are all producers and consumers of information, a demand that requires a powerful infrastructure to manage. "CMOP's cyber-infrastructure enables the free and timely flow of vast quantities of information among all producers and consumers, while also adding value to the information through QC and analysis tools," says Baptista. "As a complete system, SATURN allows for transformative advances in the scientific understanding of coastal-margins, while simultaneously helping integrate science in regional management and enabling the training of a scientifically and technologically savvy workforce."

NEWS WATCH

COLUMBIA RIVER TREATY

CMOP is working with the Columbia River Inter-Tribal Fish Commission and other organizations to study the impact of the changes in hydropower regulation anticipated as a consequence of the renegotiation of the 1964 Columbia River Treaty between Canada and the US. Since 1964, the Columbia River Treaty has offered significant flood control and power generation benefits for both the U.S. and Canada. In 2024, the 60-year treaty is scheduled to end, opening the opportunity to renegotiate the terms and potential impacts of the treaty. The SATURN collaboratory and CMOP's current research efforts will help characterize the current state of the Columbia River coastal margin, and anticipate future effects on ecosystem health and fisheries. The goal is to provide negotiators with objective information to facilitate science-based decisions.

A WINDOW ON THE MICROBIAL ENVIRONMENT

CMOP is scheduled to take delivery in fall 2011 of an Environmental Sample Processor (ESP) which can be pre-programmed or triggered remotely to collect samples. Purchased from Spyglass Biosecurity, Inc, thanks to a grant from the M.J. Murdock Charitable Trust, the ESP will allow autonomous, on-site collection and near real-time analysis of water samples from the estuary. Addition of the ESP to the SATURN observation network will facilitate comprehensive testing of hypotheses about microbial roles in estuarine processes. The sampling capabilities of the ESP will be particularly useful for understanding the roles of microbial communities in oxygen dynamics in the South Columbia River channel, and for monitoring algal bloom populations and their effects.

At top: OHSU diver Michael Wilkin prepares sensors for deployment at the Marsh Island station of the CORIE observation network in the Columbia River estuary. *Photo: Courtesy of CMOP*

CMOP IN THE CLASSROOM

CONNECTING STUDENTS WITH THE SEA

To establish a "pathway" leading to scientists, engineers, and citizens capable of using a systems approach to addressing complex problems, CMOP is creating education and outreach programs for students and teachers at the K-12 and university levels. Close integration of CMOP's science and technology with the educational activities ensures students' exposure to leading-edge research and its application to coastal margin challenges. Through each educational effort, CMOP strives to broaden participation of traditionally underrepresented groups, in particular Native Americans, the traditional stewards of the environment.

CMOP graduate students receive hands-on training and experience in the laboratory and the field, with access to research cruises, advanced sensors and instruments, and extensive physical and biogeochemical observational data. Students are trained throughout their program in a highly interdisciplinary manner, providing them the skills to understand and solve complex environmental problems through integrative studies across multiple scales, from molecular to global. Additionally, CMOP students regularly attend and present at national and international conferences, co-author publications, mentor high school and undergraduate research interns, teach K-12 science classes and camps, and pursue their own passions as co-PIs, adjunct instructors, fellows, and student government leaders.

During the summer, CMOP's labs swell with high school and undergraduate interns eager to participate in ground-breaking research. The interns, with guidance from frontline mentors and senior scientists, are immersed in the scientific environment through their own research projects designed to contribute to CMOP's research initiatives. Interaction doesn't stop when the summer is over, with many interns joining their CMOP mentors and educators in giving presentations at national conferences or co-authoring their contribution to CMOP publications.

CMOP also offers science enrichment opportunities for middle and high school students through key partnerships in the Pacific Northwest. Working with one of our founding partners, Saturday Academy, CMOP graduate students, staff and investigators develop and teach short-term classes and week-long summer camps to introduce CMOP science to middle and early high school students through interactive, memorable activities to spark long-term science interest.

CMOP is developing a rigorous curriculum that engages primarily Native American high school students in a culturally relevant, place-based learning experience. Designed as a three-year progressive program, the curriculum combines Western environmental science, traditional ecological knowledge from the mid-Columbia River tribes, and a respect for water and cycles of the Sacred Foods to teach students the relevance of ecological sustainability through a meaningful personal experience. Recognizing that true sustainability in K-12 education lies with the teachers, CMOP offers a number of teacher professional development opportunities to inspire and enable inquiry-based ocean science activities in the classroom.

At top: OHSU divers Michael Wilkin and Jon Graves. *Photo: Courtesy of CMOP*

MEET THE DIRECTOR

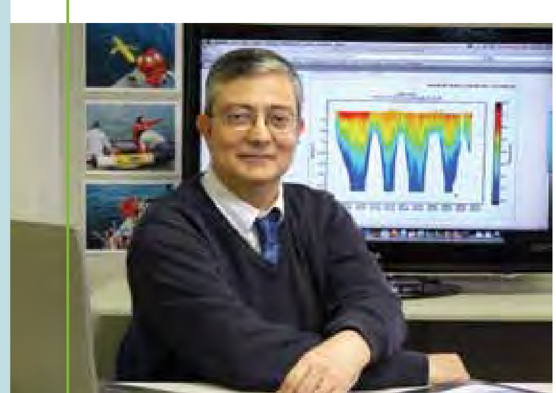
António Baptista

CMOP director António Baptista sees the Columbia River and the Pacific Northwest as an ideal laboratory for studying the impact of climate change and resource management on coastal margins. This is a complex problem requiring contributions from many disciplines, and Baptista is no stranger to establishing collaborative science programs.

Fifteen years ago, he began work on CORIE, a multi-purpose observation and prediction system and the precursor to CMOP's SATURN collaboratory. Ten years ago, he was the founding head of OHSU's Division of Environmental and Biomolecular Systems, which merged environmental science and engineering with biochemistry and molecular biology. For Baptista, creating CMOP seemed to be the logical next step to advance the concept of team science with societal relevance.

"As a society, we require a better scientific understanding of the potential effects that climate and human activity will have on coastal margin ecosystems, to ensure positive outcomes for environmental sustainability, economic development, and public health," says Baptista. "At CMOP, we see addressing this requirement as our Grand Challenge. Having invested earlier in building a collaboratory as a multi-purpose infrastructure for Columbia River studies, we are now entering the exciting phase of exploring how and to what extent collaboratory-enabled science can meet the Grand Challenge. In particular, we should be able to learn a great deal about the estuary as a 'bioreactor' that reflects many of the behaviors and changes of the entire region."

Reflecting back on the first five years of CMOP, Baptista is particularly fond of the emergence of a Center culture that is strong and highly effective in both advancing and applying science. He credits his colleagues for buying deeply into the concept of "team science," often putting the interests of the collective ahead of their own, and actively exploring ways to leverage each other's diverse expertise. "Sharing data, tools, and concepts is the accepted norm within CMOP," he affirms. "Our science can serve as a catalyst for new educational pathways and as the basis for objective regional decision-making."

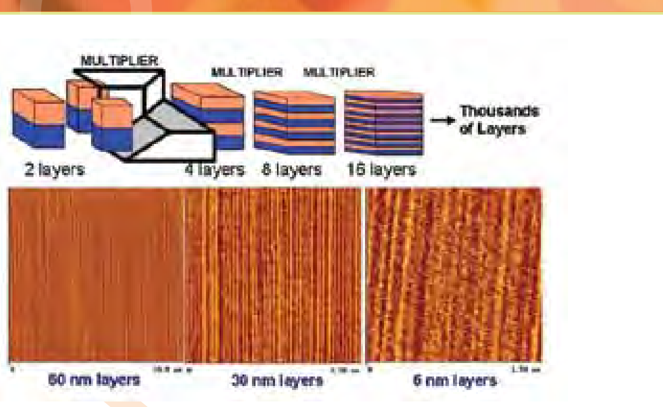


Antonio Baptista, director of CMOP
Photo: Jeff Schilling/CMOP

CENTER FOR LAYERED POLYMERIC SYSTEMS CLiPS

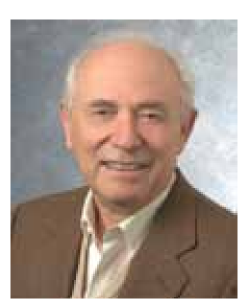
MAKING MULTILAYERED MATERIALS WITH NOVEL PROPERTIES

MANY LAYERS MEAN MANY POSSIBILITIES. THAT'S THE CENTRAL IDEA OF THE ENABLING TECHNOLOGY BEHIND THE CENTER FOR LAYERED POLYMERIC SYSTEMS (CLIPS), HEADQUARTERED AT CASE WESTERN RESERVE UNIVERSITY.



CLiPS researchers are working at the intersection of polymer science, engineering, chemistry, physics, and biology to catalyze the development of nanolayered materials and to facilitate their transfer to the commercial sector through partnerships with industry and other organizations.

Serving as center director is Eric Baer, who holds the title of Distinguished University Professor, and is the Herbert Henry Dow Professor of Science and Engineering in the department of macromolecular science and engineering at Case Western Reserve University.


Eric Baer

The center is using a unique enabling process that takes two polymer melts and combines them as two layers, multiplies the layers to four, and doubles that again as many times as desired. Soon you have thousands of layers of alternating polymers, and these layers can be as thin as 50 angstroms. When polymers are combined in this so-called "forced assembly," magical things can happen. The multilayered material can behave quite differently than the starting ingredients. What was once brittle becomes ductile in a multilayer. Colorless ingredients now give off a color without the presence of dyes.

As layers become thinner and thinner, the effect of the interface between these materials begins to dominate, says center investigator Donald Paul, professor of chemical engineering at the University of Texas at Austin and director of the Texas Materials Institute. "What happens is not so well understood," he admits. "Therein lies the frontier."

CLiPS researchers have developed tunable multilayer polymer lasers, one using stretchable elastomeric polymers and one using previously developed laser sheets. Both of the lasers demonstrate how simply folding the pliable polymer sheets can create lasers whose emission color can be tuned.

"Generally lasers are not so easily tunable or so inexpensive. Because these lasers possess those attributes, they have potential applications in remote

Graduate students Matthew Mackey and Jessica Patz

sensing, medicine, communications, and displays," says Ken Singer, a CLiPS project leader and associate director for external affairs.

In the case of elastomeric lasers, folding the structure places a thick dye-infiltrated skin layer between multilayer polymer reflective structures. As the laser is stretched, the output color can be tuned over a 50 nanometer range.

Another thrust deals with barriers and membrane systems that have applications, for example, in the food industry. Keeping vegetables fresh requires that the packaging material allow the right exchange of gases in and out of the package. Because each vegetable has unique needs in terms of gas transport, researchers are exploring the possibility of tailoring the performance of multilayered materials to extend shelf life of produce and perhaps even control the timing of ripening of packaged fruit.

Currently, gas separation membranes are produced by methods that rely on the use of large quantities of environmentally undesirable solvents. But CLiPS' multilayer coextrusion method can entirely remove solvents from the production process. "This is a good example of a value-add application of the multilayering process," says Baer. "The films produced are not only better and safer for the environment, they open up new horizons for their use." □

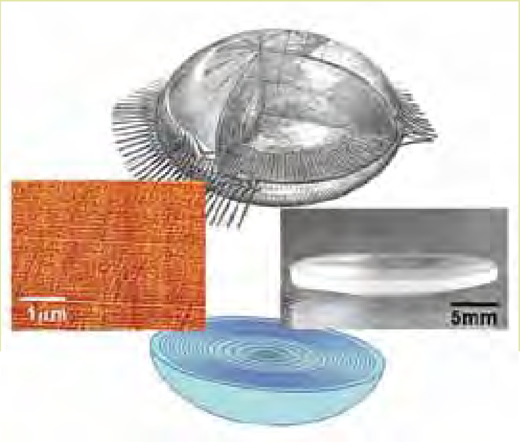
KNOWLEDGE TRANSFER

LAYERED LENS TECHNOLOGY FOR ADVANCED CAMERAS

Researchers at the center have taken inspiration from nature in the development of nanolayered lenses that are not unlike the lenses in the eyes of fish.

In fish lenses, the material's ability to bend light, or refractive index, gradually changes with depth inside the lens: in other words, they have a refractive index gradient. "We are able to copy that using the nanolayer approach," says center research chair Eric Baer.

Lenses of this type exhibit a wider field of view with less aberration than conventional lenses having no index gradients. The "gradient refractive index" or GRIN lens shown in the figure below mimics a segment of the octopus lens. It contains more than 500,000 nanolayers.



Gradient Refractive Index (GRIN) Lens

Polymer Envoy Santiago Chabrier and his graduate student mentor, Guojun Zhang

NEWS WATCH

FOCUS ON STARTUP COMPANIES

Research from the Center for Layered Polymeric Systems (CLiPS) has led to the establishment of two new science and materials-based start-up companies.

PolymerPlus LLC, founded in 2010 out of Case Western Reserve University, is a Cleveland, Ohio based start-up which has incorporated a CLiPS multilayer polymer processing technique to produce films with hundreds or thousands of layers. PolymerPlus is developing manufacturing facilities and an infrastructure to transform these nanolayered polymer films into gradient refractive index polymer lenses for strategic lightweight imaging and energy collection devices. Stemming from unique interactions of light with the polymer nanolayers, these new lenses may be able to combine the optical power of a series of glass or plastic lens components into a single lens. Utilizing a forced-assembly process to coextrude nanolayered polymer films, PolymerPlus aims to manufacture a new class of polymer lenses with improved optical performance and reduced weight leading to miniaturized optical systems and more effective solar cell devices.

Advanced Hydro, founded in 2008 out of the University of Texas, Austin, is utilizing a membrane coating based on the attachment of mussels to ship hulls. The approach has achieved improvements in water filtration performance and reduced fouling, thereby extending the life of commercial water filtration membranes. Advanced Hydro aims to extend the lifetime and reduce the overall cost to operate membrane-based water filtration systems.

PRE-COLLEGE EDUCATIONAL INITIATIVES

The Polymer Envoys Program is the keystone of CLiPS pre-college educational initiatives, providing significant hands-on research experience and mentoring to a select group of high school students from urban school districts, primarily the Cleveland Metropolitan School District.

The Polymer Envoys program matches a high school student with a graduate student in a longitudinal relationship that lasts two or three years and encompasses a six-week session every summer and weekly participation during the school year.

While hands-on research is the principal focus and activity of the program, the Polymer Envoys' experience is enriched by workshop sessions that focus on topics such as the physical and chemical properties of polymers, math skills, guidance and practice with oral presentations, and tips for navigating the college application process, among others.

Polymer Envoys employ their new presentation skills through outreach activities that engage a large number of pre-college students, especially those from underrepresented groups. These efforts help in the recruitment of new students to the program.

Based on the success of the program it has been expanded to all CLiPS partner institutions. "We are very proud of our Polymer Envoys," says Pamela Glover, CLiPS executive director for education and planning. "Twenty students have graduated from the program to date – and all of them are in college. Sixteen of them are studying in STEM fields. This record of success far exceeds the college admissions rate of the resource-challenged, primarily inner-city high schools that these students attend."

Glover is joined in managing CLiPS education programs by Tryreno Sowell and Pamela Cook, directors for education and diversity at CWRU and at the University of Texas, respectively. David Schiraldi, CLiPS associate director for education & diversity, provides technical leadership to the Center's educational vision and programming.

David Schiraldi

Pamela Glover

FACULTY VIEWPOINT

Kenneth Singer & Donald Paul

Q: How do you like participating in the center?

Singer: You have all these people working together, doing things I can't even imagine doing alone... So it really is a team. We have very frequent meetings, pretty much every week, between the faculty and students. We're trying to get the students to collaborate with each other.

Whenever you have a large group working on something, there's a lot of overhead in communication. You meet more, but the payoff is you have many hands helping with the work—you just have to coordinate all the hands.

The laser is a great example of why the team mode is needed. I brought the idea of doing this to the group. Eric and Anne had been working on the process for many years without knowing what the possibilities for lasers were. Then Chris Weder made the dye that goes into the laser to make it work, and he had a key idea on how to get a result quickly. It's not just individual expertise—there's a real synergy there.

It's a creative force; a forcing function that helps people to be better or more creative than they were. What team science does is to take you beyond the cutting edge—when you get together with somebody has an idea that you haven't thought about before, it increases the creativity.

By yourself, you can only be so creative; you can't imagine things you haven't thought about. Everybody improves upon each others' ideas, and there's a certain element of competitiveness—a good kind.

Everybody brings their little corner of science and you end up with a big room.

Q: Why a center?

Paul: Case Western Reserve University has the capability of making laminated thin layer systems. We don't have that at the University of Texas at Austin (UTA) but we have measurement and theoretical expertise that complements expertise at Case.

This is research that would not have happened individually just because of the different skill sets and capabilities that are involved.

I think the students are really excited about the center because it offers a rather different kind of project than just a normal Ph.D. student would pursue. They really do have to interact with these other people, and we envision that UTA students will probably have to go to Cleveland and interact with people at Case, and that's an enriching experience that normally doesn't happen.

To make progress in science and technology, we really need both modes of operation—team and individual. We need an appropriate balance. There are some ideas that happen by only one mode or the other...

You can't be interdisciplinary until you're disciplinary. You have to learn your area first before you have anything to offer to interdisciplinary efforts.

Top: Donald Paul
Kenneth Singer

James Aldridge

Graduate student Ricardo Andrade with students

EDUCATION AND DIVERSITY

CLiPS diversity efforts are integrated in all areas of the Center, from the hiring of faculty and staff through the recruiting of graduate and undergraduate students.

One focus is the summer REU program, which attracts students from across the country to participate in CLiPS research at CWRU. These students work for ten weeks during the summer, often returning in succeeding years. "We have found that CLiPS REU student alumni can be good candidates for the Center's Ph.D. programs," says Pamela Glover, CLiPS executive director for education and planning.

Another focus is the interaction with CLiPS Affiliate Schools. These institutions have high academic standards but do not offer doctoral degrees in CLiPS fields. The Affiliate schools participate in collaborative research and educational activities with the center. This Affiliate pipeline is also a source of graduate school candidates for CLiPS. One such example is James Aldridge, who is in the Ph.D. program in Macromolecular Science and Engineering at CWRU. James engaged in CLiPS research when he was an undergraduate at affiliate Youngstown State University, and is an alumnus of the REU program.

CENTER FOR MICROBIAL OCEANOGRAPHY: RESEARCH AND EDUCATION C-MORE

CENTER LINKS MARINE MICROBES TO ECOLOGICAL PROCESSES

Established in August 2006, C-MORE is focused on a comprehensive understanding of the diverse communities of microbes in the sea: what their genes code for, how they work together to control the flux of energy and matter in the ocean, and how all of this may change in the future.

Above left: The Kilo Moana

Top: C-MORE Hale

Bottom: Micrograph of oceanic microbes. *Photo: Courtesy of Ed DeLong*

Located at the University of Hawaii, the center is focused on "linking genomes to biomes." So how do you connect the narrow focus of molecular genetics to the broad focus of ecology? With the "three Cs": collaboration, cooperation, and communication.

The ultimate goal of C-MORE is to achieve a new understanding of the role of microbes in global ocean processes. C-MORE represents a sustained effort to understand how the genetics of individual microbial cells are connected with the behavior of populations, and furthermore, to understand the roles different populations play in ocean biogeochemistry, and ultimately, in global ocean processes, including climate change.

Research at C-MORE depends on cooperation and collaboration among individuals whose diverse expertise includes microbial genetics, population ecology, biogeochemistry, satellite-based oceanography, ocean ecosystem modeling, engineering and instrument development, and many other disciplines. Each component of C-MORE research contributes to the "genomes to biomes" goal.

The center is headquartered at the University of Hawaii, led by center director David Karl. Investigators also are located at the Massachusetts Institute of Technology, Woods Hole Oceanographic Institute, Monterey Bay Aquarium Research Institute, the University of California, Santa Cruz (UCSC), and Oregon State University.

Many of C-MORE's researchers have been working together for more than 10 years, notes C-MORE research coordinator Edward DeLong of MIT. "In the end, the thing that will really make everything work together in a sustained way is a deep level of trust. And I think because we are all friends, colleagues, and scientific collaborators—and have been so over a good amount of time—we have already established that," he says. C-MORE researchers communicate daily through email, telephone, in-person conferences and teleconferences, aided by the state of the art communications capability of C-MORE Hale ("the house of C-MORE"), a new University of Hawaii building dedicated to the Center.

Microorganisms dominate the living biomass in the world's oceans, and just like humans, they contain genes which allow particular types of activities to occur, such as taking up different types of nutrients or performing photosynthesis. Because of the enormous diversity of different types of microorganisms in the ocean, and the fact that we cannot isolate most of them, an understanding of their genetic composition and capabilities comes from analysis of all gene sequences in seawater collected at different locations, a research approach known as metagenomics.

Samples collected from several locations during a C-MORE cruise between American Samoa and Hawaii have been analyzed by Jonathan Zehr, Karl, and colleagues. This region has several distinct types of oceanic habitats. Over a million fragments of genes were analyzed from these samples using a high throughput DNA sequencing technology. In another approach, MIT researcher Sallie W. Chisholm and colleagues have examined the genetic inventory of microbial cells. Chisholm's group uses a flow cytometer to sort individual cells based on their characteristic fluorescence as they pass through a laser beam. Each cell's genome--the DNA that encodes all of the genes that define the cell's ecological niche–is amplified in a way that provides enough DNA for genome sequencing. The approach can be focused on particular groups of microbes to understand their intrinsic diversity, or to look at the broad diversity of microbes. Along with metagenomics, this approach has uncovered an astounding diversity of metabolic pathways in uncultured bacteria–providing an unprecedented window into marine microbial diversity.

C-MORE scientists also study specific components of microbial communities. Matthew Church of the University of Hawaii and colleagues examined processes controlling the growth, diversity, and carbon removal of diatoms, among the most productive and wide spread of marine photosynthetic organisms. □

SCIENCE AT A DISTANCE

C-MORE DEVELOPS SEA-GOING SENSORS FOR MARINE MICROBIAL RESEARCH

The Environmental Sample Processor (ESP), suspended below a surface float, drifts in the open ocean with the R/V Western Flyer nearby. *Photo: Philip Sammet copyright 2010 MBARI.*

Traditional marine investigations all too often have required transporting samples to a laboratory for subsequent testing. What researchers really need is a sea-going instrument that could automate molecular analyses so that specific organisms, genes, and gene products could be analyzed easily in real time.

C-MORE partners have given life to this vision through the development of the Environmental Sample Processor (ESP). The ESP employs DNA and protein probe arrays along with the method of quantitative polymerase chain reaction (PCR) to analyze a wide variety of marine species and samples.

The instrument has been applied in the field on a variety of platforms including coastal moorings, a coastal pier, an open ocean drifter, research ships, and a benthic lander rated to a depth of 4,000 meters for use on deep-sea cable observatories. It supports two-way communications for transmitting results and downloading new instructions so that its mode of operation can be altered remotely.

"For the first time, ocean-observing systems that allow investigators to carry out interactive experiments and test hypotheses remotely from a molecular biological perspective are being realized," says C-MORE researcher Chris Scholin.

While Center investigators utilize the ESP in an open ocean setting to study microbial mediated cycling of nutrients and energy, other academic and government groups are currently evaluating the utility of the machine as a tool for augmenting water quality monitoring networks for ocean and freshwater systems. C-MORE, through the Monterey Bay Aquarium Research Institute, is loaning ESP instrumentation necessary to conduct these tests as one element of the Center's broader technology transfer portfolio.

A CONVERSATION WITH THE DIRECTOR

David Karl

University of Hawaii undergraduate students deploying instruments for spectral analysis observations.

Microbial oceanography is a field full of surprises. It seems every time scientists think they have it all figured out, they find out there's more to learn.

When C-MORE director David Karl graduated with a Ph.D. in 1978, he was ready to leave the field because he thought that we knew all there was to know about the ocean. "We'd been studying this for a hundred years. There were clever and intelligent people in the field and we had books and we had paradigms and we had models. And I thought all that there was left was to dot the i's and cross the t's—and I didn't like to do that kind of stuff. So I was thinking about going into some other field that might be more pioneering and more cutting-edge.

"Well, the year that I graduated, a group of scientists who are now part of our center discovered the second-most abundant group of organisms in the sea—before that, we didn't even know about these organisms. A decade later in 1988, the most abundant group of plants in the ocean was discovered.

"We established C-MORE in 2006 because we thought that a comprehensive, interdisciplinary, and collaborative approach was needed to make real progress in microbial oceanography. We have not been disappointed. Based on the extensive laboratory experiments, field observations, and ecosystem modeling conducted across the C-MORE institutions we are beginning to re-write the textbooks, but much more work needs to be done.

"New discoveries are likely as we move forward with the center. The next five years should be a thrilling experience."

Teacher using a sextant aboard a C-MORE cruise.

Deployment of the Environmental Sample Processor (ESP). *Photo: Philip Sammet copyright 2010 MBARI.*

MICROBIAL OCEANOGRAPHY BRINGS K-12 EDUCATION ALIVE

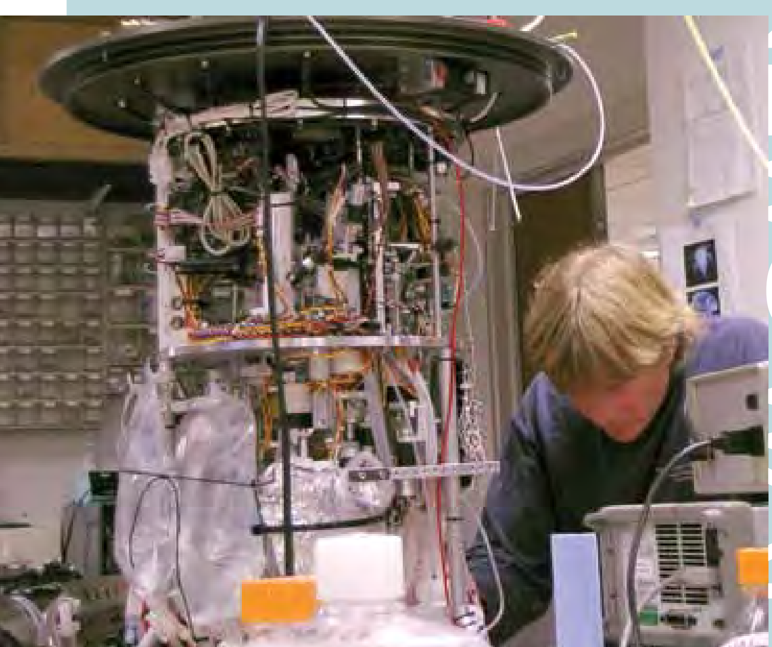
The ocean is an integral part of island life in Hawaii; teachers capitalize on this fact by using the interdisciplinary field of oceanography to teach students about biology, chemistry, and physics.

Hawaii's teachers want oceanography educational resources that they can bring into the classroom, especially those that incorporate the latest scientific research, says C-MORE Education Director Barbara Bruno.

An example is C-MORE Science Kits, which are rooted in C-MORE research and aligned with state and national education standards. Each kit contains lesson plans and all the equipment and supplies needed to conduct hands-on activities and labs on a particular topic in oceanography. They are available on loan free of charge throughout the Hawaiian Islands and at C-MORE partner institutions in California, Oregon and Massachusetts.

Teachers are also excited to participate in professional development experiences, such as research cruises. Each month, the Hawaii Ocean Time-series (HOT) program monitors the ocean's biogeochemistry at a deepwater site located 100km north of Oahu. Teachers are invited to participate on select cruises, where they work alongside HOT scientists to collect and analyze data. Teachers can communicate with their students while on board through a real-time Internet link.

C-MORE is committed to providing undergraduate research experiences, and is especially interested in serving underrepresented groups such as Native Hawaiians and Pacific Islands. C-MORE Undergraduate Scholars, most of whom are from underrepresented groups, conduct research in Hawaii during the academic year. During the summers, they can conduct research at a C-MORE partner institution, which can serve as a testing ground for graduate school. Once in graduate school, they have the opportunity to participate in a world-class summer course taught by C-MORE investigators.



Chris Scholin working on the Environmental Sample Processor (ESP) in the laboratory. *Photo: Kim Fulton-Bennett (c) 2006 MBARI*

GLOBAL CHANGE AND THE FATE OF THE OCEANS

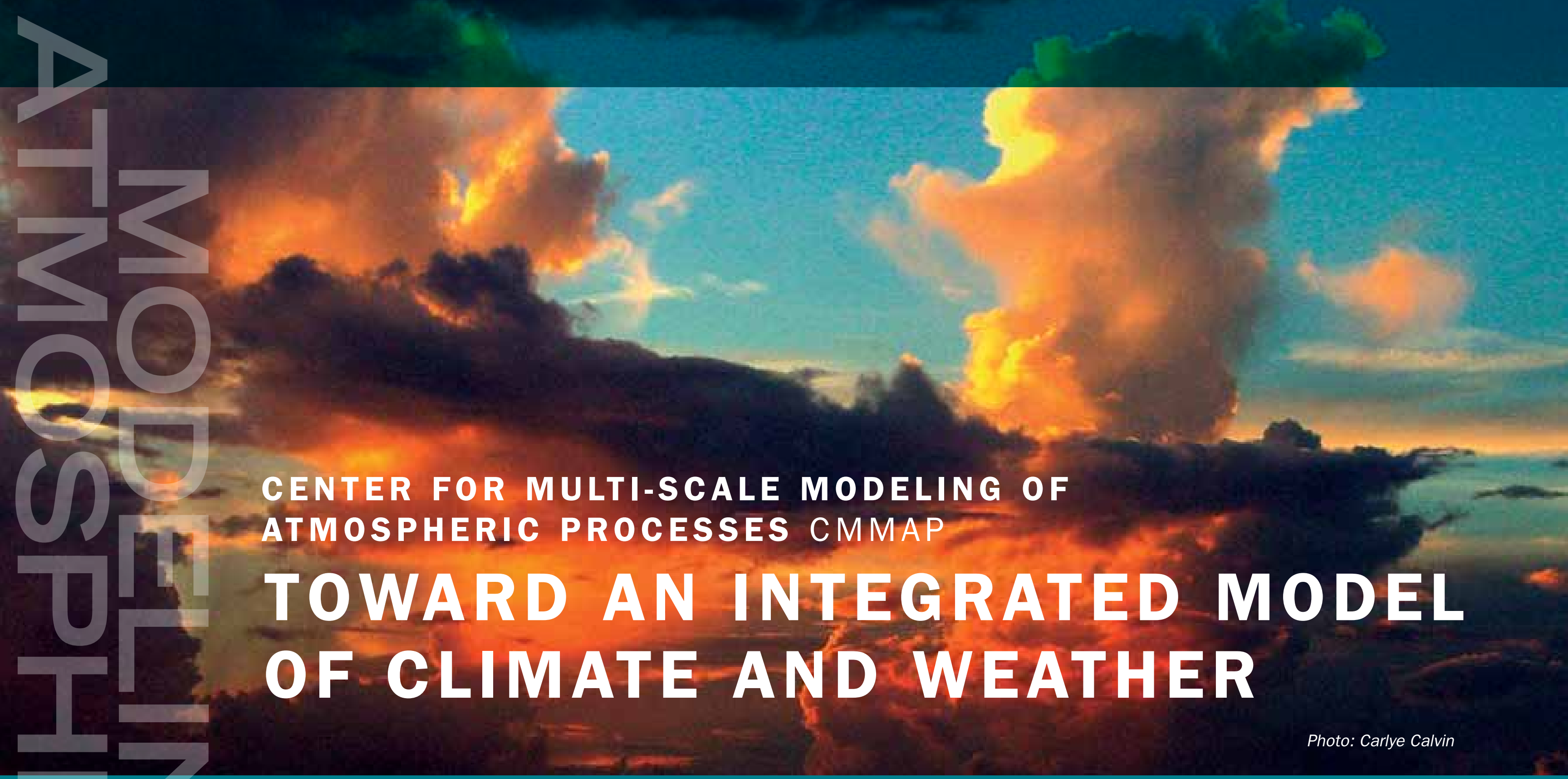
"Microbes are critically important to processes that influence climate change," says C-MORE associate director Paul F. Kemp, explaining that human reliance on fossil fuel combustion continues to increase atmospheric and oceanic CO_2 inventories, and the latter has made the oceans significantly more acidic.

"By the end of the 21st century, surface ocean pH is expected to drop by 0.3 pH units," says Kemp. "It remains unclear how such changes will influence ocean ecosystem structure and processes, or how the various components of the pelagic food web may affect marine elemental cycles in an increased pCO_2 world."

Center investigators are examining how marine nitrogen-fixing bacteria respond to changes in CO_2 in seawater. "These species play a pivotal role in ocean ecology by providing a biological source of new nitrogen to large parts of the ocean, and we are only beginning to understand what controls their distribution and abundance," she says.

In a CO_2-rich world, the dominant marine microorganisms and associated processes may be different than what we see today," says Kemp. "Collaborative studies within C-MORE will greatly improve our ability to predict the fate of a future ocean."

MODELING OF ATMOSPHERIC PROCESSES



CENTER FOR MULTI-SCALE MODELING OF ATMOSPHERIC PROCESSES CMMAP

TOWARD AN INTEGRATED MODEL OF CLIMATE AND WEATHER

Photo: Carlye Calvin

Critical mass can be defined as an amount necessary to have a significant effect or to achieve a result. For scientists in the field of atmospheric science and climate change, the creation of the Center for Multi-Scale Modeling of Atmospheric Processes (CMMAP) provides the critical mass needed to tackle fundamental problems that have remained mysteries for far too long.

CMMAP's research and knowledge-transfer goals are to improve climate and weather forecasting for scientists around the globe by building atmospheric models that will more accurately describe cloud processes than anything developed thus far.

Established in July 2006, and based at Colorado State University in Fort Collins, CMMAP is a partnership of nine degree-granting institutions and many additional collaborators. The center brings together scientists from a broad range of disciplines to work towards this common goal. In addition, like all STCs, its mission goes beyond research to include a range of education and diversity programs.

The center is undertaking work on many of the same atmospheric science topics that scientists have been targeting for years. What sets the center apart, however, is the scale at which they are able to tackle these issues. "We're using new mathematical methods to simulate in the computer the way the clouds interact with the global circulation of the atmosphere, relying on extremely powerful computers in a way that wasn't possible before," says center director David Randall. Today, many of the world's major modeling centers are moving quickly to develop such capabilities, he notes.

With enough computing power, center researchers are developing the ability to actually simulate individual clouds and atmospheric circulation. This critical mass in computing power and resources is allowing the center to tackle several phenomena that scientists have long sought to understand. The end results include improved understanding of important climate phenomena, such as the Asian Monsoon, a seasonal reversal of winds in the Northern Hemisphere.

Scientists go through multiple phases in their research, first developing a new model that will more accurately represent the atmospheric effects of interest and evaluating the model based on comparisons with actual observations, and then eventually applying the model to understand how clouds interact with global systems like oceans and land surfaces. Projects range from the macro to the micro scales: everything from observations of entire weather systems to the properties of individual ice crystals.

Until now, groups of research studying these phenomena have had trouble communicating because there weren't global models that took into account data sets from these different scales.

Historically, modeling has been done in roughly three levels of granularity, or resolution: global climate models, which operate on the scale of thousands of kilometers; cloud system resolving models, which represent processes between 1 and 500 km in scale; and large-eddy simulation models representing individual clouds on a scale between 10 m to 1 km. These distinctions in resolution are done for practical purposes and have little to do with the existence of actual differences in nature. Center researchers are trying to incorporate information from these different scales into one unifying model. □

AN INTERVIEW WITH CENTER DIRECTOR
David Randall

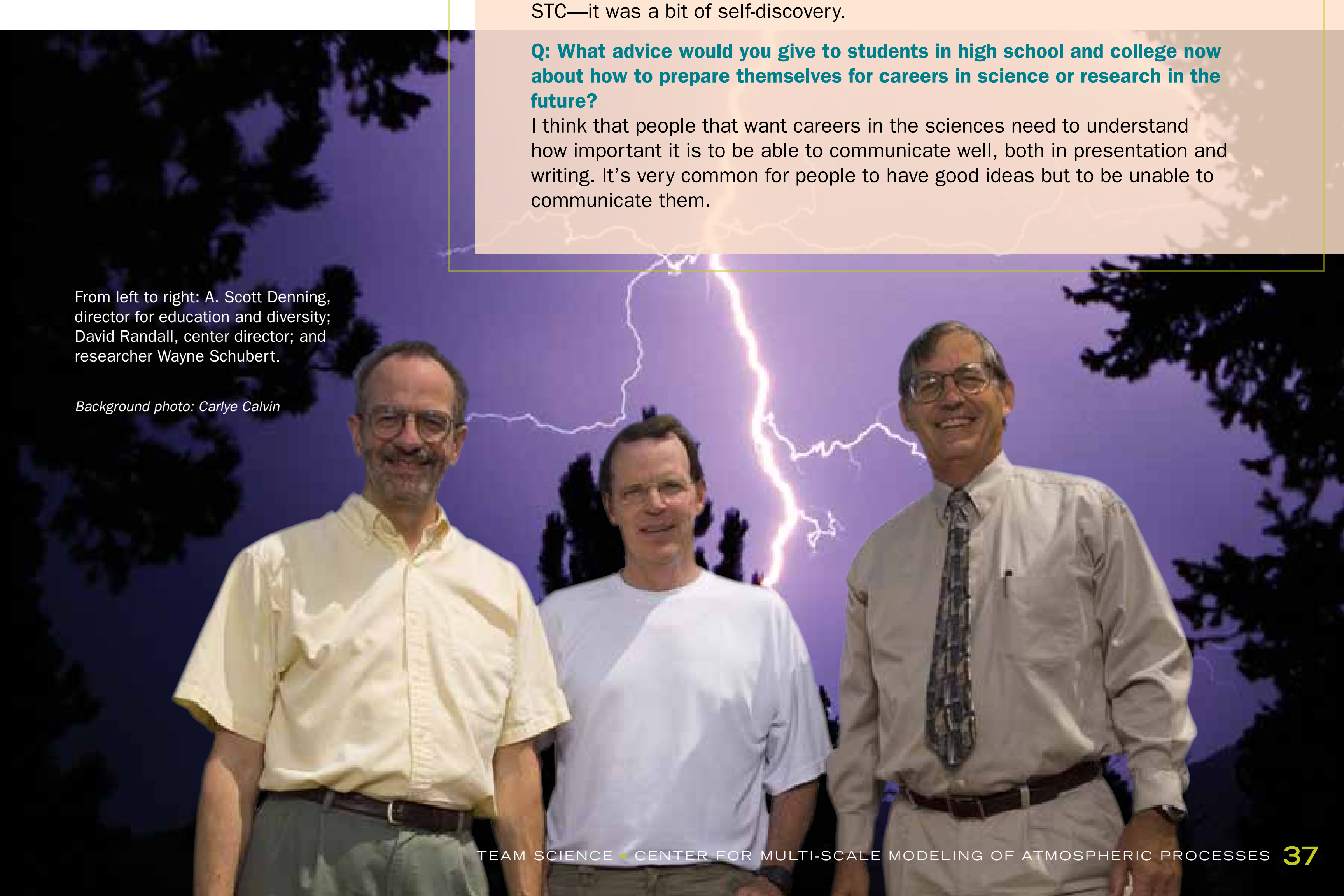
Q: What should the public know about interdisciplinary centers?
NSF has struck a good balance between single principal investigator projects and the centers. Most NSF money goes to single-PI projects, but we need larger centers to attack the bigger problems.

CMMAP is a center, not a project, in part because it brings together scientists from a broad range of disciplines at dozens of institutions. The team includes climate modelers, cloud modelers, and experts on turbulence, radiation, cloud physics, and observations. In addition, like all STCs, its mission goes far beyond research. CMMAP devotes enormous amounts of time and energy to its education and diversity programs.

Q: How do you view the interaction between research and education in the center?
STCs are special because they aim to change a whole field of research, and because they provide an opportunity to combine research and education in creative and interesting ways. With the perspective that comes from almost four years of nurturing the center, we can see that CMMAP's education mission is highly complementary to its research and knowledge transfer missions. Our education activities make our research activities work better, and vice versa. The interdisciplinary collaborations within the Center allow us to accomplish more than either component could do separately.

Q: How did you get to this point in your career?
It's not what I expected. When I took my faculty position in 1988, I came from a job in NASA. I thought that I'd get my feet under me and I'd have three or four grad students and a postdoc and that would be my lifestyle. It turns out that's not my natural mode of operation, and I found that out as it happened. I apparently tend to naturally build these collaborations, these structures like the STC—it was a bit of self-discovery.

Q: What advice would you give to students in high school and college now about how to prepare themselves for careers in science or research in the future?
I think that people that want careers in the sciences need to understand how important it is to be able to communicate well, both in presentation and writing. It's very common for people to have good ideas but to be unable to communicate them.



From left to right: A. Scott Denning, director for education and diversity; David Randall, center director; and researcher Wayne Schubert.

Background photo: Carlye Calvin

Above: Little Shop of Physics director Brian Jones, a CMMAP education partner, and a group of students use a fish tank full of gelatin to demonstrate light scattering in the atmosphere and why the sky is blue. Jones is the 2011 recipient of the Robert A. Millikan Medal given by the American Association of Physics Teachers to recognize educators who have made notable and creative contributions to the teaching of physics.

Photo: University Corporation for Atmospheric Research

CMMAP EDUCATIONAL PROGRAMS REACH DIVERSE AUDIENCES

As CMMAP looks to improve education in climate science at all levels, CMMAP scientists and educators are also looking at fresh and novel ways to connect with a diverse range of students, teachers, and communities.

Broader education is very much a part of CMMAP's strategy. The center has the advantage of being situated at Colorado State University, where there is already an active educational outreach program called the Little Shop of Physics, directed by physics education guru Brian Jones, which provides hands-on experiments to K-12 students.

Because Little Shop of Physics (LSOP) involves undergraduate students at CSU, the effort delivers a double impact. "The undergraduates have lots of face time with the kids, learning about teaching and learning about working with schools," says CMMAP education and diversity director Scott Denning. "We're delivering the material, but we're also developing science educators."

Denning and Jones have developed a 2-credit course on Weather and Climate for Teachers that combines advanced undergraduate content with pedagogical innovation and a library of classroom inquiry modules to give teachers the tools they need to succeed. The course has so far been offered to 170 K-12 teachers over five summers, and is available as a "kit" including all science content, media, and inquiry activities at http://www.cmmap.org.

The CMMAP-LSOP team is forging new connections with Native American communities that are traditionally underrepresented in math and science fields. Each week of the academic year, the LSOP team of undergraduate interns and professional educators takes a van of hands-on instructional materials to schools. Over school breaks, the team makes extended trips to the Navajo, Southern Ute, Moutain Ute, Shoshoni, Arapaho and Lakota reservations.These trips are conducted in partnership with Colorado State University's Native American Cultural Center (NACC).

Scott Denning is in the forefront of this photo, where outreach participants "bounce" around like molecules inside a box.

CENTER RESEARCH SHEDS LIGHT ON THE ASIAN MONSOON

The Asian monsoon is a seasonal reversal of winds that brings copious rain to the densely populated regions of India and Southeast Asia during the northern hemisphere summer. Monsoon rain is characterized by a cycle of heavy rainfall interspersed with comparatively dry spells. The cycle repeats about every 30 to 50 days.

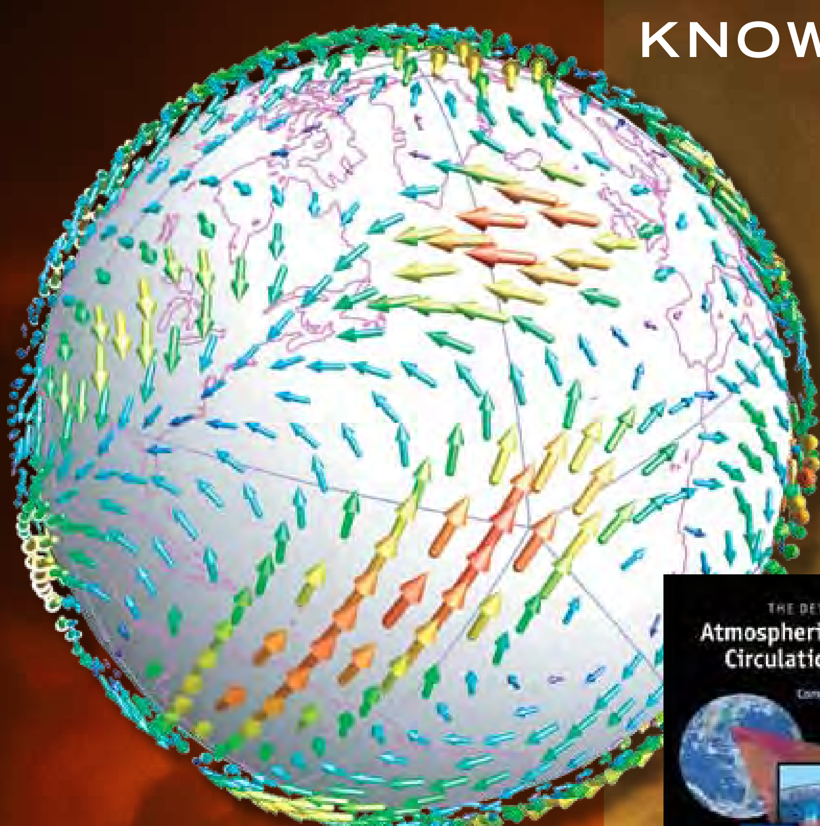
Despite recent advances in our understanding of what causes rainfall onset and dry periods, the simulation of the monsoon using atmospheric circulation models remains a challenge, notes Charlotte DeMott, CMMAP research scientist.

Most models can simulate the summertime average distribution of rainfall over India and Southeast Asia, but they struggle to simulate the wet-dry cycle of precipitation. In other words, monsoon rainfall in the models happens too frequently and too gently compared to the real world, where torrential rains fall for 1-2 weeks every 4-5 weeks.

"Scientists have understood for some time that the way models represent convection–that is, thunderstorms and other cloud types–is the likely culprit for the poor simulation of the monsoon," says DeMott. "These clouds are simply too small and evolve too fast for models to track them individually over the entire globe, even when the models are run on the world's fastest and biggest computers. Most models instead calculate the average effects of these clouds over areas of about the size of Connecticut, without modeling the clouds themselves."

CMMAP has developed a new way of representing convection. "Instead of trying to model all of the clouds everywhere and all of the time, we asked 'What if we just model some of the clouds everywhere and all of the time?'" says DeMott. "This is a job that modern super computers can handle. When we ran our model with these kinds of clouds, we found that simulated monsoon rainfall occurred with the expected wet-dry cycle. This type of model is now being tested to see if it can be used to improve forecasts of monsoon precipitation."

KNOWLEDGE TRANSFER



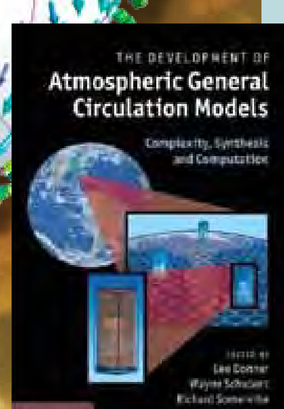
Sphere image: Ross Heikes

THE CMMAP LEGACY

CMMAP is working to disseminate information on a broader scale, beyond the formal education programs in place.

The Center's project to create a book, "The Development of Atmospheric General Circulation Models: Complexity, Synthesis, and Computation," is now completed, leaving an important legacy that documents the roots and evolution of the field of atmospheric science. Editing and final formatting were completed at the end in 2010 and the book was published by Cambridge University Press and made available to the public in January 2011. The Center acknowledges "the tremendous effort and attention to detail provided by Leo Donner that helped make this project a success."

And a journal launched by the Center in 2009 is now being published by the American Geophysical Union. Called the Journal of Advances in Modeling Earth Systems (JAMES), it is the first open-access journal to be published by AGU. Center Director David Randall, professor of atmospheric science at Colorado State University, continues as editor.



REMOTE SENSING

CENTER FOR REMOTE SENSING OF ICE SHEETS CReSIS

CENTER PUTS ICE SHEETS ON THE CLIMATE CHANGE RADAR SCREEN

Fernando Rodriguez inspects an antenna installation. *Photo: Cameron Lewis*

Top in background: Satellite view of broken sea ice. *Photo: CReSIS*

Left to right: Associate Director of Science David Braaten and Center Director Prasad Gogineni in Antarctica

> **"Polar ice sheets are changing significantly," says Prasad Gogineni, director of the Center for Remote Sensing of Ice Sheets (CReSIS). "Some of these changes have never been observed in human history. We really don't know why they're changing, what is causing these changes—that is really what we're trying to understand."**

Headquartered at the University of Kansas (KU) in Lawrence, Kan., the Center for Remote Sensing of Ice Sheets (CReSIS) takes as its focus one of these largest gaps of knowledge in the field of climate change research: how collapsing polar ice sheets contribute to sea level rise.

Toward this mission, the Center has developed radar systems and other new technologies to map the polar ice sheets to a depth and scale never accomplished before. The researchers have already begun collecting data to drive models for better prediction of this poorly understood consequence of global climate change.

"How fast and how much sea level is going to rise—that's in a nutshell what we want to know," says David Braaten, Associate Director of Science for CReSIS.

Indeed, the 2007 report by the assembly of scientists and officials known as the Intergovernmental Panel on Climate Change (IPCC) finds ice sheet changes to be an area of concern for further research. The report acknowledges that current models would not have predicted the extent of increase in ice sheet melting that has been observed within the last decade.

As a world-class research center dedicated to the study of the polar ice sheets, CReSIS is playing a central role in filling this information gap and assessing the potential effects of melting-induced sea level rise on human populations.

"Even one meter of sea level rise would affect about 100 million people worldwide," says Prasad Gogineni, CReSIS Director. "There's no way to make a good estimate about sea level rise because we don't know enough yet about the behavior of the ice sheets," adds Braaten.

Mapping Uncharted Territories

In order to understand how an ice sheet moves, scientists essentially need to map its top, bottom, edges, and interior. They need to understand what is going on at the surface of the ice where new ice is accumulating, what the layers inside the ice reveal about its past movement, what is happening at the sides that might constrain the ice, and what the ice is flowing over—if it is ground, what the surface is like; if it is fluid, how much this helps the flow of the ice.

Since its launch in 2005, one of the Center's greatest achievements has been its success with synthetic aperture radar (SAR)—a system that can penetrate deep ice to provide a high-resolution record of the bed underneath. Work by CReSIS in Greenland was the first to use this technology successfully through roughly three kilometers of ice, and CReSIS work with SAR radar was recently highlighted by *IEEE Spectrum* magazine.

"Understanding what's happening at the ice bed is extremely important," says Gogineni. "Right now there are not many tools available to do that over large areas."

As the radar passes over the ice—either on the surface or in the air—the radar casts its signal at an angle downward and records the reflected returns in a top-view swath of what is just to either side of the radar's path. By sweeping lawnmower-fashion back and forth, the researchers can put the swaths together and map a large area.

Much of the CReSIS fieldwork to this point has involved proof-of-concept exercises with this technology and initial ground-based surveys. But the goal is to soon put the radar on uncrewed aerial vehicles (UAVs), which can cover more area more quickly. Researchers first tested aerial "drones" in Greenland in 2008, and then also on Antarctic ice sheets in 2009. The Meridian UAV recently underwent testing with CReSIS radar in Greenland and successfully sounded ice from the runway.

Additionally, researchers affiliated with the Center are already creating data sets using depth sounder radar and seismic surveys to map the ice and ice beds in cross-sections downward. They are working with satellite data to analyze the velocity of ice movement. They are further developing existing sensor systems to survey large areas remotely.

Team Science for Timely, Coordinated Research

Much of the work on developing new technologies takes place back at the universities within the CReSIS partner system. Work on such projects as the design of aerial drones and miniaturized systems to be carried on aircraft require the coordination of engineers and scientists from various fields. This coordination also provides opportunities for a wide range of students at the undergraduate and graduate levels.

CReSIS researchers and students come together from the fields of aerospace, electrical engineering, computer science and engineering, geology, geography, and even education. Universities partnering in CReSIS include KU; Elizabeth City State University, a historically African-American university in North Carolina; the Indiana University; the University of Washington; the Pennsylvania State University; Los Alamos National Laboratory; and the Association of Computer and Information Science Engineering Departments at Minority Institutions. CReSIS also collaborates with various industry and international partners.

"The greatest advantage of the Center is that it brings together the engineers, the people who go into the field, and people like myself who take the data and analyze it," says Kees van der Veen, a professor in the department of geography at KU.

Braaten notes that the Center brings people together more often than would happen if they only met at periodic conferences and meetings. This efficiency also serves a greater purpose because of the time-sensitive nature of research on sea level rise. "It's not something we can wait twenty years to solve," he says. □

HANDS-ON RADAR SIMULATOR

In October of 2010, CReSIS participated in the USA Science and Engineering Festival in Washington, D.C. One of 15 NSF organizations chosen to attend the event, CReSIS was the only representative from the state of Kansas and featured a radar simulator designed to give interested participants the chance to fly a model of the Meridian aircraft over a block of simulated ice and view the radar results on a computer screen. The exhibit allowed participants to observe the way in which fast 2-D motion results in 3-D imaging and sounding and demonstrates other aspects of radio-glaciology.

While the Expo marked the first time CReSIS offered a hands-on demonstration of radar to children, the exhibit will be redesigned to be portable, enabling more interactive outreach opportunities for the Center. CReSIS plans to develop a traveling display of both the radar simulator and the UAV controls platform that can easily be transported to schools around Kansas, as well as to the Center's partner institutions, allowing students across the country to get a glimpse of all CReSIS technologies.

CReSIS Deputy Director Carl Leuschen performs in-the-field repairs to the depth sounder at Byrd Camp, Antarctica in 2010.
Photo: Cameron Lewis

Below: Radar depth sounder antenna array mounted below the Twin-Otter wing during flight operations in Antarctica in 2010.
Photo: Cameron Lewis

Photo: Thomas Overly © 2006

MEET THE DIRECTOR

Prasad Gogineni

Prasad Gogineni began work on remote sensing of ice sheets in 1992. This work gradually led to the predecessor program for CReSIS, called the Polar Radar for Ice Sheet Measurements (PRISM) project.

Gogineni credits time at NASA with insights into writing largescale proposals and managing large projects. In his current program, he continues to enjoy working with students, and sees great promise for CReSIS in the years ahead.

"I am very excited about what the Center can do—I really feel that we are on the cusp of a breakthrough to make major advances in glaciology and modeling of the ice sheets."

Middle school students conduct an experiment at CReSIS partner institution Elizabeth City State University in North Carolina in 2011.
Photo: Cheri Hamilton

MODELING AND 3D TOPOGRAPHY

The Center's long-term goals are to characterize ice thickness and bed topography in rapidly changing ice-sheet regions, develop diagnostic and predictive ice-sheet models, and contribute to future assessments of sea level change in a warming climate.

To achieve these goals, the Center uses the data gathered by radars and seismic instruments in conjunction with satellite data to implement models that can identify the processes responsible for abrupt changes in the ice sheets. The Center's Modeling Team consists of groups at the University of Kansas (KU), the Pennsylvania State University (PSU), the University of Washington (UW) and Los Alamos National Laboratory (LANL). These modeling efforts are supported by Indiana University, Elizabeth City State University (ECSU) and Polar Grid.

To assist modeling efforts that need detailed bed topography, CReSIS produces fine-resolution 3-D topography maps generated from data collected using synthetic aperture radars (SAR). The science community has already begun to use detailed bed topography maps generated by CReSIS to explain some of the rapid changes that have been observed.

CReSIS ice thickness and bed topography work was recently highlighted in National Geographic Magazine. CReSIS graduate student Josh Meisel and his CReSIS research provided data for National Geographic's June 2010 issue, as well as an online interactive feature on climate change at the poles entitled "Greenland's Vanishing Ice." The terrain under the ice sheets is the final frontier for mapping the earth's surface.

CReSIS GEARS UP TO TAKE TO THE AIR

Having deployed radar technologies on ground-based vehicles and aerial missions during 2008 and 2009 in Greenland and Antarctica, CReSIS will continue aerial surveys in 2011 and 2013. "For basin-scale work, you really need aerial surveys," says CReSIS Associate Director of Science David Braaten. Aerial surveys are planned for both Greenland and Antarctica, utilizing the NSF Twin Otter and the CReSIS-developed UAV.

NEWS WATCH

Glacial ice from Greenland reaches the ocean in 2005.
Photo: Leigh Stearns

SECURE TECHNOLOGY

TEAM FOR RESEARCH IN UBIQUITOUS SECURE TECHNOLOGY TRUST

CENTER TACKLES GRAND CHALLENGES IN CYBERSECURITY

Computing technologies are part of our nation's critical infrastructure. They form a part of everything from financial systems and the energy grid to healthcare, telecommunication, and transportation systems. Enhancing cyber security and computer trustworthiness is therefore of increasing importance as a scientific, economic, and social problem.

In response to this need, the Team for Research in Ubiquitous Secure Technology (TRUST) aims to transform the ability of organizations like software vendors, utilities, and government agencies to design, build, and operate trustworthy information systems.

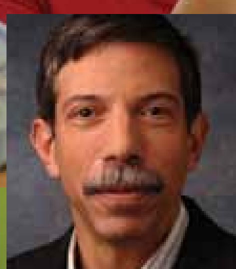
Headquartered at the University of California, Berkeley, and led by center director S. Shankar Sastry, the center is working to catalyze collaboration between computing experts, social scientists, and the legal and policy communities to strengthen the security and trustworthiness of our nation's computing and critical infrastructures. Academic partners in TRUST with UC Berkeley include Carnegie Mellon University, Cornell University, San Jose State University, Stanford University, and Vanderbilt University.

Sastry, whose research is in the area of secure sensor networks and network defense, is a professor in the Departments of Electrical Engineering and Computer Sciences and Bioengineering at the University of California, Berkeley and is the NEC Distinguished Professor of Engineering and the Dean of the College of Engineering.

Researchers at TRUST are working on three major research thrusts aimed at improving the trustworthiness of information systems for the nation's critical infrastructures, including the financial sector (banking and financial services), healthcare delivery (health IT systems and medical data), and physical infrastructures (power, water, gas, telecommunications). "The theme of the center is restoring trust to all infrastructures: physical, electronic, and information," says Sastry.

Over the last decade, the world has seen a rapid increase in computer security attacks at all levels, from the so-called "phishing" scams that lure people into revealing sensitive information to Internet attacks that paralyze Web sites. The center has developed many kinds

Kenneth Birman, computer science professor at Cornell University



Fred B. Schneider, computer science professor at Cornell University and chief scientist of TRUST

Steve Wicker, Cornell University

CRITICAL INFRASTRUCTURE PROTECTION

Critical infrastructure, including power plants, water systems, and electric power networks, are controlled by devices that measure parameters of the system and activate controllers. Those devices are referred to as SCADA (Supervisory Control and Data Acquisition) networks and Industrial Control Systems (ICS). "Control systems are at the heart of our nation's critical infrastructure," says Sastry. "As such, we feel it is vitally important that existing networks are secured and next-generation infrastructure is designed, developed, and deployed to ensure trustworthy, high-confidence operations."

To this end, the center's work on secure sensor networks responds to the need to build a new generation of technology to control our nation's physical infrastructure. TRUST researchers have developed models of attack and corresponding solutions, leveraging traditional security concepts but also areas such as game theory, says Sastry. These solutions are built into the infrastructure systems as security safeguards. Prototypes and software are now being transferred into practice, starting with oil and gas networks and power networks.

At the same time, the center is exploring privacy concerns with emerging technologies in areas such as energy consumption. TRUST researchers at Cornell, led by Stephen Wicker, professor of computer and electrical engineering, are addressing such concerns through novel system architectures that enable the benefits of emerging technologies such as Advance Metering Infrastructure (AMI) while protecting individual consumer privacy. "We are developing a set of privacy-aware design practices for next-generation infrastructures such as demand response," says Wicker. "While there are many related technical and policy issues, we see this work serving as a roadmap for embedding privacy awareness into information networks."

of improved technologies to combat phishing, spyware, botnets, and related threats. But new technologies are only part of the answer.

"The solutions to today's cyber security ills or trustworthiness problems are not going to come only from the technical side or from the policy side of the house—but rather, from both sides working together," says Fred B. Schneider, computer science professor at Cornell University and chief scientist of TRUST.

These advances may come from research in computer science and engineering—but "sometimes the answer involves changing the law instead of changing the technology," says Kenneth Birman, computer science professor at Cornell. For example, TRUST researcher and School of Information professor Deidre Mulligan of UC Berkeley worked closely on California legislation that requires companies to track down and inform anybody whose private information was disclosed as a result of company negligence. The law passed, and now many other states have enacted similar legislation. Recent TRUST policy work is addressing issues such as paths to identity theft, privacy in social networking and social media, and the use of web browser tracking technologies for targeted advertising. In such areas, TRUST is conducting research that is addressing technology and policy by crafting solutions that address both business functionality and privacy.

When the center started, the kind of connections between legal scholars and technology researchers was relatively rare, says Sastry. "Now, each one of the partner campuses has an activity in terms of public policy, public health, or social sciences rolled into their agenda which adds to the richness of the issues being discussed," says Sastry. "It's gratifying to see all the wonderful links and connections that wouldn't have happened without the center."

Another planned legacy of the center is the establishment of a science base for security to move computer security from a reactive to proactive mode and beyond deploying defenses for known attacks but building secure systems in a principled way. The goal of such a "science of security" is to create networks where security is not an afterthought. According to Schneider, such a science of security "would articulate and organize a set of abstractions, principles, and trade-offs for building secure systems, given the realities of the threats and of our cyber security needs." Adds Sastry, "these new capabilities will require the architecture of the infrastructure to change. The idea is that what ultimately replaces them will be more secure and resilient."□

Deirdre Mulligan, TRUST policy director and professor of information at the University of California, Berkeley

EDUCATING THE NEXT GENERATION OF CYBERSECURITY EXPERTS

TRUST education director Kristen Gates

Educational efforts at TRUST, led by Kristen Gates, place an emphasis on enhancing the experience of undergraduate and graduate students by bringing them into contact with leaders in cyber security. “Not only are we helping to educate and inspire students but we’re also helping to energize and invigorate younger faculty that are bringing these cyber security and technology issues into their classrooms at our partner institutions,” she notes.

A core program of the center is its Research Experiences for Undergraduates (REU). This eight-week program held annually in the summer offers talented undergraduate students from across the country the opportunity to gain research experience. The center places undergraduate students in cohorts at all partner campuses, working with a faculty advisor and graduate student mentors on topics directly related to TRUST research thrusts. “The REU students were enthusiastic, motivated, and jumped right into the research,” says Berkeley law professor and TRUST-REU faculty advisor Chris Hoofnagle, whose REU students researched online tracking techniques. “They were quite successful at uncovering practices that raised a number of privacy issues,” says Hoofnagle. “Their work was covered in the press but, more importantly, resulted in privacy improvements on some of the Internet’s most popular websites.”

TRUSTED HEALTH INFORMATION SYSTEMS

Janos Sztipanovits, Vanderbilt University

TRUST researchers Janos Sztipanovits and colleagues at Vanderbilt University are involved in efforts to develop secure and trustworthy health information systems. Given the nature of these systems, there is an inherent tension between the goals of providing access to information to those who ought to have it, and protecting information from those who ought not to have it.

“Because Vanderbilt is at the forefront of this research nationally, we have a unique window into a laboratory where cutting edge work is going on,” notes Schneider.

A health portal at the Vanderbilt medical school with thousands of patient records has been made available to TRUST as a test bed for research on access and privacy issues. Called “MyHealthAtVanderbilt,” the system is one of the largest operational healthcare portals in the world, according to the center. “MyHealthAtVanderbilt” gives patients secure messaging with their providers. They can make appointments online and see the contents of their medical records.

More broadly, TRUST researchers are working on things such as a theory of privacy that is amenable to automation. “The challenge is to help organizations understand how to treat sensitive data, what they can and can’t use it for, and how to track its use,” says John Mitchell, Stanford principal investigator and professor of computer science. “We want to help organizations build information systems a with a privacy policy that helps them manage sensitive information correctly.”

John Mitchell, Stanford University

A CONVERSATION WITH THE DIRECTOR

Shankar Sastry

When it comes to cybersecurity and computer trustworthiness, “the problems are so big, there is not the talent in any one university to put this together. So I thought we needed a coalition,” says center director S. Shankar Sastry.

“I’m operating on a sense of conviction that the science and technology is important, but getting it out before it’s too late is as important. That requires people with research credentials who are also committed to transitioning results to stakeholders.

“Some researchers feel they come up with the best technologies and they just throw it over the wall, and then they get frustrated the world doesn’t change.

“But the reason it doesn’t is that there are important social, legal, economic, privacy considerations that do need to be addressed. And I think an STC is a place to do that.”

“The STC is also enabling researchers to think broadly about projects of national importance. For example, we are working to advance a science base for security—a means of moving computer security from a reactive mode to a proactive mode, taking the field beyond the current approach of deploying defenses for known attacks to building secure systems in a principled way.”

> “The problems are so big, there is not the talent in any one university to put this together. So I thought we needed a coalition.”
>
> — SHANKAR SASTRY

WEB BROWSING: TO TRACK OR NOT TO TRACK

The Internet makes available large amount of information to anyone, anytime, usually for free. While beneficial to users, organizations that produce and make available that content incur costs in doing so. Thus, most websites make use of online advertising. To maximize the effectiveness of advertising, many websites track the activities of users who visit their sites, often by using “cookies”—small files stored on users’ computers—to capture that information.

This presented an interesting opportunity for TRUST researchers to address privacy concerns of end users and policy issues about what information websites should collect and how it is used.

“The political consensus was, if you don’t want to be tracked you can take steps to opt out,” says Chris Hoofnagle, a TRUST researcher and Berkeley law professor. Awareness of issues in this area by TRUST and others led to web browser features that allow users to limit or prevent the storage of cookies from websites.

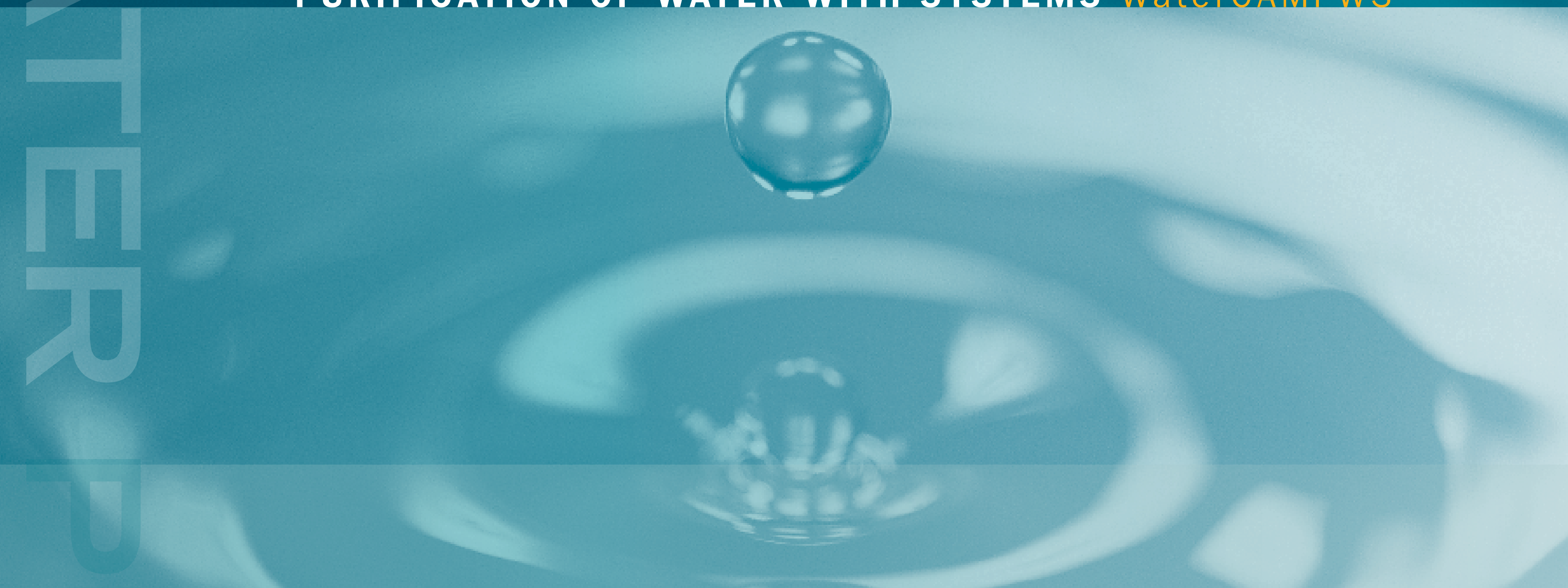
Lately, though, websites have made use more sophisticated means of tracking that circumvent conventional web browser cookies, for example employing software that “respawns” browser cookies that have been deleted by the user. TRUST research in this area highlighted such practices, prompting a number of popular websites to change their tracking activities and privacy policies. “All of this is about is whether your technical actions, your privacy-seeking behavior, will be affected by advertisers,” says Berkeley’s Hoofnagle. “It’s a major issue that will get more and more attention in the months ahead.”

Related research at Stanford by Jonathan Mayer and Arvind Narayanan, security researchers working with professor John Mitchell, has led to the development of web browser technology that supports a “do not track” mechanism—a means by which web browsers tell websites and online advertisers not to track their activity. “People get creeped out by some of the advertising that happens online,” says Mayer, who, along with Narayanan has created software that can be installed as an add-on to web browsers and is working on ways web servers can process request by users not to be tracked.

This work has not only raised public awareness of online tracking activities, but it has gotten the attention of the Federal Trade Commission and Obama administration, which is pushing for legislation that would compel organizations and online advertisers to respect opt-out mechanisms. “We’re really excited about what we’ve created,” says Mayer. “Do Not Track has the ability to make a meaningful impact in the protection of online privacy.”

WATER PURIFICATION

THE CENTER OF ADVANCED MATERIALS FOR THE PURIFICATION OF WATER WITH SYSTEMS WaterCAMPWS



A LEGACY OF WATER

Safe and abundant water is a basic requirement for every aspect of human health and an essential component of many human activities. However, decreasing water quality and increasing water scarcity and cost are threatening the health and well-being of people worldwide.

The quality of existing water sources is being compromised by water-borne pathogens from inadequate sanitation, toxic compounds from industrial wastes, pharmaceutical compounds introduced into water systems, agricultural practices, heavy metals in aquifers, and toxic disinfection byproducts from the water treatment process. Aquifers are suffering from declining water levels, saltwater intrusion, and inadequately replenished fresh groundwater. Major river systems are experiencing periodic water shortages because of declining snowpack storage and the loss of glaciers. The competing and ever-increasing demands on limited water supplies of energy production, agriculture, and industry are increasing water scarcity, pushing up water costs, and threatening economic development.

Addressing these complex issues to ensure the availability of clean, abundant water for human use is one of the most critical problems facing the U.S. and the world, says Mark Shannon, director of the WaterCAMPWS. Fortunately, the development and application of new technologies offers some important solutions.

For almost 10 years, the research mission of the WaterCAMPWS, headquartered at the University of Illinois at Urbana-Champaign (UIUC), has been to increase the supply of potable water through the development of novel ideas and the facilitation of supply-enhancing technologies. Team science efforts, organized around the dual themes of water and health and water and energy have focused on the technologically promising areas of desalination and reuse, disinfection, and decontamination.

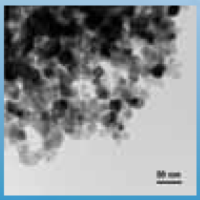
The WaterCAMPWS is currently in its final year of a ten-year funding cycle, and the results of the Center's sustained research efforts clearly demonstrate the value of team science. Significant results range from important additions to the body of fundamental knowledge that are essential for future breakthroughs in water science to the development of devices that will immediately and directly benefit the public.

One such research result is a type of sensor called the catalytic beacon, developed by the Yi Lu research team and their collaborators at the WaterCAMPWS. Yi Lu is a professor of chemistry, biochemistry, and physics at UIUC. This technology is a general platform for detecting a wide range of metal contaminants. A DNA sensor can be made to recognize a particular target with up to million-fold selectivity compared to other metal ions in the water. The sensors are biocompatible and biodegradable, so the technology is environmentally benign. A device using this technology has been transitioned into commercial production via a start-up

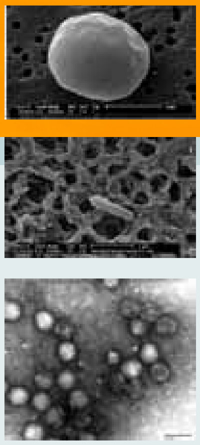
THREATS TO AMERICA'S WATER SUPPLY

More details can be found at http://www.watercampws.org/index.php?menu_item_id=8

- Increased demand by energy production
- Agricultural run-offs, such as:
  - Nitrates
  - Herbicides
  - Phosphates
  - Hormones
  - Pesticides
- Leaching of radioactive materials and heavy metals
- Depletion of aquifers
- Contamination of aquifers by:
  - Salt water
  - Pollution
  - Toxins



TiON nanoparticles. Nitrogen-doped titanium dioxide shows promise for photocatalytic water disinfection. *Image courtesy of Jian-Ku Shang, materials science and engineering, UIUC.*



Disinfection Targets: Waterborne pathogens (top to bottom: protozoa, bacterial spores, viruses) are a major cause of disease/death in developing countries, and an emerging threat to public health in the U.S.

company, DzymeTech. The approach enables rapid, on-site, and real-time detection and quantification of toxic metal ions such as lead, uranium, and mercury in water and other environmental samples. Detection and quantification is down to 11 parts-per-trillion–much lower than the maximum contamination levels defined by the U.S. EPA. Products based on this patented technology will change the way water testing is carried out, making it possible to identify water contamination issues rapidly, monitor the progress in decontamination efforts, and ensure the safety of drinking water.

In continuing research, teams led by Yi Lu and Benito Mariñas, a professor of environmental engineering at UIUC, are pushing the boundary of this technology to achieve detection of infectious viruses over other targets, including non-infectious viruses.

Technologies are needed that can harvest water for reuse from municipal or industrial wastewater streams. However, when used for wastewater treatment, most commercial membranes become fouled by dissolved or suspended biological molecules. A successful team science effort by center researchers resulted in the commercial production of nanotechnology-enabled membranes via a start-up company, Clean Membranes. The new membranes have substantially higher fluxes than commercial nanofiltration membranes and are completely resistant to fouling. The work was led by the now late Anne Mayes of MIT.

The unique feature of these membranes is their special "comb" copolymer coating formed by the local separation of hydrophobic "spines" and short, hydrophilic "teeth" of the combs into distinct domains. The water-absorbent teeth form a brush-like coating on the membrane surface that completely inhibits the adsorption of biological molecules, delivering unsurpassed fouling resistance.

A team at the WaterCAMPWS also has addressed the problem of disinfection byproducts in treated water. The disinfection of water was a major public health achievement of the twentieth century, but an unintended consequence of disinfecting water is the production of toxic drinking water disinfection byproducts (DBPs). The WaterCAMPWS team produced the world's largest mammalian cell toxicity database for drinking water disinfection byproducts. The effort, led by Michael Plewa, a professor of genetics at UIUC, developed and calibrated in vitro mammalian cell cytotoxicity and genotoxicity assays to integrate the analytical biology with the analytical chemistry of these important environmental contaminants. The results demonstrate that these data can be used to direct human cell toxicogenomic studies on DBPs to determine biological mechanisms of toxicity, select specific DBPs for future in vivo animal toxicity studies, and aid in the processes to rationally regulate drinking water contaminants to protect the environment and human health.

Key accomplishments of the WaterCAMPWS team science research efforts are:

- Comparison of nanomaterials such as graphene and carbon nanotubes for suitability in purification membranes by means of molecular dynamics and spectroscopy studies.
- Development of new membrane designs with improved uniformity and fouling resistance.
- Ion-exchange fibers that promise low-cost water treatment options for problem contaminants like perchlorate.
- Evaluation of the cytotoxicity and genotoxicity of drinking water disinfection byproducts.
- Assessment of the effects of natural organic matter on visible- and ultraviolet-light disinfection mechanisms.
- Demonstration and evaluation of chlorine-free disinfection systems using metal-oxide photocatalysts. □

STUDENTS MAKE WATER RESEARCH WORK

Students and Oaxaca, Mexico, community members taking water samples.

Pictured above at left: On site interviews with women in the Bondo communities. One of the Bondo water representatives is there translating for Dana Al-Qadi (UIUC) from English to Swahili.

Moving research findings from the laboratory into the real world and educating students in a hands-on, team-science environment are key components of an integrated engineering design course offered by the WaterCAMPWS at UIUC. The course, CEE 449, also has a humanitarian mission: it focuses on developing sustainable approaches for providing safe drinking water and adequate sanitation to impoverished rural communities throughout Mexico, Ethiopia, and Tanzania.

Developed by Benito Mariñas, a UIUC professor of environmental engineering and acting director of the WaterCAMPWS, CEE 449 is continually updated and improved through incorporation of current WaterCAMPWS research and creates a hands-on, team science experience for students from the WaterCAMPWS and UIUC in collaboration with faculty and students from the Nelson Mandela Institute of Science and Technology in Tanzania, the Addis Ababa University in Ethiopia, the King Abdula University of Science and Technology in Saudi Arabia, and the Universidad de Las Americas–Puebla in Mexico.

One important aspect of CEE 449 is international trip participation. Team members from UIUC participate in week-long trips to Mexico, Ethiopia, or Tanzania. Activities include field trips to target communities to gather data on relevant local socioeconomic and cultural priorities; recruiting local authorities as partners; exploring possibilities for

SPOTLIGHT ON START-UPS

Not only do start-up companies serve an important role in transitioning laboratory research to industry and society, but they also effectively leverage the Center's funding. Because customers are an important source of product evaluation and development ideas, start-ups are a source for market input. Even as the Center's research provides and expands underlying science, start-ups speed the expansion/extension of technologies to new applications.

Cbana Labs, Inc., (www.cbana.com) is one of four start-up companes with roots in the WaterCAMPWS research laboratories. Founded by Mark Shannon, UIUC professor of mechanical engineering and center director, Cbana Labs develops novel adsorbents and microanalytical devices for the capture and analysis of pollutants, drugs, and other dangerous materials. Three major components are needed for advanced microscale detection systems: preconcentrators for gas/liquid sampling; separators to minimize false positives; and microscale sensors. Cbana has developed novel and proprietary technologies in all three areas, including a family of novel adsorbents built on upon proprietary metal-organic frameworks (MOFs). Previously, MOFs were not widely used because of their relative instability and because synthesis was a long and costly process. Cbana's MOFs, called Banasorb®, are thermally and mechanically stable and can be synthesized in as little as 25 seconds. They are made of a fully customizable, three-dimensional nanoporous material that can be engineered to selectively adsorb species of interest and have a capacity that is an order of magnitude better than adsorbents such as granulated activated carbon.

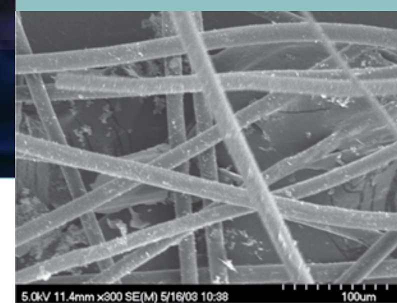
The Center's three other start-up companies are:

- DzymeTech: functional DNA-based sensor technology–Prof. Yi Lu (UIUC)
- Clean Membranes: new UF membranes with high flux and fouling resistance–Prof. Anne Mayes (MIT)
- Oasys Water: forward osmosis based desalination process–Prof. Menachem Elimelech (Yale)

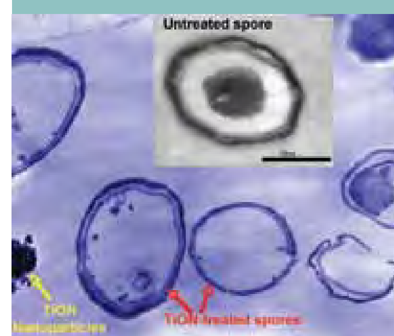
Sensor researcher Yi Lu of the WaterCAMPWS works with students.

Students from UIUC and community members in Oaxaca, Mexico conducting drinking water tests in 2011.

Top Photo: Metropolitan Water Reclamation District of Greater Chicago



Left: TiON fibers. *Image courtesy of Jian-Ku Shang, materials science and engineering, UIUC.*



Bacillus Subtilis spores killed by TiON. *Image courtesy of Jian-Ku Shang, materials science and engineering, UIUC.*

creating an educational component for design implementation and maintenance; determining the water quality of potential water sources in-situ; collecting water samples for subsequent analyses; and water quality process testing. Samples are also brought back to UIUC for specialized measurements such as toxic metal analyses.

Based on data gathered in the field and laboratory, students select candidate water quality control processes to produce safe drinking water and adequate sanitation. Faculty members design laboratory experiments to assess the efficiency of these various processes at treating the contaminated waters.

Most recently, CEE 449 teams targeted two communities in Mexico, Tarriahua and Las Cucharas. In their final presentations, students outlined the issues confronting those communities and detailed plans for water treatment as well as community education. With the completed plans, the communities can make proposals to their respective governments for funds to implement the building of the plants.

DEVELOPING DIVERSE HUMAN RESOURCES TO ADDRESS THE WATER CRISIS

Developing the diverse human resources needed to conduct water research into the future is an essential part of the WaterCAMPWS effort. Communities across the U.S. and the world need plentiful potable water. Today's decreasing water quality coupled with increasing scarcity and cost signal a crisis that will reach pandemic proportions within the next two decades if revolutionary advances in the science and technology of water are not made.

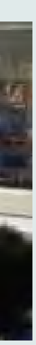
Fortunately, students who take up the challenge of water research are deeply committed to addressing this global problem. Many WaterCAMPWS students have first-hand knowledge of the health risks caused by poor water quality and have undertaken personal missions to solve this crisis.

Graduate, undergraduate, and sometimes even high school students are research team members and active partners in the Center's activities. They co-author papers appearing in major scientific journals, make presentations at national and international professional conferences, and support WaterCAMPWS activities directed at educating elementary and secondary school teachers and students and the general public about the issues surrounding water. The Center's students are also active in hands-on national and international humanitarian projects that apply and enhance the knowledge they have gained in the laboratory and classroom.

Early in the Center's history, all high school, undergraduate and graduate activities, and diversity and education programs were melded into one seamless effort. To achieve this, the Center applied the cross-cutting themes of academic development, research experience and professional development to its internal and external education programs.

External undergraduate recruitment programs and pre-college educational programs that incorporated the most recent findings from the Center's research efforts were crafted to create a sustainable "pipe-line" of qualified candidates, with emphasis on increasing the participation of traditionally underrepresented students (URG). This demonstrated dedication to an integrated, high-quality experience for all undergraduate students yielded enormous benefits for all students and the Center. It also resulted in a 45% graduation rate among URG students at the WaterCAMPWS, a rate 10% above the norm nationwide and for the University of Illinois College of Engineering.

As the end of its 10-year funding cycle approaches, the Center leaves a legacy of students who have already emerged as dedicated, well-qualified researchers and whose work has, and will continue to have, significant impact on real-world water problems.



BIOPHOTONICS

SHEDDING LIGHT ON LIFE

Extract a lot of information, but use a gentle touch. That's biophotonics: studying the interaction of light with biological materials and systems.

Because light can be used to analyze living tissues in a minimally invasive manner, advances in the field of biophotonics will be key to new clinical tools and biomedical instruments.

This is the challenge facing a band of scientists, engineers, biomedical researchers, clinicians, and instrument developers at the Center for Biophotonics Science and Technology (CBST), headquartered at the University of California, Davis (UCD) under the leadership of center director Dennis Matthews.

It's a job that is facilitated by state-of-the-art facilities, equipment and instrumentation for CBST within a dedicated building adjacent to the UCD Medical Center in Sacramento, Calif. The $20-million, 40,000-sq-ft Oak Park Research Building also houses laboratories for the study of aging, infectious disease, and cancer research.

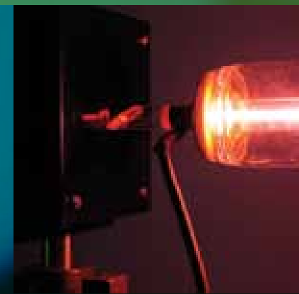
CBST is "pushing the envelope" of imaging science and filling gaps in existing technology. Tools such as X-rays, computerized tomography (CT scans), and light microscopy are able to image life down to the level of tissues and cells. On the other hand, recent advances in studying the human genome have revealed much about the structure of biological systems at the atomic and molecular scale. But in between these two scales, a critical gap exists in the ability to image at the level of groups of biomolecules and structures within the cell.

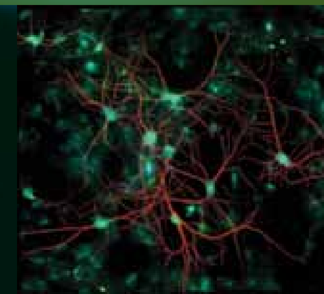
That's why CBST is supporting several research projects aimed at new bioimaging tools. These projects include work to develop X-ray lasers to enable diffraction imaging of single biomolecules, new gene based optical labels for fluorescence imaging, and unprecedented levels of resolution with light microscopy.

"We have come up with the capability to use optical illumination to image something that's ten times smaller than the wavelength of the light we're using," explains Matthews. "We can basically look at objects 50 nanometers in size and resolve them using 500-nanometer light." Related research was commercialized with the help of Applied Precision, Inc. and a research instrumentation grant from the NSF, with second-generation Optical Microscope eXperimental (OMX) instruments already under development.

CBST is developing a host of new gadgets not only to study single cells in the lab but also to characterize tissues in living organisms. For example, professor Laura Marcu's group has developed tissue diagnostic systems for in vivo detection of disease and has worked with physicians to test them in animals and in patients. A portable, endoscopic microscopy system based on fluorescence lifetime imaging makes it possible to non-invasively characterize tissues and diagnose diseases during an operation. The group developed an instrument for diagnosing head and neck tumors based on changes they can detect in the biochemical composition of tissues between pre-cancerous and cancerous states using a kind of laser spectroscopy called time-resolved laser induced fluorescence. Professor Marcu and collaborators also developed a multimodal tissue diagnostic system that combines several methods of imaging using light and sound waves to perform structural and chemical analysis of tissue.

Over the last few years, CBST scientists have developed laser trap Raman spectroscopy, a non-destructive, accurate, and label-free technique that records the molecular fingerprint of cells. Center researchers have combined micro-Raman spectroscopy with optical trapping to sort and study cells





CBST education director Marco Molinaro, second from right, with students.

while leaving them intact, without fluorescent tagging. “We can study cells in their native state, getting a molecular fingerprint,” says Matthews. “This capability is going to be important for treating cancer, and we’re focusing initially on pediatric leukemia patients.”

CBST scientist James Chan and his collaborators are currently developing a way to use laser beams much like ultra tiny tweezers to hold individual cells in place or maneuver them precisely in order to make Raman spectroscopic measurements on them. Laser tweezer Raman spectroscopy has been applied to research in cancer, stem cells, infectious disease, and cardiovascular applications. Most recently, the technology was used to distinguish cells from the lining of the aorta from those of veins. That capability will be critical in order to sort and purify engineered stem cells for medical therapy. □

A CONVERSATION WITH THE DIRECTOR

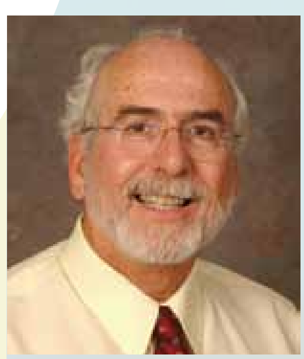
Dennis Matthews

“Team science is the only kind of science I’ve been involved with for a very long time,” says center director Dennis Matthews. “In graduate school, I worked in a nuclear physics laboratory, and in order to get anything done, you soon found out you had to go charm a bunch of people to work with you.

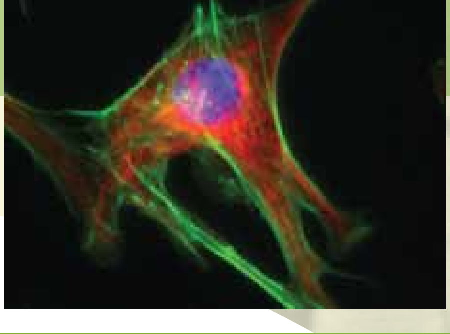
“Then, working at Lawrence Livermore National Laboratory, every project there was a team science and engineering project—it’s too complicated to pull off in the single investigator model. You’ve got to get a team of experts to work with you to accomplish the objectives.

“The academic way of life in the past has used the merit system as a way of providing rewards. The merit system is based on individual performance—being PIs on a grant, being the first author on a paper, and so forth. That system is evolving to reward people for working in a team science approach. This is not new. All major agencies, including the National Institutes of Health and the National Science Foundation, recognize that the academic environment should reward team effort.

The academic department is the fundamental unit of governance for professors. Getting departments to change their procedures is hard, but I think it’s going to come, as people see more and more reward for it. Universities are changing some of the ways they are organized—for example, an office of research having its own faculty lines to allocate for interdisciplinary work.”



Dennis Matthews, director of the Center for Biophotonics Science and Technology



RESOLVING CELLULAR STRUCTURES ON THE NANOSCALE WITH LIGHT MICROSCOPY

Biological structures previously too small to be resolved using optical microscopy can now be revealed using structured illumination and other super-resolution techniques. Scientists at the University of California, San Francisco invented a new technique, called Structural Illumination Microscopy (SIM), with funding from CBST and other sources.

Previously, CBST chief scientist Thomas Huser, a UC Davis professor of internal medicine, led an NSF Major Research Instrumentation award to develop the first commercial Optical Microscope eXperimental (OMX) system, in collaboration with Applied Precision, Inc. (API) of Issaquah, Wash. Recently, API was acquired by GE Healthcare.

A second-generation system has already been co-developed by CBST and API scientists, culminating with CBST implementing the first such system in the U.S. at the time of this writing in mid-2011.

"The center and API have amazing synergy," says Joe Victor, CEO of Applied Precision. "Both organizations are very engineering oriented. That doesn't mean they aren't science oriented as well—but what you find often in a lot of academic organizations is a heavy weight on the science side and not too heavy on the engineering side. What you see at this center is really a core competency in both. We see a potential for multiple collaborations." he adds.

OMX fills an existing gap in microscopy. It covers the intermediate length scales between standard fluorescence microscopes and electron microscopy. Since the first commercial OMX system was installed at CBST, researchers have been targeting a number of important biological applications in this range.

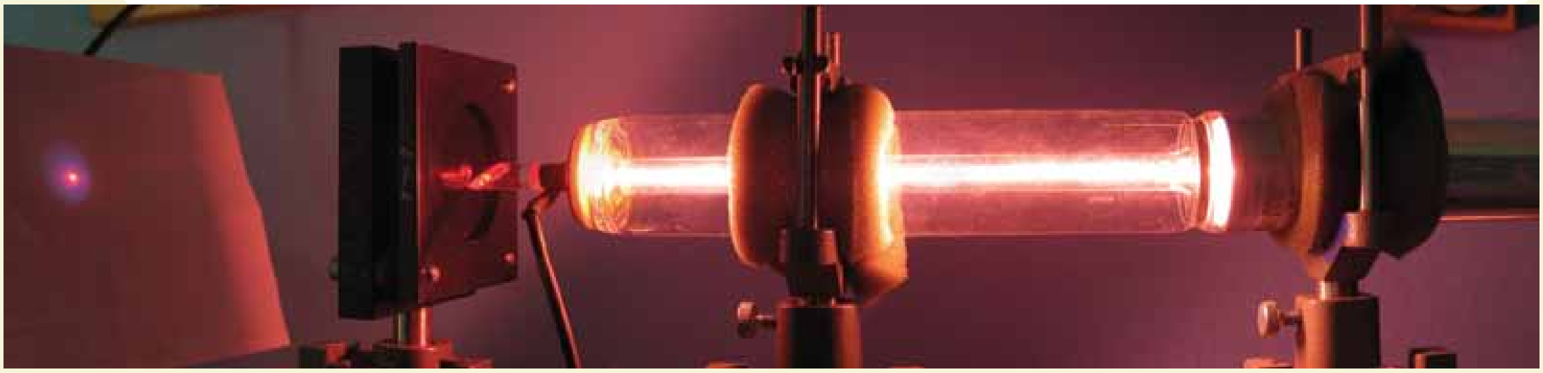
In a highly successful collaboration among physicists, physicians, engineers, and other researchers from Mount Sinai School of Medicine in New York and CBST, scientists produced the first evidence of direct cell-to-cell transfer of HIV. High-speed tracking of the HIV virus revealed several unique modes of motion, suggesting that HIV transport occurs not simply by passive diffusion, but through more active mechanisms of motion, such as virological synapse formation.

Center scientists imaged HIV-1 virus particles inside infected T cells, and applied super-resolution microscopy and spinning disk confocal microscopy to visualize the location at different time points of individual viruses. Research now indicates that HIV virus particles are transmitted from infected to uninfected cells via virological synapses, which are clusters of virus at the point of host cell-to-target cell contact. This research is expected to lead to more effective HIV vaccines.

In another project, CBST scientists are collaborating with physicians to study the mechanisms of HIV1 pathogenesis in the gut mucosa. As the main physical barrier protecting the body from the environment, the gut mucosa is the primary interface where viral infection initially occurs, and it is widely believed to sequester HIV during the latent phase of infection.

Super-resolution microscopy was also used to investigate the role of autophagy, i.e. programmed intracellular recycling, in response to traumatic brain injury (TBI), with the goal to determine whether this process can be monitored as a prognostic indicator for recovery after TBI. CBST researchers teamed up with neuroscientists as well as a small company to collaborate on this project, which can have important implications for more than 1.5 million people affected by TBI annually in the U.S. alone.

Other applications in cancer, liver disease, and regenerative medicine also have been explored. In addition to its use in research, the OMX system is being used in the training of students as part of CBST courses in advanced microscopy.



Helium Neon laser. *Photo: Marco Molinaro*

NEWS WATCH

ECOSYSTEM FOR BIOPHOTONICS INNOVATION

CBST has received a $1 million, two-year grant from the NSF to develop an “Ecosystem for Biophotonics Innovation” program and to accelerate commercialization of biomedical technologies developed by Center researchers. The grant is matched at least one to one by third-party investments from CBST partners.

The ecosystem will be nurtured by an educational and business alliance between CBST, the Sacramento Area Regional Technology Alliance (SARTA) and its MedStart initiative, third-party investors, a pediatric cancer foundation, and a national laboratory. The goal is to foster the commercialization of innovative bioinstrumentation and medical technology while educating students and postdoctoral researchers in entrepreneurship, product design, and development. Among the technologies proposed for commercialization are an ultra-short pulse laser scalpel; a home blood-testing device; a 3-D wide-field super-resolution optical microscope that improves upon existing OMX technology; and single-cell Raman spectroscopy systems.

“We are very excited to develop the Ecosystem for Biophotonics Innovation (EBI) program as a unique alliance of committed partners,” says CBST Director Dennis Matthews, principal investigator of the grant. “This program will enable faster translation of research-based technologies into start-ups or existing firms, leading to new jobs and economic growth, while also providing hands-on training and learning opportunities in entrepreneurship.”

UNIVERSITY OF CALIFORNIA BIOPHOTONICS ALLIANCE

CBST has worked with university and government partners to establish the University of California Biophotonics Alliance (UCBA). The goal of the alliance is to capitalize on the significant research in biophotonics that occurs on all the UC and California-based national laboratory campuses, in order to accelerate biophotonics discovery and innovation, for the benefit of bioscientists, physicians and patients.

UCBA will organize a UC Biophotonics Industry Forum in January 2012 to connect biophotonics faculty, students, and other researchers with colleagues from California companies, leading to collaborative research, knowledge transfer via licensing, scientist exchanges, and student internships and jobs.

CBST Spring Science Workshop 2011

Pictured in background: Cells in Raman trap

TEAM SCIENCE 101

The bell rings as the last few students filter into the seminar room and take their seats. One of the instructors begins to speak.

“As a research physician in a top-ranked medical research institution, you are aware of the need for improved technology to measure narrowing of carotid arteries. At a seminar, you discover that a brilliant faculty member in the physics department may have such a technology—a supersensitive wide-bandwidth microphone—but he hasn’t filed a patent for his concept nor has he any known interest in applied research or medicine or anything but single-investigator, discovery-based research.

“You are given the challenge of putting together a multidisciplinary team to translate this technology into medical practice, and bring it to Phase II clinical trials in only two years. How should you proceed?”

The scenario is used in a course actually taught by CBST director Dennis Matthews, Marco Molinaro, and Frank Chuang at the University of California, Davis, in conjunction with the NIH-funded Mentored Clinical Research Training Program.

Not the typical chalkboard talk you might associate with graduate or medical school, the course tackles real-world problems that transcend traditional academic departments. It’s one of the ways that the center is transforming the graduate educational experience.

“Students can be woefully underprepared for the team working environment, especially if they go into industry, where it is very team-oriented,” says Matthews. “With our students, what our center tries to do is to instill in them the value of working together with other disciplines.”

EARTH-SURFACE DYNAMICS

Background: Mississippi River Delta. Image taken 5/24/2001 by ASTER, the Terra Satellite's Advanced Spaceborne Thermal Emission and Reflection Radiometer. *Image: USGS National Center for EROS and NASA*

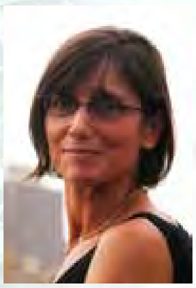
Inset photo left by Dan Marshall

Inset photo lower right by Jon Chapman

NATIONAL CENTER FOR EARTH-SURFACE DYNAMICS NCED

THE SURFACE IS THE ENVIRONMENT

Civilization, by its very nature, has involved reshaping the natural environment to fit human needs. We have altered landscapes to enhance food supplies, reduce exposure to natural dangers, and promote commerce.



Efi Foufoula-Georgiou

We have converted approximately 50 percent of the world's surface to grazed or cultivated cropland. We have built dams to control rivers for hydropower, irrigation, and flood mitigation. Nearly six times more water is now held in storage than occurs in free-flowing rivers. Climate change and a growing imbalance among freshwater supply, consumption, and population have dramatically altered the hydrologic cycle, a situation that may intensify over the next century.

During its nine-year tenure, the National Center for Earth-surface Dynamics (NCED) has ushered in a new era of investigation to better understand landscape dynamics and their response to change. Headquartered at the St. Anthony Falls Laboratory at the University of Minnesota, NCED has facilitated the development of a quantitative, predictive Earth-surface science through the integration of many fields: geomorphology, ecology, hydrology, sedimentary geology, engineering, social sciences, and geochemistry and through the synergistic combination of field investigations, physical experiments, and computational models.

"It is a paradigm shift that will enable us to address the challenges of the future and provide science-based solutions for adaptation and mitigation of environmental change," says center director Efi Foufoula-Georgiou.

The center's mission is to understand the dynamics of the coupled processes that shape the Earth's surface and furthermore, to use this knowledge to deliver the science-based solutions necessary for addressing environmental change. The research program is organized around three main themes looking at watersheds, stream systems, and deltas. "Our Deltas program seeks to understand the processes of delta dynamics in support of restoration of the Mississippi River Delta, as a prototype initiative that can contribute to the protection and restoration of the many threatened deltas around the world," says Foufoula-Georgiou. "Our research uses the subsurface stratigraphy of modern deltas to infer rates, spatial patterns, and mechanisms of natural delta building processes. Simultaneously, we perform experiments and field studies to develop predictive models of the processes by which deltas build land and maintain themselves and their associated ecosystems against subsidence and sea-level rise."

In one area of NCED work, results have revealed a major shift in sediment sources in the Upper Mississippi River system. Excessive loads of fine sediment and their associated turbidity, eutrophication, and degradation of water quality are common problems for rivers that drain agricultural lands. Identifying the causes of, and developing countermeasures for, the excess sediment is challenging in large watersheds due to their scale and complexity. "But adopting mitigation strategies without an understanding of watershed-scale sediment dynamics threatens to be wasteful at best and destructive at worst," notes Foufoula-Georgiou.

TRANSFER OF TOOLS

Methods to calculate the movement of sediment might sound like mere mud pies to some people, but it's an important outcome of center research.

"As humble as it may be, sediment is what a lot of the world is built on," notes Paola. Knowing how fast it flows from one place to another is critical to understanding how the earth's surface evolves—and how long, for example, a reservoir will remain in service, what will happen to the lake behind a dam, or how fast you could fill in drowned marsh land in a place like the Mississippi Delta.

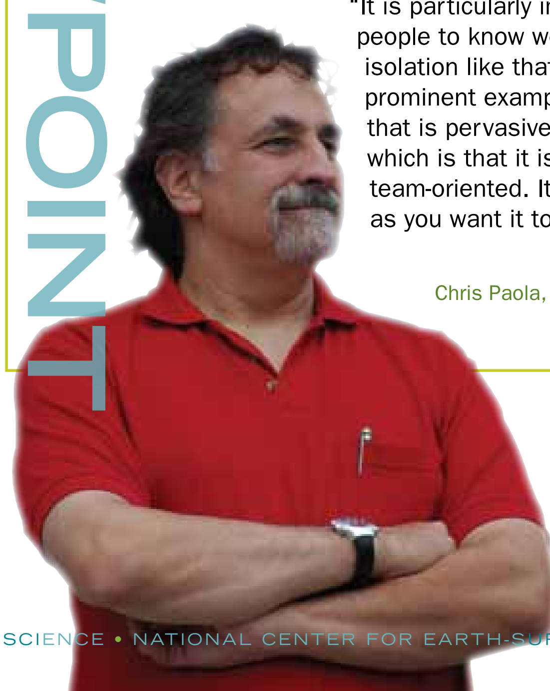
The Army Corps of Engineers is expected this year to adopt some of NCED's sediment transport tools, which means the technology would become part of the national standards for calculating the flow of particles in rivers.

VIEWPOINT

Chris Paola

"When I interact with the public, particularly kids, they don't understand science is not done in isolation," says NCED researcher Chris Paola. "Most people think that scientists work by themselves in laboratories wearing white lab coats," he notes, "but science is one of the most intensively social disciplines there is.

"It is particularly important for young people to know we rarely work in isolation like that. The STCs are a prominent example of something that is pervasive across science, which is that it is very social, very team-oriented. It's as team-oriented as you want it to be."



Chris Paola, former NCED Director

To identify the sources and mechanisms of erosion and sediment transport in the Minnesota River Basin, NCED researchers constructed a sediment budget for the Le Sueur River, a tributary and primary contributor of sediment to the Minnesota River. Based on similar topographic history and land use, the sediment dynamics of the Le Sueur are likely representative of other tributaries to the Minnesota River. They found a" surprising shift" in sediment sources, suggesting that recent changes—including extreme precipitation events; installation of agricultural ditches and subsurface tile drains; and increased soybean cultivation and decreased evapotranspiration—have acted to amplify erosion of bluffs and stream banks. "The implication for landscape managers is clear," says Foufoula-Georgiou. "The strategy implemented for sediment reduction must first and foremost address the primary amplifier of erosion, the altered hydrology of the watershed."

On another front, NCED research on the swimming behavior of green algae has important implications for understanding toxic algal blooms. In lakes, deltas, and oceans, very thin surface layers of the water may contain concentrations of tiny phytoplankton up to two orders of magnitude above ambient concentrations. These layers are important "hot spots" of ecological activity.

Thin layers range in size from microns to centimeters vertically and can extend for kilometers horizontally, persisting for hours to days. The layers enhance zooplankton growth rates within coastal oceans and are essential for the survival of some fish larvae. At the same time, however, many phytoplankton species found in the layers are toxic, and they may enhance fish mortality and cause harmful algal blooms. So it's important to be able to predict the onset, lifetime, and destruction of thin layers, but a definitive explanation has eluded scientists. Since the layers are often found in oceanic regions where shear flows are prevalent, it has been hypothesized that hydrodynamic shear contributes to thin layer formation by disrupting the vertical migration of phytoplankton.

NCED researchers have discovered surprising swimming patterns of a kind of green algae that supports this hypothesis. They used a method called high-speed holographic particle image velocimetry to study algae swimming in situ in moving flows, and found that the organisms were moving in response to fluid flow. The researchers hypothesize that the shear-guided swimming minimizes drag and physiological stress. At high shear rates, the algal cells aggregate into two dimensional thin slices, identical in form to thin layers in oceans. □

CYCLES: TEACHERS DISCOVERING CLIMATE CHANGE FROM A NATIVE PERSPECTIVE

CYCLES is an approach for understanding and teaching about global climate change that reflects the similarities between Native American and scientific explanations of the natural world as interconnected processes that are cyclical.

In native culture, the medicine wheel symbolizes the interconnectedness of the Earth, air, water, and fire. This relationship is recognized in science through an Earth systems approach based on the interconnectedness of the geosphere, atmosphere, hydrosphere, and biosphere, with the energy flow of these systems derived from the "fire" of the Sun and the interior of the Earth.

CYCLES is a three-year program, facilitated by NCED researchers and currently co-funded by NASA, targeting middle and high school science teachers from reservation schools or schools with significant native student populations. The program incorporates satellite observations, regional and global models, and cultural experiences.

A cohort of 20 CYCLES teachers were selected in the summer of 2011 to pilot test this new approach over the next 3 years. During summer workshops, teachers are actively involved in doing climate change science, both in the field with local projects and with existing NCED and NASA data. Teachers also learn how to use computational tools to visualize and model climate change to answer questions about local and global effects of environmental change. During the academic year, teachers attend additional training days and are expected to implement lessons and activities from the summer workshops in their classrooms with support from the CYCLES staff.

GRADUATE CERTIFICATE PROGRAM IN STREAM RESTORATION FILLS AN EDUCATION GAP

On a sunny day in central Minnesota, thirteen students armed with equipment and waders set up their cross-section lines and begin to measure channel topography. They are starting an investigation on the Maple River, where a local landowner has complained about bank erosion. The Department of Natural Resources wants to enhance fish habitat, and the Minnesota Pollution Control Agency hopes to reduce turbidity and improve water quality of the river.

These students are the first participants in the Stream Restoration Science and Engineering Graduate Program (SRSE), started by NCED at the University of Minnesota (UMN).

Stream restoration requires a complex understanding of engineering, physical, biological, and social sciences, yet few practitioners have such integrated training in these fields. NCED aims to fill that gap with a new year-long, interdisciplinary program, which completes its first year in June 2007. The certificate may be taken as a stand-alone qualification or incorporated into a master's or doctoral program. It is currently the only year-long graduate degree in the country specifically aimed at stream restoration, according to NCED.

WELCOME TO THE ANTHROPOCENE

BY PATRICK HAMILTON, DIRECTOR, GLOBAL CHANGE INITIATIVES, SCIENCE MUSEUM OF MINNESOTA

Humans now are the dominant agents of global change.

This idea has emerged as a main message over the course of nine years of collaboration between the National Center for Earth-surface Dynamics (NCED) and the Science Museum of Minnesota (SMM).

The work began first with the creation of the "Big Back Yard." This 1.75-acre, outdoor environmental science park at the museum opened in 2004 and is centered on a nine-hole mini-golf course that helps people explore human/landscape interactions as they follow the movement of water and sediment from the uplands of North America to the Gulf of Mexico.

NCED and SMM then turned their attention to the creation of a major traveling exhibit about water organized in partnership with the American Museum of Natural History (AMNH). "Water: H2O = Life" opened at AMNH in late 2007 and focuses on the fundamental importance of water on our planet, the growing stresses humans are placing on global freshwater supplies and the innovations available to help address our planetary water challenges. Two copies of the Water exhibit now are touring venues around the world.

NCED and SMM's latest collaboration is "Future Earth"—exhibits, Internet kiosks and public programs to help audiences appreciate that collectively all seven billion people on Earth now rival natural processes in modifying the planet, that a diverse portfolio of technological, economic, social and political innovations is needed for people to successfully adapt to and mitigate the global changes that humans have set in motion, and that Earth now is home to the wealthiest, healthiest, best educated, and most innovative, creative and interconnected cohort of humans in history. The "Future Earth" exhibit opens at SMM in fall of 2011.

Entry to the *Water: H20 = Life* exhibit displays messages on a curtain of fog. *Image: American Museum of Natural History*

The Big Back Yard.
Image: Science Museum of Minnesota

This dataset (http://sos.noaa.gov/datasets/extras/facebook.html) was created by an intern at Facebook who plotted 10 million pairs of friends on Facebook. The result is a stunning map that shows the connections between people and highlights the regions with readily available access to the internet. Africa, with limited internet access is rather dim, while China, with many internet users is dim due to the use of a popular Chinese social networking site and government restrictions. From the creator upon refining the visualization - "After a few minutes of rendering, the new plot appeared, and I was a bit taken aback by what I saw. The blob had turned into a surprisingly detailed map of the world. Not only were continents visible, certain international borders were apparent as well. What really struck me, though, was knowing that the lines didn't represent coasts or rivers or political borders, but real human relationships. Each line might represent a friendship made while traveling, a family member abroad, or an old college friend pulled away by the various forces of life." *Image: Courtesy of Facebook*

Eric Jolly

PRESIDENT, SCIENCE MUSEUM OF MINNESOTA

Since joining SMM in 2004, museum president Eric Jolly has worked to cultivate a close working relationship with NCED, in part through the negotiation of a memorandum of understanding (MOU) that facilitates communication between SMM and UMN. Toward this end, Jolly has drawn upon his experience as a psychology professor and university administrator. He is a nationally acclaimed leader in the field of science education and science literacy.

"The MOU allowed us to have a portal," Jolly explains. "It can be difficult to find a way in to a major research university-to an outside institution, a university can be overwhelming. You don't know exactly where to go-it's not intuitive. Having an MOU helped that," he says.

"There's a reciprocity in this that's pretty astounding," says Jolly. "I consider this one of the best examples of public-private partnerships in the country."

The energy that the players bring to the collaboration is infectious. "People have accused me of having too much fun," says Jolly. "I get to play scientist, educator, keeper of incredible treasures, and it's all aimed at my passion: science as an essential literacy for our youth—science education as a civil right in many ways."

NETWORKED SENSING

CENTER FOR EMBEDDED NETWORKED SENSING CENS

IMAGINE IF:

Mobile technologies could be used to help individuals and their doctors monitor and manage health symptoms, treatments, and side effects throughout the day.

Ecosystems could be equipped with chemical, physical, acoustic, and image sensors to continuously monitor environmental change.

Buildings could detect their own structural faults and respond to seismic events.

These are the kinds of dreams that researchers at the Center for Embedded Networked Sensing are turning into reality through a collaboration between computer scientists, statisticians, biologists, and engineers under the leadership of center director Deborah Estrin.

The approach uses sensors, computers, and wireless communication in systems that are distributed throughout the environment. These smart sensors and actuators allow people to monitor aspects of the world as a function of time and space in order to derive new knowledge that couldn't be obtained otherwise.

Embedded and networked sensing systems promise to reveal previously unobservable phenomena widely affecting our society by exploiting connections between the physical world and the Internet. In the same way that the development of the Internet transformed our ability to communicate, the ever-decreasing size and cost of sensors, mobile technologies, and computing components are setting the stage for detection, processing, and communication technology to be embedded throughout the physical world. The approach is aimed at fostering a deeper understanding of the natural and built environments and, ultimately, enhancing our ability to understand and manage these complex systems.

Center researchers are working to harness the power of mobile phones and the ubiquitous wireless infrastructure for applications in areas as diverse as public health, environmental protection, urban planning, and cultural expression.

Sustainable design, healthy living, and effective stewardship of the world's limited resources all require a deeper understanding of how countless individual actions generate global effects and how individuals relate to their local environments.

Previously, scientists, policy-makers, and the public have had to choose between examining the broad characteristics of large populations and looking at small groups in detail. With the approach of participatory sensing, CENS researchers are developing ways to help individuals, families, and communities monitor and improve their own health behaviors, adopt sustainable practices in resource consumption, and participate in civic processes.

PARTICIPATORY SENSING

The proliferation of smartphones with built-in GPS, high-quality cameras, excellent user interfaces, and easily downloaded applications has opened the door for participatory sensing. The power in this approach comes not only from the devices, but also from their connection to the Web.

Smartphones have already transformed cellular phones into something much more than personal communication devices. Now, with growing interest in community engagement and a greater appreciation for the importance of the environmental and social determinants of health, smartphones have become vital, accessible, and affordable public resources for environmental assessment and health promotion, says Estrin.

CENS research applications include data-gathering campaigns, in which participants make observations about the world around them; and mHealth, in which individuals use their devices to manage a wide range of health concerns, from diabetes, high blood pressure to depression and obesity.

Data capture can be defined from the top down, as when volunteer groups or

Engineers for CENS installing a robotic sensing system on the San Joaquin River in the California central valley.

Water quality and flow sensors positioned at the surface of the river.

individuals collect data for researchers, public officials or clinicians; or from the bottom up, as when communities with a common interest organize to systematically identify, document, and communicate issues that concern them.

PARTICIPATORY MHEALTH

Participatory mHealth leverages the power and ubiquity of mobile technologies to assist individuals and their doctors in monitoring and managing symptoms, side effects, and treatment for chronic illnesses outside the clinical setting, and to address the lifestyle factors that can bring on or exacerbate these conditions.

"We are taking advantage of the massively proliferated cell phone technology to apply mobilized and in-situ sensing observations to community health and public health issues," says CENS director Deborah Estrin.

People may be exposed to different levels of environmental and health risk depending on their particular lifestyles, which involve familiar variables such as diet and exercise but also where they go, what they breathe, how they travel, and other factors.

Principles of embedded network sensing may help researchers gain a better understanding of exposure levels encountered by individuals in their daily lives. In the case of asthma, for example, data from weather information and smog and pollution sensing stations might be combined with detailed location information and activity level information on patients collected through a cell phone to gain a better understanding of the disease.

By empowering individuals to track and manage their key health-related behaviors and outcomes, this approach has the potential to greatly improve people's health and quality of life while simultaneously reducing healthcare costs, says Estrin.

Participatory mHealth incorporates a variety of techniques, including automated activity traces, reminders, and prompted inputs. Intended to be used episodically rather than continuously, it can assist patients with adherence to their treatment regimen and provide useful information for clinicians. Employed by individuals, it can glean insights into what might be contributing to the recurrence of a chronic problem, or help them track and sustain a plan to become healthier through better diet, exercise, sleep, and stress management.

The software and methodology are adaptable for a wide variety of chronic disease interventions. For example, a pre-diabetic woman can use an application to keep tabs on how her eating and exercise habits affect her weight and energy levels. Her mobile phone prompts her for self-reports on her daily intake of carbohydrates and her daily exercise, while reminding her to check and record her weight and fatigue levels. A middle-aged man who doesn't respond well to the latest medication for psoriasis is trying to understand what combination of diet, stress and environmental exposure are most likely to lead to flare-ups. He can launch a data campaign via a social networking site for psoriasis sufferers, asking each volunteer member to download and use an application for systematic self-monitoring. The result: a large data set from which patterns can be mined to unravel the mystery of the condition.

VIEWPOINT

FROM THE DIRECTOR

Deborah Estrin

"I grew up with the Internet research community, which taught me about the value and the transformative effect of a community going after a vision together. No one person can create it—no one person could create the Internet, for example. That's my technical culture. That's how you have impact."

— CENS DIRECTOR DEBORAH ESTRIN

ENVIRONMENTAL APPLICATIONS

In another area of the CENS program, research has focused on developing embedded networked sensing technology to study soils, groundwater, and riparian systems. One application was a large-scale deployment on a major river segment: the confluence of the San Joaquin and Merced Rivers in Central California, a very important agricultural base for the nation.

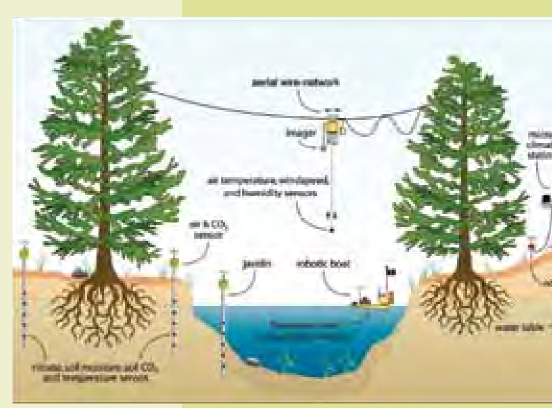
"In the Central Valley, there is a long-standing problem of high salt concentrations from agricultural runoff," explains Jeffrey Goldman, program development director at CENS. Previously, the state made makes measurements only very sparsely along the river at a single point. CENS research was aimed at providing a much more detailed view of the mixing, says Goldman, obtaining data that would be needed to better manage the flow of water and irrigation in the Central Valley.

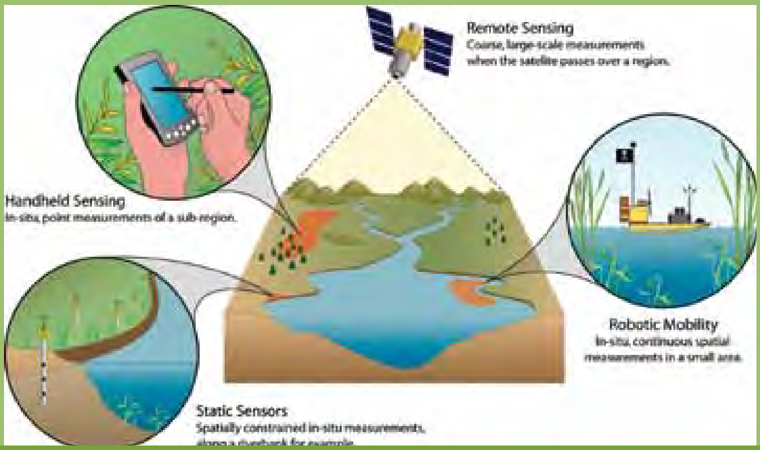
CENS researchers strung cables across the river and suspended a robotic shuttle from the cables. The shuttle can be controlled to move across the river and then up and down within the water in a grid pattern to make measurements on properties like nitrogen levels, dissolved oxygen, salt concentration, and flow."By deploying these technologies we've been able to see how mixing occurs, something that wasn't previously understood," notes Goldman.

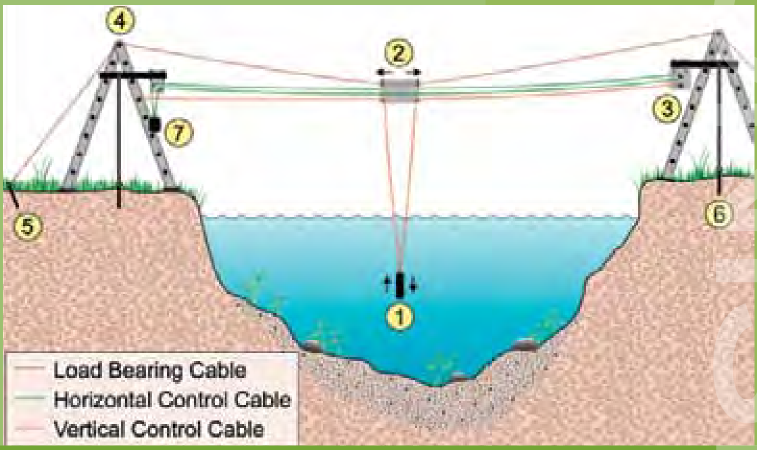
FUTURE DIRECTIONS

Besides these and many other applications, CENS researchers are exploring the fundamental research questions about the scientific and engineering design of embedded systems, and that work has helped this emerging field to evolve. "We've ended up in a different place than anticipated," Estrin admits. "Five to ten years ago we had an initial conception about what the problems were. But we've really learned from the experience what the real problems are and where the real challenges and opportunities are."

Throughout this process, communication has been key, says Goldman. "Engineers and computer scientists (each) have their own language. Left to their own devices, they would come up with something very neat, but not necessarily the most useful in the field," he laughs. "Explaining from the perspective of the biologist or seismologist in the field how the instrumentation needs to work—what's important and what's not—is critical to making things work."







CENS RESEARCHERS "MOBILIZE" IN SUPPORT OF EDUCATION

The goal of Mobilize is to strengthen computer science instruction in the educational system and to develop innovative methods for educating and engaging students–particularly those in underserved schools–in the area of computational thinking. At the heart of Mobilize is "participatory sensing"–a method of data collection and analysis in which students use mobile phones and web services to systematically collect and interpret data about issues important to them and their communities.

Mobilize is an NSF-supported partnership between the Los Angeles Unified School District (LAUSD), UCLA (through CENS and the Graduate School of Education), and the Computer Science Teachers Association (CSTA).

Smart phones are critical to the process of the kind of participatory sensing that is the heart of the Mobilize project. On the ground level, students use the phones to collect and record data in real-time. Observations are automatically tagged with geo-location and timestamp. Students can also use the phone to take pictures that are important for the data analysis component of the Mobilize curriculum.

The phones are more than a "hook" used to appeal to kids' fascination with technology--they are an invaluable tool for data collection and analysis, which is the crux of computer science education and key to the goals of the project," says center director Deborah Estrin.

The partners have designed a high school curriculum in which students learn about spatial analysis, temporal analysis, and text interpretation through their own data collection and analysis project. Through the use of custom designed participatory sensing software, students will embark on data campaigns using mobile phones and web services to learn about: the nature of data, its representation, formats, and protocols for sharing. They learn principles of computational thinking, problem-solving, and gain experience with algorithms, the rules governing data collection and strategies for analysis. They use tools of statistics and visualization and experience first-hand the intersection of mathematics, science, and civic engagement.

CISM MODELS ENHANCE SPACE WEATHER FORECASTING

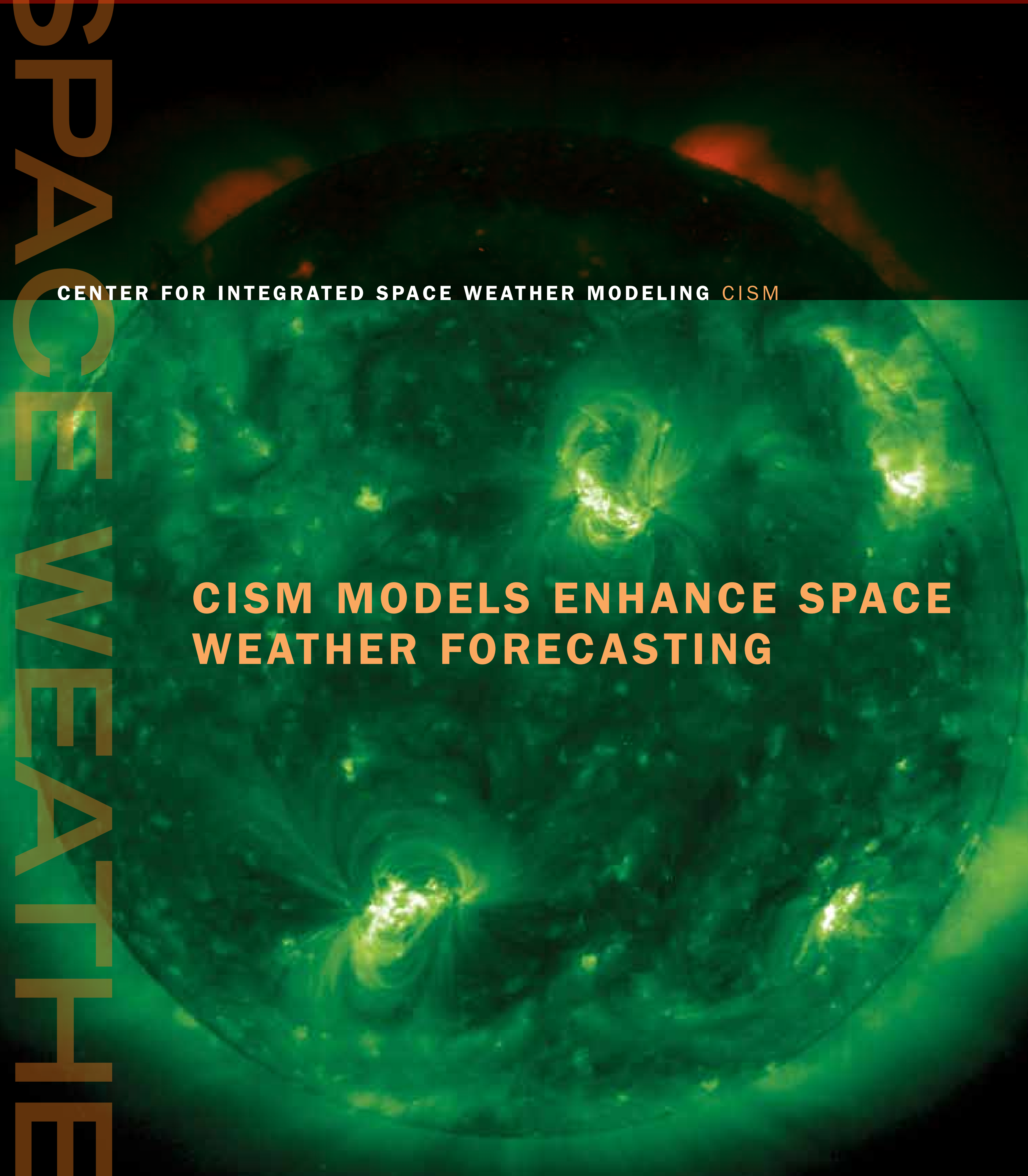


Image of the Sun in the extreme ultraviolet range showing the solar corona at a temperature of ~1 million K. Recorded Sept. 11, 1997. *Image: SOHO_EIT, http://sohowww.nascom.nasa.gov/gallery/EIT/eit029.html*

Thanks to the magnetic cocoon surrounding the Earth, many people live out their lives oblivious to the harsh reality of our space environment.

That is, unless you happen to run a power grid in New England, or you're on a polar flight from Chicago to Hong Kong and all the communications are blacked out.

Then you know firsthand that the sun is capable of lashing out with tentacles of radiation that travel through space at enormous speeds and buffet our planet's magnetic shield, wreaking havoc with electrical systems and satellites.

Whether you're combating corrosion in pipeline operations, conducting an offshore survey using high-precision GPS navigation, or just trying to get a clear satellite TV signal, you may be very interested in the latest space weather forecast.

Forging a better understanding of space weather is the mission of the Center for Integrated Space Weather Modeling. CISM researchers are developing new models of the entire system from the sun to the Earth, ones that are more comprehensive and powerful than ever before. And they are working to transition the models into practice in partnership with NOAA's Space Weather Prediction Center (SWPC), Boulder, Colo.

Now in the testing stage, the technology is poised to dramatically improve the quality of space weather forecasting in the near future.

At top right: The forecast and analysis branch of NOAA's Space Weather Prediction Center, Boulder, Colo., has the responsibility for providing the nation's real-time space weather services 24 hours per day. *Photo: SEC*

The Forecast Room

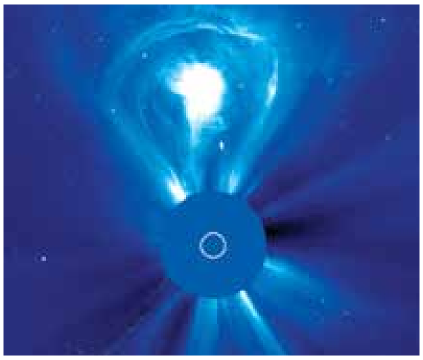
It's staffed 24/7, but most days, life is pretty calm in the forecast room at SWPC, says Joe Kunches, chief of the SWPC forecast and analysis branch. Around the room are monitors with real-time data feeds from NOAA and NASA satellites. Operators are eyeing plots of the solar wind speed near Earth, the magnetic field in the solar wind, the X-ray flux coming from the sun, and the energetic particle flux.

Conditions can be stable for a long time and then change fast. "When the sun has a flare, the X-ray flux, for example, can increase a millionfold in minutes," says CISM director Jeffrey Hughes.

It's a wild ride. Operators are watching graphs, they're hearing audio alarms. "You've got a whole lot of stuff coming at you very quickly," says Kunches. "You're on the phone, you're sending e-mails, and predicting when the next threshold may be reached or when it will taper off—and all the while the phone is ringing with customers asking, 'What is going to happen to my operation in six, twelve, twenty-four hours?'"

Next-Generation Models

In the past, models were developed to study pieces of the system, rather than to go from the sun to a forecast in a single step. While CISM has improved the models that describe regions of space, they have focused on coupling them together in a "Sun-to-the-Earth" chain.



This "lightbulb" coronal mass ejection (CME) shows the three classical parts of a CME: leading edge, void, and core. Taken Feb. 27, 2000 by the LASCO C3 coronagraph. In coronagraph images, direct sunlight is blocked, revealing the surrounding faint corona. The approximate size of the Sun is represented by the white circle. *Image: http://sohowww.nascom.nasa.gov/gallery/top10/top10_detail_c3bulb_cropt.html*

Because of those innovations, two main advances in the forecasting ability of SWPC are expected. First, it will be possible to predict, up to a week in advance, the varying structure of the solar wind, important to forecasting power disruptions. This component went into routine operation at SWPC in fall 2011.

Second, technologies are being transferred to model the magnetosphere and ionosphere. These are important for polar flights and communications. Forecasters will be able to model the Earth's environment from the upper atmosphere (~100 km above sea level to distances just beyond the moon. For comparison, 100 km is below the orbit of the space shuttle (200 km), below satellite orbits (above 400 km), and at the lower boundary of the ionosphere (important for radio transmissions). Operational use is expected in the 2013-2014 time frame.

"The CISM-SWPC partnership is going to accelerate the transition of models into operational practice," says Howard Singer, chief of the SWPC science and technology infusion branch. "We've been able to give CISM researchers information about what the needs are, and they, in turn, provide us models that we can run in our test bed, determine what sort of improvements are needed, and feed that back to the developers. There's a nice synergy here, and a good interaction between scientists, developers, and users."

A closeup of an erupting prominence with Earth inset at the approximate scale of the image. Taken July 1, 2002. *Image: SOHO Top 10 Images, http://sohowww.nascom.nasa.gov/*

EDUCATING THE NEXT GENERATION OF "SUN-TO-EARTH" SCIENTISTS

"Typically our field has thought of itself as several related but separate disciplines—solar physicists, interplanetary medium types, the magnetosphere types, the upper atmosphere specialists," says CISM director Jeffrey Hughes.

"Part of what CISM is trying to do is to make everybody think, 'You're a space-physicist sun-Earth-system person,'" says Hughes. "Maybe you concentrate on a certain piece of it, but you're studying part of a larger system, and you think of it that way."

Executive director Jack Quinn contrasts this approach to his own experience. "When we were graduate students, I learned primarily about the Earth's magnetosphere, and I was involved in team science—because space science has always been team science—but it was teams of other magnetospheric physicists," he reflects. "Now, the students in CISM are growing up interacting all the time with all of those different, previously separate disciplines—to them, it's the way it should be. It's normal."

Moreover, they're gaining other professional skills—things like action items, due dates, publishing, fund

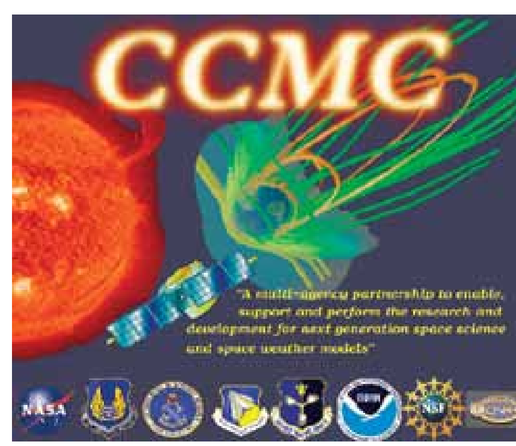
raising, and knowledge transfer. "They're getting a leg up on what we learned much later on," says Hughes.

To help prepare incoming graduate students, CISM organizes a space weather summer school. Lectures in the mornings are complemented by hands-on sessions in the afternoon in which students gain experience with CISM models and software.

Part of the transformation taking place is the development of pathways for diverse students to enter the discipline. In order to increase the participation of African American students in this field, CISM has helped establish a graduate program in space science at Alabama A&M University. The effort builds upon an existing undergraduate physics specialty in space science there, "so now a track exists for students to continue their graduate studies as members of the CISM team," say the CISM directors.

HOW'S THE WEATHER TODAY?

Our planet is bathed in a solar wind—the continuous flow of matter blown away from the sun, traveling through space at speeds of up to 1.5 million miles per hour. The composition of the solar wind resembles the sun itself: mostly protons—hydrogen atoms stripped of their electrons—and other elements. When the particles are trapped along the Earth's magnetic field lines at high latitude, we see the effects as auroras, the delicate, shifting curtains of light in the night sky. When an aurora is seen at lower latitudes, it's a sign of solar storms. The largest are caused by solar flares and coronal mass ejections (CMEs). Flares last for minutes or hours and originate in a thin layer close to the sun's visible surface. They give off energetic particles and high-energy photons, including ultraviolet light, X-rays, and gamma rays. Traveling at the speed of light, the light waves reach the Earth days ahead of particles released in the same event. Flare activity usually follows the 11-year sunspot cycle. CMEs consist of matter thrown out from the corona, the sun's outer atmosphere, visible as the "halo" during a total eclipse. These events occur when the magnetic field lines get tangled due to different rates of rotation of the sun's polar and equatorial regions. The tangled lines can snap in a violent explosion, spewing huge volumes of solar atmosphere at speeds of up to several million miles per hour.



CISM MODELS REACH SCIENTISTS AROUND THE WORLD

Want to run your own simulation of space weather? Researchers can, thanks to a multiagency partnership called the Community Coordinated Modeling Center (CCMC). Models developed at CISM and by other scientists are made available over the Web at no cost for use by researchers around the country and the world through the CCMC. http://ccmc.gsfc.nasa.gov

NEWS WATCH

A NEW "HEADS UP" ON SOLAR STORMS

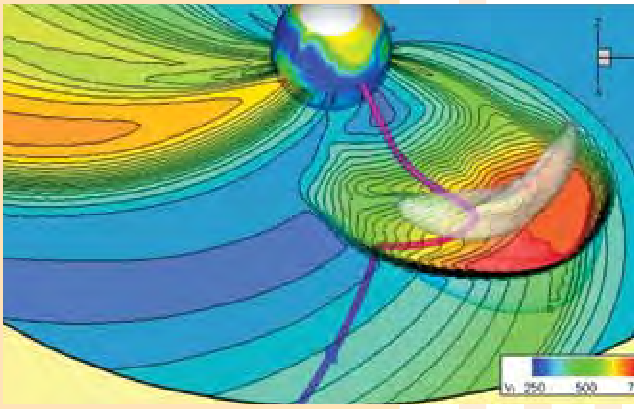
The first physics-based model for predicting space weather transitioned from research to operation in October 2011.

The development responds to the growing need to protect global communications infrastructure from severe space weather disruptions. With the next solar maximum expected by 2013, the deployment comes not a moment too soon.

The model will provide advance warning of high speed streams of solar plasma and coronal mass ejections (CMEs) that may severely disrupt or damage space- and ground-based communications and satellite operations. It's an outgrowth of a partnership between the Center for Integrated Space Weather Modeling (CISM) and the Space Weather Prediction Center of the National Oceanic and Atmospheric Administration (NOAA).

"It's very exciting to pioneer a path from research to operations in space weather," says CISM director Jeffrey Hughes of Boston University. "The science is having a real impact on the practical problem of predicting when solar storms will affect us here on Earth."

The model uses maps of the magnetic fields on the surface of the sun, derived from telescope observations, and predicts what the solar wind will be like for the next few days. "It completely revolutionizes how these predictions are made," says Hughes. Previously, forecasters just estimated the speed of the solar wind and assumed it would have that speed all the way to Earth. "This is actually doing a physics calculation of how the solar wind is going to evolve," adding that it predicts not only the solar wind at Earth, but at other points in space—"on Venus if you like." It's a capability likely to grow in importance as space tourism and manned space explorations take flight in the future.

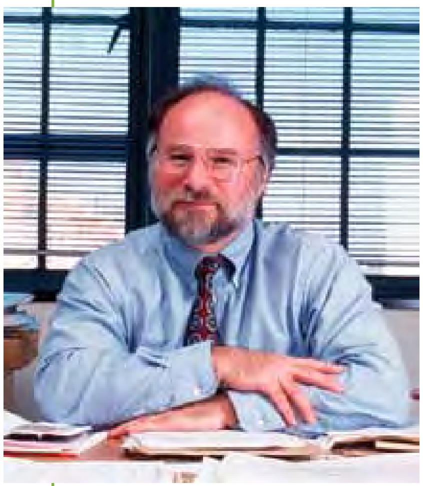


A coronal mass ejection (CME) in a model. The CME is the gray cloud toward the lower right. Image: Dusan Odstrcil, George Mason University

A CONVERSATION WITH THE DIRECTORS

Jeffrey Hughes & Jack Quinn

"If a center is to be successful, it's got to have a clear idea of why it needs to be one, and what it is that makes the center important," says CISM director Jeffrey Hughes.



CISM director Jeffrey Hughes

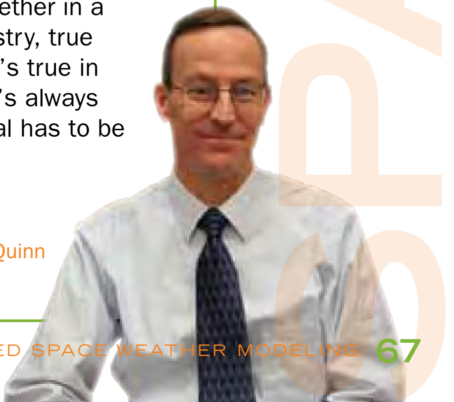
"If the reason is just 'We're going to enhance research in this field,' it probably shouldn't be a center. The approach should be employed in carefully selected cases in which the problem warrants this treatment—'Here's a problem that none of us can tackle alone. The goal is worth it, this kind of investment is needed.'"

The goal of modeling work at CISM is threefold: to support science, to supply forecasting tools, and to develop teaching tools. From the beginning, Hughes saw this as a natural fit with the integrated STC goals of scientific research, knowledge transfer, and education.

"We're an STC that's known even before we wrote the proposal what we wanted to do. That doesn't make the task any easier," he laughs, "but at least it was clear."

It's a balancing act to divide his time on science, education, and center management, says Hughes. "It's still a bigger management task than we thought, and we're coming to grips with that."

Executive director Jack Quinn points out, "there's a certain energy overhead in centers, but that's part of working together in a team. That's true in industry, true in engineering projects, it's true in building hardware—there's always that overhead. So the goal has to be worth that."



CISM executive director Jack Quinn

Bernard Kippelen of Georgia Tech, front, holds solar cell (inset). *Photos: Nicole Cappello, Georgia Tech.*

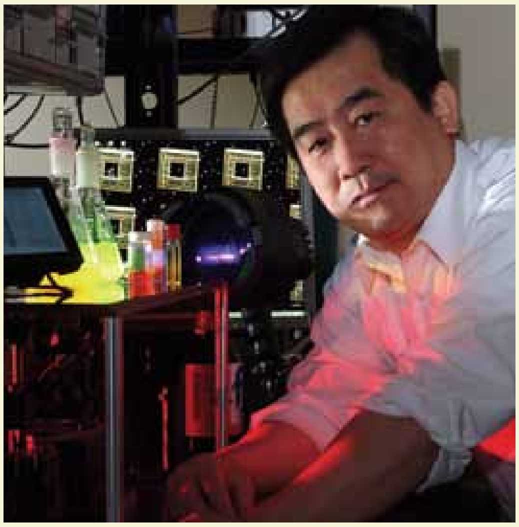
CENTER ON MATERIALS AND DEVICES FOR INFORMATION TECHNOLOGY RESEARCH CMDITR

CENTER HAS ITS "HIGH BEAMS" ON

Existing electronic and photonic devices based on inorganic materials such as silicon, gallium arsenide, and lithium niobate are about to "hit the wall"—that is, they are approaching their practical limits in terms of speed, flexibility, and cost.

Researchers at the Center on Materials and Devices for Information Technology Research (CMDITR) are working on organic-materials-based technologies that may provide attractive alternatives to those based on inorganic materials. Outcomes of center research are expected to provide the technological foundation for a thousandfold increase in throughput of telecommunications and information systems.

The center's research program has helped to attract interest from federal agencies, says center researcher Larry Dalton, emeritus professor of chemistry at the University of Washington (UW) and founding director of the center. "NSF-funded technology has produced complementary interest among mission-oriented agencies to focus on translation of basic research into defense applications."



UW Professor Alex Jen; At right: Susan Ermer, Lockheed Martin Corp.

Ultimately, center researchers hope to lay the groundwork for radically new approaches to the design of computers and sensors, with a move to ultrafast "all-optical" technologies and ubiquitous, embedded systems. CMDITR research will be key to the development of next-generation radar and navigation systems that will enhance U.S. defense capabilities, transform transportation, and facilitate space exploration.

Benefits in the energy sector are also targeted, including the commercial deployment of practical, inexpensive, and lightweight solar cells.

The manufacturing operations needed to produce organic-based technologies not only will provide exquisite control of material structure on very small scales, but are also expected to employ manufacturing processes and materials that are safer, cheaper, and more environmentally benign than those employed in the silicon-based semiconductor industry.

One research area, led by Alex Jen, UW professor and Boeing/Johnson Chair of Materials Science and Engineering, concerns electro-optic (E-O) materials, used to convert information between the electronic and photonic (light) domains at ultrahigh speeds. These materials can be used in devices called electro-optic modulators that transform electrical signals into optical signals and back again as signals enter and leave the ends of a fiber-optic cable. If you've made a long-distance telephone call lately, you've likely used electro-optic modulators.

The process involves the fast and efficient manipulation of the refractive index (ability to modulate light) of a material with an applied electric field. Efforts at the center are therefore aimed at developing suitable materials with high E-O activity, a measure of a material's ability to undergo change in its refractive index with an applied field.

CMDITR researchers have developed and tested a class of novel organic materials that achieve an order of magnitude improvement in E-O activity compared to the best inorganic rivals. The new materials also are specially designed to self-assemble into a structure that facilitates fabrication for computing and communication applications, explains Jen, who is director of the UW Institute of Advanced Materials and Technology.

The new high E-O materials offer several advantages: They can be produced in thin films with much smaller size than their inorganic counterparts, offering the possibility of higher density of integration and higher speed and bandwidth for information technology applications. Devices made of these new materials also have the advantage of a lower drive voltage and therefore, lower power consumption.

This research thrust is of keen interest to Susan Ermer of Lockheed Martin, an industrial affiliate of the center since its inception. Ermer works on the research side of the organization—as she puts it, the side required to "have the high beams on."

"We have ongoing projects in the area of electro-optic materials and devices and we know that this center has creative expertise and depth of knowledge and extensive networks. We've got a long-standing interest in this very specific area, but beyond that, we also see that this interdisciplinary group of people who have been brought together in the center are the ones that have the headlights on into the future," she says.

"In industry, you often have many people who have no choice but to be putting out brushfires, and that's what keeps the enterprise going," says Ermer. "As a research site, though, we should be looking to the future, but very frequently we're tied up in day-to-day things. The relationship with the center allows us to have these pioneers scouting out there and we get the benefit of that." □

VIEWPOINT

A CONVERSATION WITH
Phil Reid

When you recently took the helm as center director, what were your main challenges?

After you get your second five years of funding, you start thinking about transitioning things. What's next, how are you going to take the science and the technology you've got going right now and make sure it lives past the end of the center. This has been our strategy all along—basically take the individual components and spin them off to self-sustaining centers in their own right. We have really talented researchers throughout the center who can provide leadership for these spinoffs—it was just a matter of going out and getting those new grants.

One such effort, located at the University of Arizona (UA) is an NSF Engineering Research Center founded in 2008 and led by Nasser Peyghambarian. It's taking the kinds of information technologies we've worked with and turning them into integrated networks–so it's kind of the next level of engineering beyond the individual device. Called the Center for Integrated Access Networks, or CIAN, it aims to create an advanced optical access network capable of delivering data more than a thousand times faster to users at lower cost than they now pay to connect to information data bases and communication networks.

On another front at UA, Neal Armstrong is leading a new Energy Frontier Research Center involved with charge transport and interfacial aspects of photovoltaic systems, again, building on work that was part of the STC. The Center for Interface Science: Hybrid Solar-Electric Materials was established in 2009 with a $15-million grant from the Department of Energy. That research is aimed at "Generation III" photovoltaic materials that are thin, flexible, and inexpensive enough to go in many applications–from rooftops to windows, awnings, even clothing.

As you near graduation from NSF STC support, how do you view the outcomes of the center?

One of the basic ideas the center was founded on was to develop techniques and approaches that allow the rational design of materials; that goal required a significant theoretical undertaking. The theoretical work we've done in order to predict the performance of materials has been substantial. We've realized that accomplishment and the work has been featured on a couple of journal covers–so there is fundamental science that we are definitely very proud of.

We've also seen organic materials come a long way. At the beginning, they had so much promise, but the fact of the matter was that people were not convinced they were robust enough thermally or photochemically to serve in a device over the long term. Just recently, the first organic materials for electro-optic switches met Telecordia standards–the industrial standard that devices have to pass in order to be commercially viable. So we've come all the way from ten years ago, when people were saying, "well, organic materials should be good for these applications, let's give it a shot," to today, with organic materials that are now recognized by the industry as being robust enough to put in applications. That's a pretty substantial accomplishment.

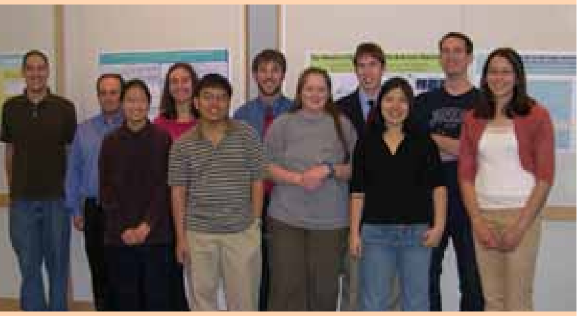
What's next?

You have this conversation about the center sunseting, but I just don't see this as an end; I see it as a new beginning, we're just moving forward. Now instead of just one center doing all these things, we've got centers on our various campuses all going after these activities, and I think the infrastructure we built to pursue nanophotonics and information technologies is really exciting–I see that as "CMDITR 2.0."

NEWS WATCH

HOOKED ON PHOTONICS

The center is trying to promote the interest of undergraduates in research with its program of summer research experiences, called "Hooked on Photonics." The program has a particular focus on lower-division undergraduates from community colleges and small four-year colleges—the so-called "gateway" undergraduates, or students with no exposure to research at their home institutions.



Left: Chemistry professor Phil Reid leads Hooked on Phonics.

OPSIS AIMS TO LOWER THE BARRIER TO MAKING SILICON PHOTONIC CHIPS

The University of Washington (UW) recently launched a program, co-funded by Intel Corp., that aims to make it dramatically easier and cheaper to manufacture silicon chips that combine light and electronics. This program will provide access to high-end semiconductor manufacturing capabilities, enabling any researcher in the world to build integrated electronic-photonic circuits in silicon.

It's called Optoelectronics Systems Integration in Silicon, or OpSIS, and it is hosted by the UW's new Institute for Photonic Integration, led by CMDITR researcher Michael Hochberg, an electrical engineering professor.

OpSIS is loosely based on the model pioneered by MOSIS, the original and highly successful foundry service for electronic integrated circuits. Founded in 1981 at the University of Southern California, MOSIS helped combine many different circuits onto a single silicon wafer.

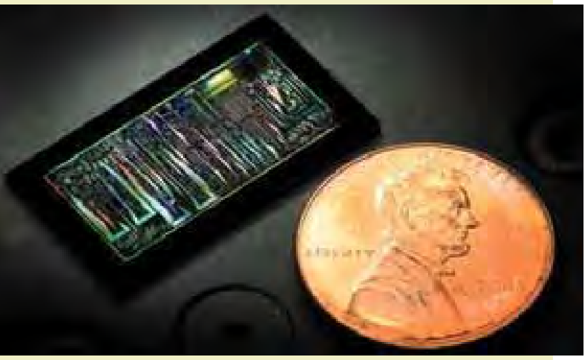
The OpSIS project will permit "shuttle runs" in which researchers cut costs by sharing silicon wafers between multiple projects. A single circuit design might use only a few square millimeters. Enabling shuttle runs, Hochberg said, can reduce costs by more than 100 times.

"OpSIS will enhance the education of U.S. engineering students, giving them the opportunity to learn the new optical design paradigm," says Justin Rattner, chief technology officer at Intel Corp. "The ability to produce such low-cost silicon chips that manipulate photons, instead of electrons, will lead to new inventions and new industries beyond just data communications, including low-cost sensors, new biomedical devices, and ultra-fast signal processors."

BUILDING A LEGACY: SUPPORT FROM SOLVAY FOR GEORGIA TECH ON ORGANIC LIGHT EMITTING DIODES AND PHOTOVOLTAICS

The Center for Organic Photonics and Electronics (COPE) was established at Georgia Tech as a vehicle to help provide a legacy for the STC so that center research at GT could continue once the STC funding was over, explains COPE founding director and CMDITR researcher Seth Marder.

An initial grant from industrial sponsor Solvay of over $4 million in 2007 was aimed at research on organic light-emitting diodes (OLEDs) and photovoltaic materials. OLEDs are thin films of organic molecules that give off light when electricity is applied. The devices could be used in everything from television and computer monitors to household lighting and handheld computing devices.



A photonic circuit next to a penny.
Photo: University of Washington

Solvay, an international chemical and pharmaceutical group headquartered in Belgium with units in many countries and a strong presence in Georgia, was looking to build a strong knowledge and innovation base in advanced materials for organic electronics, according to Léopold Demiddeleer of Solvay Corporate R&D and New Business Development. “COPE was right on target, at the right time and at the right location for us,” said Demiddeleer in the grant announcement at that time. “This winning partnership will take advantage of the world-class expertise of COPE and the industrial potential of Solvay in this highly challenging field. I consider this as the first critical step of a major long-term program for the company.”

And indeed, over a 5 year period, the Solvay-funded program at COPE expanded to cover surface modification of conductive oxide electrodes to improve charge injection properties and to include organic field effect transistors (OFETs).

As of 2011, Solvay had invested well over $10 million in the research at Georgia Tech, and in addition, helped to create new state-of-the-art facilities for organic electronic materials development. In January of 2011, Bernard Kippelen, a professor in GT’s School of Electrical and Computer Engineering and CMDITR researcher, took the helm as director.

Marder, a professor of chemistry and biochemistry who was recently named Regents’ Professor at Georga Tech, says the STC provided a “launching pad for us to get a lot of the research going that enabled us to attract Solvay as a sponsor. It is consistent with the STC’s philosophy to get work going and to inspire industrial support that both enhances the work going on within the STC and potentially, a vehicle to transition that work into industry.”

In 2008, Solvay created the Solvay Global Discovery Program, which now includes not only Georgia Tech faculty, but also researchers at the Chinese Academy of Sciences, (Beijing), Princeton University, University of Washington, and Imperial College London.

The collaboration has led to numerous patent applications and the creation of the Solvay-COPE Symposium, which includes both academic talks on cutting-edge research and an industrial forum to focus on issues related to transitioning new materials into commercial products. Industrial participants in the symposium have included companies such as Plextronics, Polyera, Cambridge Display Technology, Solamer, and Lockheed Martin Corporation, in addition to Solvay and others.

CENTER FOR ADAPTIVE OPTICS CfAO

ADVANCING THE SCIENCES OF SKY AND EYE

The Center for Adaptive Optics (CfAO) has brought together two very different worlds in science: one that treats the astronomically large, and another that treats the very small.

These realms—astronomy and vision science—have found common cause in the need for technologies to obtain very clear, sharp images. Together, they are advancing a remedy.

It's called adaptive optics (AO), a method for removing the blurring of images caused by changing distortions in optical systems. Turbulence in the Earth's atmosphere, for example, causes images of stars and planets to appear fuzzy. But by using adaptive optics, ground-based telescopes can see as clearly as if they were in space. Imperfections in the eye cause blurring of images, but adaptive optics for vision science provides a way to sharpen an image of the human retina.

Headquartered at the University of California, Santa Cruz (UCSC), the center has united a team of astronomers, physicists, engineers, and vision and life scientists in the quest for next-generation adaptive optics.

When the center started in 2000, AO wasn't something that the astronomy community had entirely accepted. NSF funding of the center helped make it a mainstay of astronomy—and transformed the field of vision science in the process.

"There has been a huge amount of cross-fertilization between those disparate communities," says center director Claire Max. "When we got started, there was one AO system for vision that was tentatively trying out what they could do. Now there are more than 50 instruments in clinical settings and university laboratories."

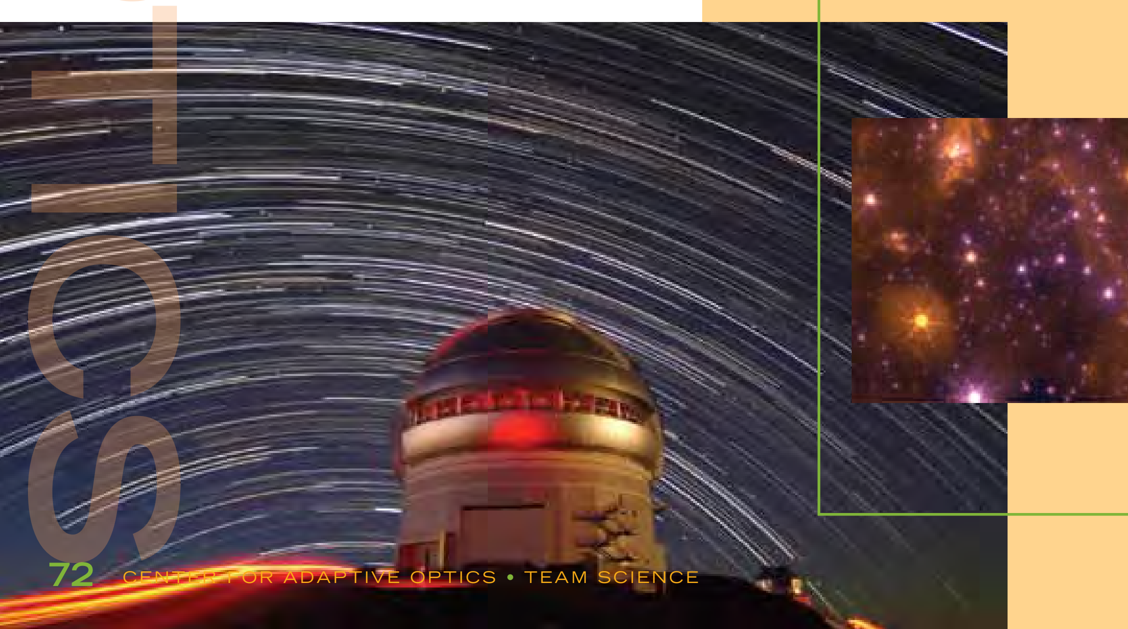
At the heart of an AO system is a wavefront analyzer along with a deformable mirror, which can change its shape rapidly to correct for distortions in the incoming light. In order to analyze the incoming wavefronts, a bright reference source of light is needed. In astronomy, the reference may be a bright star or an artificial star created by aiming a laser beam up into a sodium layer that surrounds the Earth at a height of about 100 km. It creates a spot of light called a laser guide star that can be used as a reference for measuring distortions caused by the Earth's atmosphere. In vision research, a laser reflected off a spot in the retina provides a reference.

Based on this information, commands are sent to actuators that exert force on the surface of the deformable mirror to change its shape—for the Earth's atmosphere, that means changing several hundred times a second.

Until recently, commercially available deformable mirrors have been relatively large and expensive, but for many applications, smaller and less-expensive mirrors are needed. The enabling technology is a micro-electromechanical system, or "MEMS," deformable mirror that consists of a reflective layer on top of a membrane under which are many tiny electrodes that impart forces on the mirror. Each device may have from hundreds to thousands of such deformation points.

The center has funded several companies including Boston Micromachines and Iris AO to spur improvements in MEMS deformable mirrors. "By setting benchmarks and performance characteristics to meet, we've helped to push the capabilities forward," notes Chris Le Maistre, managing director of CfAO.

One legacy of the center is the Laboratory for Adaptive Optics (LAO) at UCSC, a facility within the UCO/Lick Observatory established with more than $9 million from the Gordon & Betty Moore Foundation. The laboratory provides a place to develop and test new AO technologies and to train postdoctoral and graduate researchers. □



Left: Star Trails Over Gemini North in Mauna Kea, Hawaii. Approximately 2 hours of stacked exposures of the summer sky over Gemini North. The setting moon provided light on right of dome and twilight provides a glow to the left side of dome, a small red light provides highlight on center of dome. A star field has been offset by about 30 minutes to show individual stars separated from trails revealing Scorpius and Sagittarius over the Gemini dome.
Photo: Gemini Observatory

Inset: Narrow-field image of the Galactic Center. Exposures were obtained at 3.8 and 2.1 micron wavelengths, assigned a color, and combined to make a false-color image. Image is 10 arcseconds in size.
Photo: W. M. Keck Observatory

"We've been able to leverage off of a lot of the work that's being done in adaptive optics in astronomy to do much better things for vision science than we otherwise would have." — DAVID WILLIAMS

David Williams, University of Rochester

AO IN THE SERVICE OF VISION SCIENCE

"The Center for Adaptive Optics has given us contact with a branch of science that we would have no commerce with at all otherwise," says David Williams of the University of Rochester. "Just listening and learning about astronomy has been a real eye-opening experience for us," he laughs at the unintended pun. "That's been exhilarating, but at a more practical level, we've been able to leverage off of a lot of the work that's being done in adaptive optics in astronomy to do much better things for vision science than we otherwise would have."

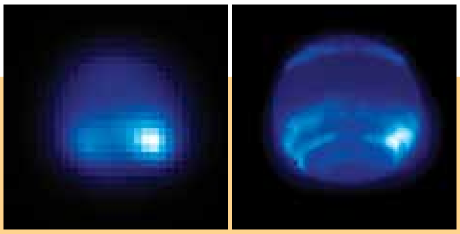
There are two main applications of AO in vision science. One has to do with correcting vision, namely, enhancements to the phoropter. If you've ever had an eye test, you know the phoropter—it's "that binocular thing you look through and the doctor asks you which is better, A or B, one or two," laughs Williams. Next-generation phoropters incorporating AO will determine your eye correction automatically in a fraction of a second. The technology is currently being developed for commercial instruments, he says.

The second application is to enhance retinal imaging for the diagnosis and treatment of eye diseases. For example, center researchers are using AO to image ganglion cells in the retina, important in treating glaucoma, one of the three major eye diseases. Using AO with fluorescence imaging, scientists are studying the layer of cells called the retinal pigment epithelial (RPE) cells, which are involved in macular degeneration. "Nobody had been able to see RPE cells in living eyes before," says Williams.

CfAO allowed vision science groups to build and maintain engineering expertise in AO, something that would not ordinarily be affordable for vision labs, says Williams. "The budgets would be prohibitively large—outside the scope of a typical NIH grant. Having the center helped us to jump-start this area of research," and it subsequently led to funding for two major research initiatives.

But the center mode of operation is not for every scientific project. What Williams worries about is over-hyping the team science. "What you need is a mix—and I don't know what the right balance is. It's very important to maintain both modes," he stresses. "It has to be grass roots, not top down. When you start to mandate something, that's when you lose the magic."

EDUCATION PROJECT YIELDS RESEARCH DIVIDENDS: EXPERIMENT IN INQUIRY-BASED TEACHING



Neptune observed in the near-infrared (1.65 microns) with and without adaptive optics. Neptune is the outermost of the giant planets in our solar system, but also has the most dynamic and rapidly-changing weather patterns. This near-infrared image is primarily sensitive to such high-altitude clouds, which appear bright against the darker disk. Adaptive optics allows ground-based telescopes to monitor Neptune's evolving weather systems and to use spectroscopy to probe different altitudes in its poorly-understood atmosphere. *Image: CfAO*

What started as a workshop opportunity for graduate students has led to unexpected dividends for researchers at the Center for Adaptive Optics and even for the university as a whole.

It was the brainstorm of education director Lisa Hunter to engage graduate students at the center in a workshop on how to teach inquiry-based learning of science for advanced high school students and undergraduates, in a process involving staff from the nearby San Francisco Exploratorium. Inquiry-based learning refers to learning science in the way that scientists actually think and work: by posing questions, designing and conducting experiments, and analyzing results.

Teaching science in this way has captured the imagination of graduate students and cultivated ideas that they have applied in their own research. It has generated a sense of community and has become "a platform that unites the whole center," notes CfAO director Claire Max. It also led to a bit of serendipity.

Through the workshop, a postdoc from astronomy met a graduate student in vision science and ended up helping to solve a problem with an optical system in the vision science lab.

The inquiry-based teaching experience has been made possible by long-term funding from the center grant. It led to the creation of a graduate course in the education department specifically for science and engineering graduate students.

CENTER FOR BEHAVIORAL NEUROSCIENCE CBN

UNDERSTANDING THE ROLES OF NATURE AND NURTURE IN ANIMAL BEHAVIOR

Mating. Aggression. Fear. Researchers at the Center for Behavioral Neuroscience (CBN) are trying to understand the basic neurobiology in animals involved in emotional responses such as these.

Above: Voles. Much of the work on social bonding behavior, or "affiliation," comes from studies of these animals.

Work in the center has helped to shed light on the roles of both nature and nurture in animal behavior. One important outcome is the understanding that hormones like vasopressin and oxytocin play important roles in the forming of social bonds and more generally, in the processing of social information.

Although researchers are still a long way from applying very many of the results to human beings, the hope is that this work "will be the underpinning for new drugs for things like autism and depression," among other conditions, says center director Elliott Albers, Regents professor at Georgia State University (GSU), the headquarters for CBN. In addition to GSU, the partnership has included Clark Atlanta University and Emory University, Georgia Institute of Technology, Morehouse College, Morehouse School of Medicine, and Spelman College.

Much of the work on social bonding behavior, or "affiliation," comes from studies of hamster-sized rodents called voles. They provide a good model for affiliation studies, explains Larry Young of Emory University, because one species of vole is very highly social and takes a life-long mate, while another species is not monogamous. "So, we can do comparative studies," says Young. "They look the same, but the behavior is very different, and we can look in the brain and find things that are different between the two species that might explain that difference in social behavior. The voles give us an opportunity to understand what that neurochemistry might be."

The researchers have found that genes for vasopressin (AVP) and oxytocin (OT) regulate social recognition. These hormones act on the brain's reward circuitry to regulate the formation of social attachments between animals. Amazingly, transferring a receptor gene for AVP into the brain increases social or pair-bonding behavior in male monogamous species of vole, and it makes the "promiscuous" male meadow voles monogamous.

Young, who has led the research group at CBN focusing on affiliation, notes that "this research, which was started in the center and has been going on for the past eight years, has really important broader implications for the study of autism, antisocial behavior, and social communication and bonding. It led to a much larger set of research efforts by others that show that these peptides also have some influence in human behavior. They've started to look at things like reading social information from the expressions of others."

The affiliation group is one of several so-called "collaboratories" that provide a research environment for about 15 to 20 researchers with similar interests.

In the fear collaboratory, led by Michael Davis of Emory, researchers have studied how we learn to be afraid of things. They're looking at how systems in the brain in the region called the amygdala are involved in conditioned emotional responses that lead to fear and anxiety, and the way in which individuals can overcome or unlearn this fear. The results hold promise for helping humans overcome post-traumatic stress disorder (PTSD), phobias, and anxiety disorders.

"The brain is plastic: it's made to change and reconfigure as function of experience. One of those changes is to acquire a response, another is to stop that response if it becomes inappropriate or detrimental," explains center co-director Walt Wilczynski. "If you are frightened by something, and it keeps happening but nothing bad happens to you, most people get used to that—they are no longer frightened, they become habituated to it." For example, when a door slams shut once, you may be startled, but if it shuts over and over again, most people ignore it.

Davis and colleagues have studied a protein in the amygdala, called the NMDA receptor, that's involved in habituation of fear. They have found that a drug that makes this receptor work better, called D-cycloserine, can enhance habituation, enabling people to lose their fear faster. D-cycloserine has already been shown to improve psychotherapy for several clinical disorders, such as fear of heights, fear of public speaking, panic disorder and obsessive compulsive disorder, says Davis, and soon it will be tested in PTSD, in which people can't habituate to a fearful memory. "This is a classic example of basic research in animals on emotional conditioning with potential applications for humans," says Wilczynski.

The leadership of CBN currently is planning for life beyond NSF center funding. One of the main legacies of the center is a major increase in faculty lines devoted to behavioral neuroscience. Funding from the Georgia Research Alliance, a government-university-industry partnership, contributed toward building that infrastructure. Over 30 new faculty lines in behavioral neuroscience have been added across all of the partner institutions.

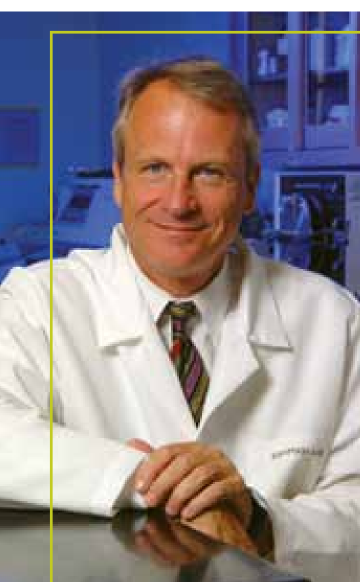
Young adds that the center has had a major effect on student recruitment to the field. "When I first came, most students didn't want to work in behavioral neuroscience because they didn't consider it to be a hard core science. But within just a few years, we completely turned the tides from behavioral neuroscience being unappealing to being a major draw of students," he notes.

What's going to emerge in the future, says Wilczynski, is more emphasis on translational and clinical research—trying to link basic research coming out of our labs with clinical problems. "And also more connections with industry—not only to see the research have an impact, but also for graduate and postdoctoral training. We have to start looking at a range of career choice for people coming out of our neuroscience graduate program."

FROM THE DIRECTOR

Elliott Albers

VIEWPOINT



Elliott Albers

"In Atlanta, we have developed a community of investigators—we all know each other, we communicate frequently, and we work together on research and educational projects, so it's been a transformation of how we do science here," says CBN director Elliott Albers, Regents professor at Georgia State University and member of the Neuropsychology & Behavioral Neuroscience Program.

These relationships take a long time to establish, "and that's one reason why the NSF STC program really has it right: it gives you ten years," he affirms.

As a result, "we're increasing diversity in the field of neuroscience, developing courses that never would have happened, and we're doing research projects that wouldn't have happened otherwise," says Albers.

"Resources provided by the Science and Technology Center (STC) program allow us to really develop an inter-institutional interdisciplinary center," says Albers. "It's probably impossible to do that in a situation where you don't have some pool of money that's really dedicated to accomplishing that goal."

"Disciplines receive the budget lines at most institutions—biology or chemistry or whatever. And people don't easily give those resources up to an interdisciplinary group. So without some mechanism like this, it just doesn't happen to any significant extent," observes Albers.

We're still struggling in society to find the right balance between single investigator efforts and team science," says center co-director Walt Wilczynski. "Now and in the future, a lot of science will be generated by single investigator grants. The role of centers is to facilitate people doing that, rather than directing people to work together on a particular problem in a top-down approach." Vehicles developed by CBN to promote collaboration, like venture grants and postdoctoral fellows grants, have been key.

"The philosophy of the CBN is that we provide guidance and we can help frame questions in general, but the interactions and particular collaborations are really a bottom-up approach. We facilitate people getting together and we provide resources that provide an incentive for people to collaborate. But exactly what the project is, who those people are, and what their contribution is going to be is really dictated by the individuals involved. There's no way from the top down that you can predict or dictate exactly what an individual should contribute," says Wilczynski.

"There's a big social element in science that's often overlooked, and it's those social bonds that stimulate the collaboration," says Wilczynski.

It's probably not unexpected that a behavioral neuroscientist would analyze team science in that way. Wilczynski laughs and adds, "Just like the studies we do on social bonding, there's a lot of individual variation in that. Some people work extremely well just by themselves and some work extremely well as part of collaborative teams. And we've had both as part of the center."

CENTER FOR ENVIRONMENTALLY RESPONSIBLE SOLVENTS AND PROCESSES CERSP

SOLVENT-FREE METHODS OF CHEMICAL SYNTHESIS LEAD TO CANCER THERAPIES, NCI CENTER

"Once you get scientists and engineers working in an interdisciplinary manner, you can't contain it," laughs Joseph DeSimone, director of the Center for Environmentally Responsible Solvents and Processes (CERSP) and the William R. Kenan, Jr. Distinguished Professor of Chemistry and Chemical Engineering at the University of North Carolina, at Chapel Hill (UNC-CH).

CERSP director Joseph DeSimone

CERSP co-director Ruben Carbonell

"Things have evolved certainly beyond the original scope of our center. Starting off with a focus on sustainability and green chemistry has led us into new cancer therapies and imaging agents," says DeSimone.

CERSP's initial goal was to establish the scientific fundamentals necessary to enable liquid and supercritical CO_2 and solvent-free processes to replace aqueous and organic solvents in a large number of key processes in our nation's manufacturing sector.

More than 30 billion pounds of organic and halogenated solvents are used worldwide each year as manufacturing process aids, cleaning agents, and dispersants.

In the future, manufacturing and service industries must work to avoid the production, use, and subsequent release into the environment of contaminated water, volatile organic solvents, chlorofluorocarbons, and other noxious pollutants.

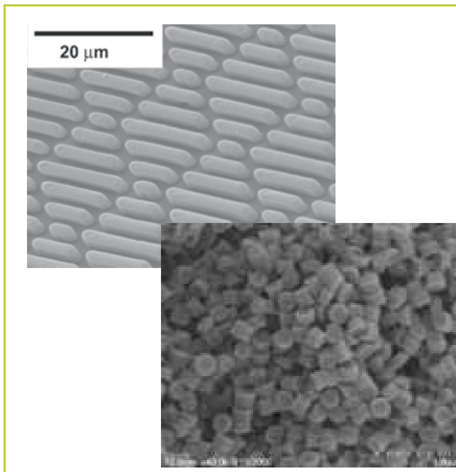
CERSP began as a multi-disciplinary effort with participants from five academic centers and two national laboratories: UNC-CH, North Carolina State University, North Carolina A&T University, University of Texas at Austin and the Georgia Institute of Technology.

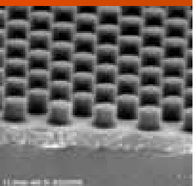
CERSP codirector Ruben Carbonell points out that many companies are focusing today on finding alternatives to fluorinated surfactants that break down into a compound called perfluorooctanoic acid, or C8, which accumulates in the body and may pose a health threat. Center researcher Keith Johnston and colleagues are looking at alternative surfactants that have different chemical structures that won't bio-accumulate and have good surfactant properties.

The manufacture of Teflon™ is a case in point. The conventional process uses a C8 surfactant to make an emulsion. An alternate synthesis, developed in the center, doesn't require any surfactants, says Carbonell. It's done completely in CO_2.

The process has been commercialized. "There's a DuPont plant in Fayetteville, North Carolina that makes Teflon™ in carbon dioxide. The technology, developed in DeSimone's lab, was licensed by DuPont several years ago," says Carbonell. One of the advantages is a smaller environmental footprint.

"There are no surfactants at all—it's just the monomer reacting in the presence of carbon dioxide. The particles grow, and when you reduce the pressure, the particles fall out of solution, completely dry and with no surfactant," says Carbonell. "And the process should be cheaper because there's no need to evaporate water at the end of the process. One of the major energy consumption points in making any polymer, but particularly Teflon-based materials, is that they're made in aqueous solvents or aqueous-organic emulsions. If you make it in CO_2 and depressurize, the polymer powder comes out completely dry. And the CO_2 is recycled for use."





Green Chemistry Pays Dividends for Research on Cancer Therapy

"What's curious—what has evolved—is that research on solvent-free methods has led to a new technology for making cancer therapeutics that we didn't anticipate," says DeSimone. It has led to us landing one of the eight centers of nanotechnology excellence funded by the National Cancer Institute, a $24-million center. It just shows the unbounded opportunities that happen when you get a bunch of good people together from different disciplines that are open-minded."

Initially, CERSP researchers were using carbon dioxide as a solvent-free method for making new fluoropolymers. They made some new materials that turned out to be excellent molding materials. The method called PRINT™—Particle Replication in Non-wetting Templates, was published in July 2005 issue of the *Journal of the American Chemical Society.*

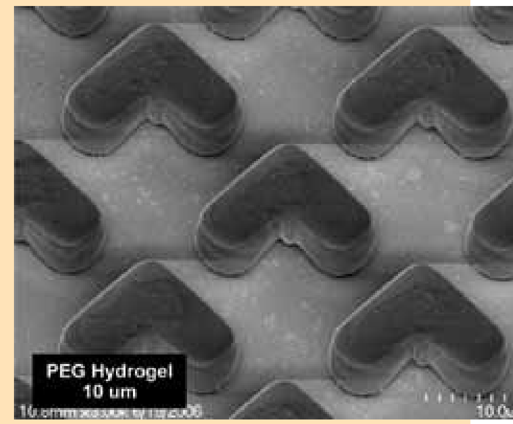
The process begins with a liquid fluoropolymer that can wet surfaces very well. It is poured into a master and irradiated to make an array of tiny molds, not unlike a little ice cube tray, which can be used subsequently for mass production of particles of uniform size and shape, creating features of nanometer size.

The breakthrough came when they realized these particles could be used in medicine. "We use these particles as basically a 'delivery truck' for therapeutics and imaging contrast agents," says DeSimone. "Because it's such a gentle technique—we're just molding—we can easily paint the particles with targeting ligands, like monoclonal antibodies. And so now we have particles that can have on the surface an antibody and in the interior have a therapeutic. We're beginning to develop the tools and methods for scale-up and we've now molded particles and done our first pharmacokinetic studies in mice to see the biodistribution of these organic carriers," says DeSimone. □

STARTUP COMPANY

LIQUIDIA MAKES NANO-ENGINEERED PRODUCTS FOR LIFE SCIENCES, ENERGY, AND MATERIALS SECTORS

Joseph DeSimone and his colleagues from CERSP at the University of North Carolina at Chapel Hill have created a startup company called Liquidia Technologies based upon the PRINT™ nanoscale molding process, targeting applications in the life sciences, energy, and materials sectors.

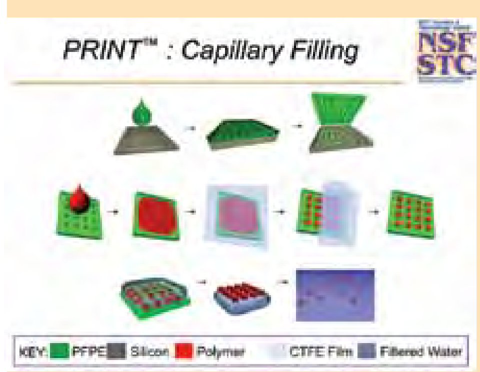


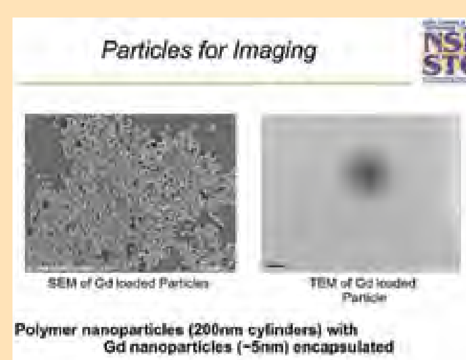
Founded in 2004, Liquidia is working to precisely design and manufacture micro- and nano-structures in bulk, with particle sizes ranging from tens of nanometers to tens of microns. These structures may take multiple forms, including particles and patterned films.

Liquidia has partnerships with several major corporations to provide gram quantities of material for prototyping and feasibility studies. Examples include supplying particles that might become part of a medical device or an active layer in a display, and making fuel cell membranes or active layers in photovoltaic devices.

The company had grown to 24 people as of spring 2007 and raised a total of $25 million, says co-founder and senior scientist Ginger Denison Rothrock, a former graduate student at CERSP. Located in Research Triangle Park and formerly squeezed into 4,000 sq ft—"quite cramped but loving it"—the company was scheduled to move into a 17,000-sq-ft facility in August 2007.

In the life sciences, Liquidia is using the PRINT™ process to make particles containing therapeutic drugs that may be used to deliver medicine to a target site and gradually release it. The PRINT process gives precise control over particle size, shape, composition, modulus, and surface properties. According to the company, "Liquidia is the only company in the world that can independently tailor these variables simultaneously in the creation of engineered drug therapies." Rothrock notes that discussions are underway with three major pharmaceutical companies for prototyping projects.





NANOBIOTECHNOLOGY CENTER NBTC

SMALL WORLD, BIG SCIENCE

The dream of developing tools and processes to interact with biosystems on the scale of individual cells and biomolecules has been the focus of researchers at the Nanobiotechnology Center (NBTC).

Researchers at NBTC have focused on the ways cells communicate with their environment at the molecular level. They have developed new devices to investigate these properties at the finest level of detail, approaching single molecule responses. Toward this end, the center has fostered close collaboration between life scientists, physical scientists, and engineers.

Center researchers have developed cell cultures “on a chip,” that is, cultures in a laboratory system that can more accurately model the response of humans to pathogens or therapeutic drugs, for example. These systems integrate different types of human cell tissue in a biological test platform that may significantly reduce the amount of animal testing involved in early-stage screening of new drugs.

Another group has worked on a laboratory model of the blood-brain barrier, which protects the brain from exposure to harmful substances in the blood stream. NBTC associate director Graham Kerslick explains that the researcher team can grow the required cell types on a sort of scaffold—a micropatterned polymer membrane—and can model how the barrier works when presented with various biomolecules, toxins, or drugs.

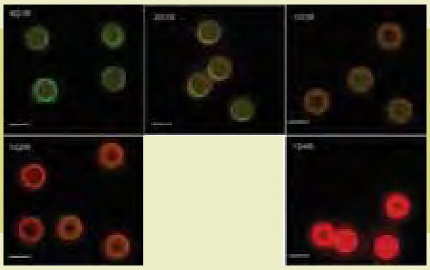
NBTC research by Kelvin Lee and colleagues on techniques to detect a suite of compounds associated with neurodegenerative diseases such as Alzheimer’s may yield a rapid diagnostic test for the disease. Currently, there is no definitive way to diagnose the condition in humans while still alive. The researchers are developing methods to detect a set of proteins in spinal fluid as a signature of the disease.

Biological imaging technology has gained a boost from the development of a new kind of nanoparticle called Cornell dots, or CU dots for short. These silica nanoparticles may be used in displays, biological imaging, optical computing, and sensors. CU dots offer many advantages over the previous technologies for imaging: not only are they many times brighter than single fluorescent dye molecules, they don’t fade as much as the alternative, called quantum dots. They provide a more constant light source and are less expensive and more inert than quantum dots.

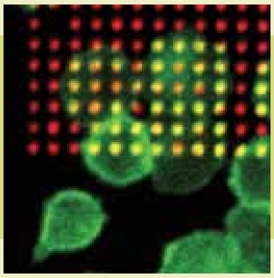
The brightly glowing particles contain fluorescent dye molecules surrounded by a protective silica shell, forming a package of about 25 nanometers in diameter. The surface may be coated with ligands to allow the particles to attach to species of interest. Harvey Hoch, chair of plant pathology at Cornell, Geneva, N.Y., notes this development is a “significant contribution. It will provide a good marker for cell studies—it’s a nice tool for microscopists and cell biologists.” Hoch is a leader in using micro- and nanofabrication technologies to address questions in biology.

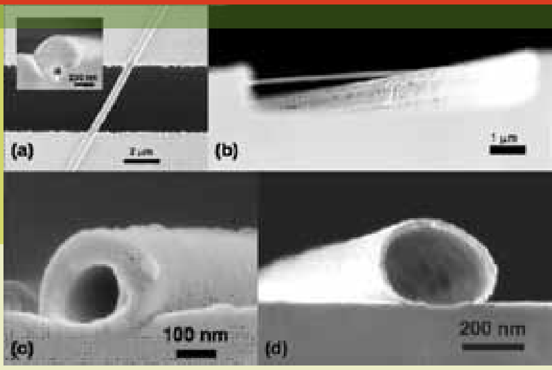
Kerslick notes the CU dot technology was licensed by Cornell to a startup company called Hybrid Silicon Technologies, Ithaca, which is looking to commercialize the capabilities of fluorescent silica nanoparticles for biological imaging applications.

On another front, a group led by Dan Luo of Cornell has created “nanobarcodes” that can be used to rapidly identify genes, pathogens, drugs, and other chemicals.



Merged fluorescent colors (pseudocolors) of nanobarcodes from individual polystyrene microbeads under a fluorescent microscope. Note that only two colors were used in the barcodes. (from *Nature Biotechnology,* 23, p. 883, 2005) *Photo: NBTC, BDA7*





Electrospun polymer nanofibers were used as templates for creating nanochannels in a variety of materials. (a) Top-down view of suspended sputtered glass nanochannel, with cross-section on bare silicon. (b) Side view of suspended glass nanochannel. (c) Cross section of chemical vapor deposited glass nanochannel. (d) Cross section of evaporated aluminum nanochannel. *Image: NBTC, BDA2*

The technique uses multicolor fluorescent tags made out of synthetic DNA that attach to the target species. Under UV light, the tags produce a combination of colors unique to the species of interest, and can be read by a computer scanner or microscope. The method has been shown to distinguish several different pathogens simultaneously.

Luo, a professor of biological and environmental engineering, has utilized short strands of DNA molecules that can self-assemble into unusual shapes. By linking these DNA structures to polystyrene molecules, he created tiny geodesic spheres about 400 nm in diameter that could carry drugs into cells, among other potential applications. DNA buckyballs created by Luo were selected by *R&D Magazine* as one of the 25 "most innovative products of 2006" in the Inaugural MicroNano 25 competition. The winners were featured the August 2006 issue of *R&D.*

Luo's research on using DNA to construct new materials and nanodevices is being commercialized by an Ithaca startup company called DNANO Systems. The company won second place at the 7th Cornell BR Ventures Business Idea Competition. The company also received funding from NYSTAR (New York Office of Science, Technology & Academic Research), which supports technology development and commercialization in New York State. □

"IT'S A NANO WORLD" TRAVELING EXHIBITION

What if you could shrink to the size of a cell and zip through a blood vessel, or see what skin and hair are made of at the molecular level?

Thanks to an exhibit developed with the help of the Nanobiotechnology Center at Cornell University, you almost can. Working with the Sciencenter, Ithaca, N.Y., and its contractors, including Painted Universe Inc., also of Ithaca the team created a traveling 3,000 square-foot hands-on interactive museum exhibition that introduces children and their families around the country to the biological wonders of the very tiny.

"It's a Nano World" exhibition has traveled the U.S., even making a stop at Innoventions at Epcot in Lake Buena Vista, Fla., in 2004. The target audience for this traveling exhibition is 5 to 8 year-old children (K-3).

At one station in the exhibit, visitors can view highly magnified photographs of familiar objects like a penny or a bee and uncover photos with decreasing levels of magnification until an easily recognizable photo of the item is revealed. At another station, visitors can stick their hands into a glove box and use special tools to separate out different "cells" based on physical properties. The "Scope on a Rope" station has flexible projection microscopes to let visitors look at their own skin, hair, and clothing, magnified either 30 or 200 times.

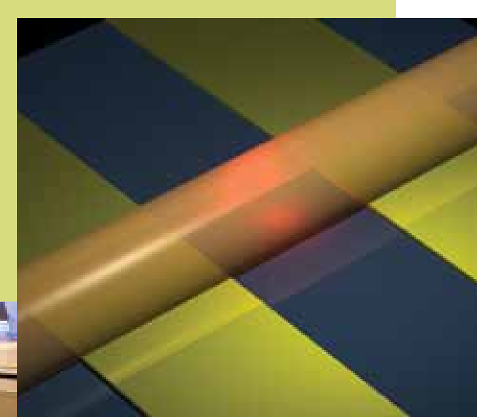
The exhibition began touring in Winter 2003, and has been seen by more than 1 million visitors at museums throughout the U.S. The project was primarily funded by the Nanobiotechnology Center (NBTC) at Cornell University through a grant from the National Science Foundation.

Check the exhibit's web site for a current schedule of locations: http://www.itsananoworld.org/

NANOLAMPS LIGHT THE WAY TO NEW FLEXIBLE ELECTRONICS DEVICES

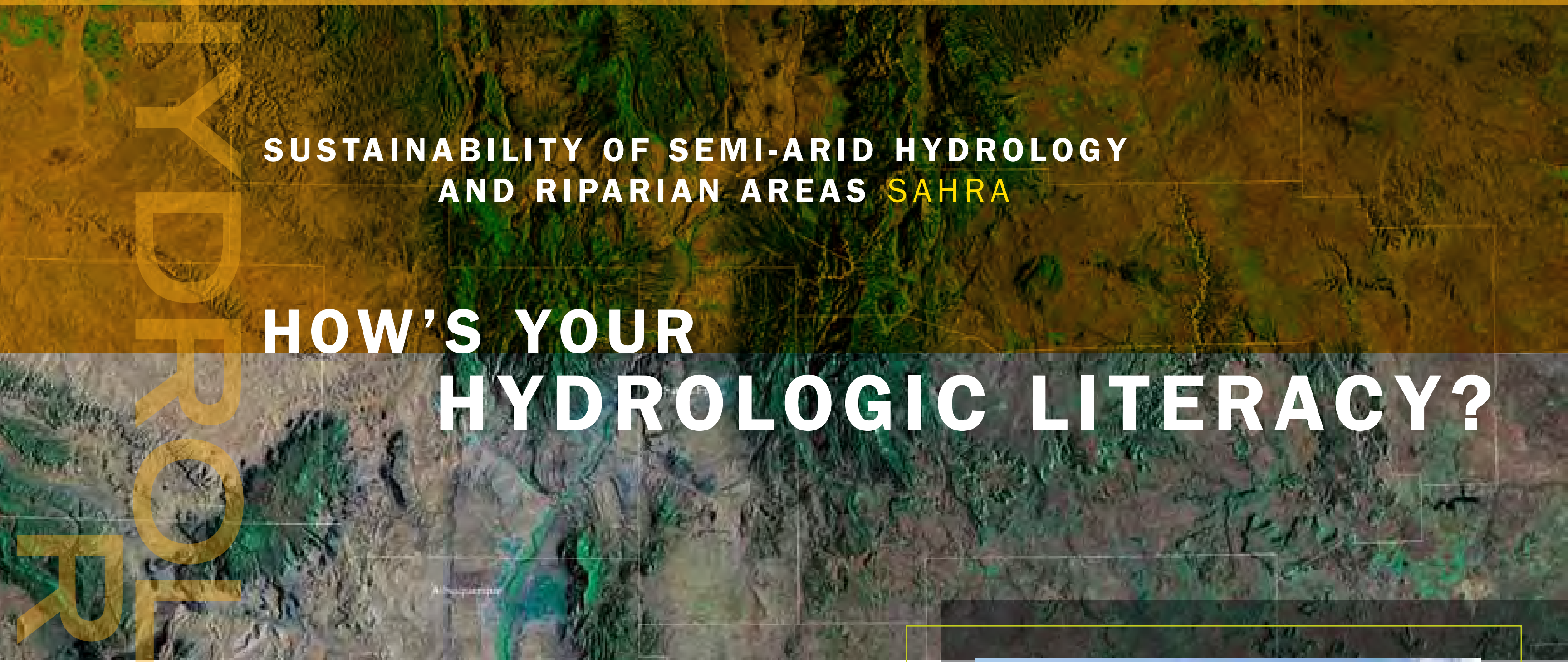
Center researchers have produced microscopic "nanolamps"—light-emitting nanofibers about the size of a virus or bacterium. It's one of the smallest organic light-emitting devices to date, made of fibers just 200 nanometers wide. Potential applications include sensing, microscopy, and flat-panel displays. The work was published in *Nano Letters.*

At right: An illustrated closeup of an electrospun fiber. During experimentation the organic devices gave off an orange glow. *Photo: Jose M. Moran-Mirabal*



NEWS WATCH

Image at left shows cell receptors that mount on a cell's surface and detect foreign bodies like allergens. Patterned "nano-keys" allow receptors to cluster in a way that activates the cell's inner machinery. *Photo: Wu, Holowka, Craighead, and Baird*



SUSTAINABILITY OF SEMI-ARID HYDROLOGY AND RIPARIAN AREAS SAHRA

HOW'S YOUR HYDROLOGIC LITERACY?

Semi-arid regions cover 1/3 of the terrestrial earth surface and contain the fastest growing populations in both the U.S. and around the world.

Water sources for these regions are regional groundwater and river systems, both primarily recharged by precipitation in high elevation areas, often far from urban and agricultural demand.

Changes in climate and land cover are affecting the amount and timing of renewable water resources as runoff and recharge.

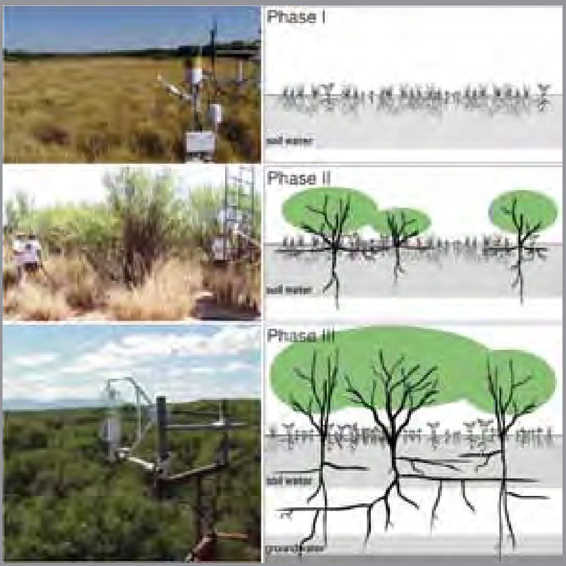
Increased demand from growing populations and changes in supply require new management strategies.

These are just some of the challenges faced by planners and stakeholders in the U.S. and around the globe when it comes to water resources. Improving the sustainability of these resources is a job that rests with elected officials, water managers, and policy experts at local, state, and national levels. Researchers and scientists must help inform these decision makers through focused research and dedicated efforts at knowledge transfer.

To address these needs, the Science and Technology Center for Sustainability of semi-Arid Hydrology and Riparian Areas (SAHRA) set out in 2000 to promote sustainable management of water resources by conducting water resources-related science, education, and knowledge transfer in the context of critical water management issues of semiarid and arid regions.

The center, based at the University of Arizona, included the partnership of over 100 other institutions. Since inception, it has trained 222 graduate students, published over 450 peer reviewed papers and 27 books, developed novel hydrological models, and established unique capabilities in science-stakeholder engagement.

Collecting water samples in the Upper Rio Grande of Colorado for geochemical studies on water and salt sources.



SAHRA researchers have found that encroachment of shrubs into grasslands has increased water loss from the sub-surface.

At top: Landsat image of New Mexico.
Photo: Image courtesy of USGS National Center for EROS and NASA Landsat Project Science Office, http://eros.usgs.gov/Imagegallery/

"The Center was unequivocally successful in meeting this mission with a legacy of research, education, knowledge transfer, and international activities that continues both at the University of Arizona and at numerous partner organizations," notes SAHRA director Paul Brooks. "The center continues to address critical issues in hydrology and water resources, building on the successes during STC funding."

"Sustainable" refers to the development and use of water resources in a manner that can be maintained in the long-term without causing unacceptable environmental, economic, or social consequences. As a university-centered effort, SAHRA research activities focus on the physical and behavioral sciences. However, the power to define unacceptable consequences and to improve sustainability of water resources properly rests with society through elected officials, resource managers, and stakeholders at local, state, and national levels. Beyond research, therefore, a major focus of SAHRA was, and continues to be, the development of effective mechanisms for synthesis, integration, education, and outreach, in support of better-informed decision-making.

Following the initial NSF award, SAHRA's focus is shifting toward promoting and facilitating the development of cutting edge, stakeholder-relevant, water-related basic research projects, while relying on established institutional strengths in translating that knowledge into usable products for resource managers. Since 2009, SAHRA has served as the springboard for over $15 million in current non-STC-funded research efforts including $4.5 million for a Critical Zone Observatory (CZO), $4.5 million for the COSMOS weather and climate program, and approximately $3 million for the Biosphere 2 Landscape Evolution Observatory.

Research Focus

SAHRA researchers organize their research around three critical questions related to the hydrology and water resources of semi-arid regions:

- *What are the impacts of vegetation change on the basin-scale water balance?*
- *What are the costs and benefits of riparian restoration and preservation?*
- *Under what conditions are water markets or water banking feasible?*

These three integrating questions were designed to maximize coordination among researchers from various fields. By placing their research within the context of these overarching questions, researchers were able to more rapidly develop the multi-disciplinary understanding needed to address knowledge gaps in semi-arid hydrology.

Research also is organized within the context of river basins. Just as the three questions were developed to link scientific disciplines, the focus on river basins, where management decisions are typically made, facilitates the transition of results into practice. The center's primary geographical focus is on: the Rio Grande/Rio Bravo, the Upper San Pedro River, and the Salt/Verde and lower Colorado River Basin. Human population centers, agricultural activities, and regional biodiversity all are concentrated along river systems, while river basins form natural management boundaries making a basin a fundamental study unit.

Decision Support Systems

Significant effort was placed in developing decision support tools that provided mechanisms to rapidly convey new findings to decisions makers and water managers. The Upper San Pedro Partnership brings together over 20 stakeholder organizations to use SAHRA decision support systems to help manage the region's limited water supply to evaluate possible future scenarios for developing and sustaining the ecosystem.

A novel aspect of this work is linking ecosystem water stress to economics. Center researchers are developing new ways to evaluate the impact of population and water use on the regional hydrology, how in turn those changes will affect vegetation and bird diversity and abundance, and ultimately, how tourists and residents respond to those changes. A unique aspect of this project is that the valuation study is directly driven by the science.

Water Markets and Water Leasing

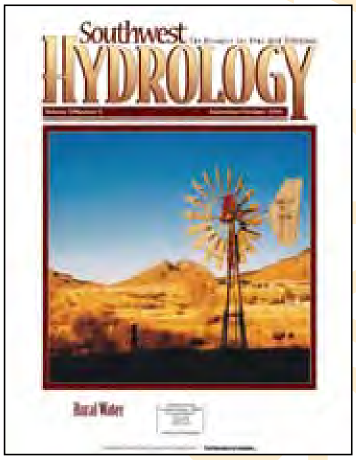
Increasingly, water markets and water banking are being considered in the Southwest as mechanisms for allocating water resources. The approach requires a detailed knowledge about factors that affect water supply and demand. Center researchers are developing new ways to improve estimates of precipitation and snow pack, and they are shedding light on the factors that affect residential and industrial demand for water. The results are being integrated into models that allow water resource managers to evaluate the potential of market-based mechanisms. Within the constraints of coupled physical, institutional, and behavioral models, SAHRA researchers developed a coupled model capable of evaluating economic and hydrologic impacts (including third-party effects) of water leasing on the middle Rio Grande and in the Mimbres river basin.

Integrated Environmental Observatories

As various earth science communities were exploring the need for integrated, multi-disciplinary observatories, SAHRA established a prototype observatory as part of its basin-scale water balance research theme. The research approach involves an integrated program of observation, modeling, and experimentation with targeted distributed data collection to assess the transferability of knowledge from individual sites to the region. These efforts have greatly improved our understanding of ecohydrological interactions and biophysical processes at plant to regional scales, on topics such as atmospheric drivers of vegetation change, snow accumulation and melt, and how vegetation affects soil moisture supply. These efforts informed both SAHRA stakeholders and the recently funded Jemez-Santa Catalina Critical Zone Observatory funded by the National Science Foundation.

Traditional and Non-Traditional Education

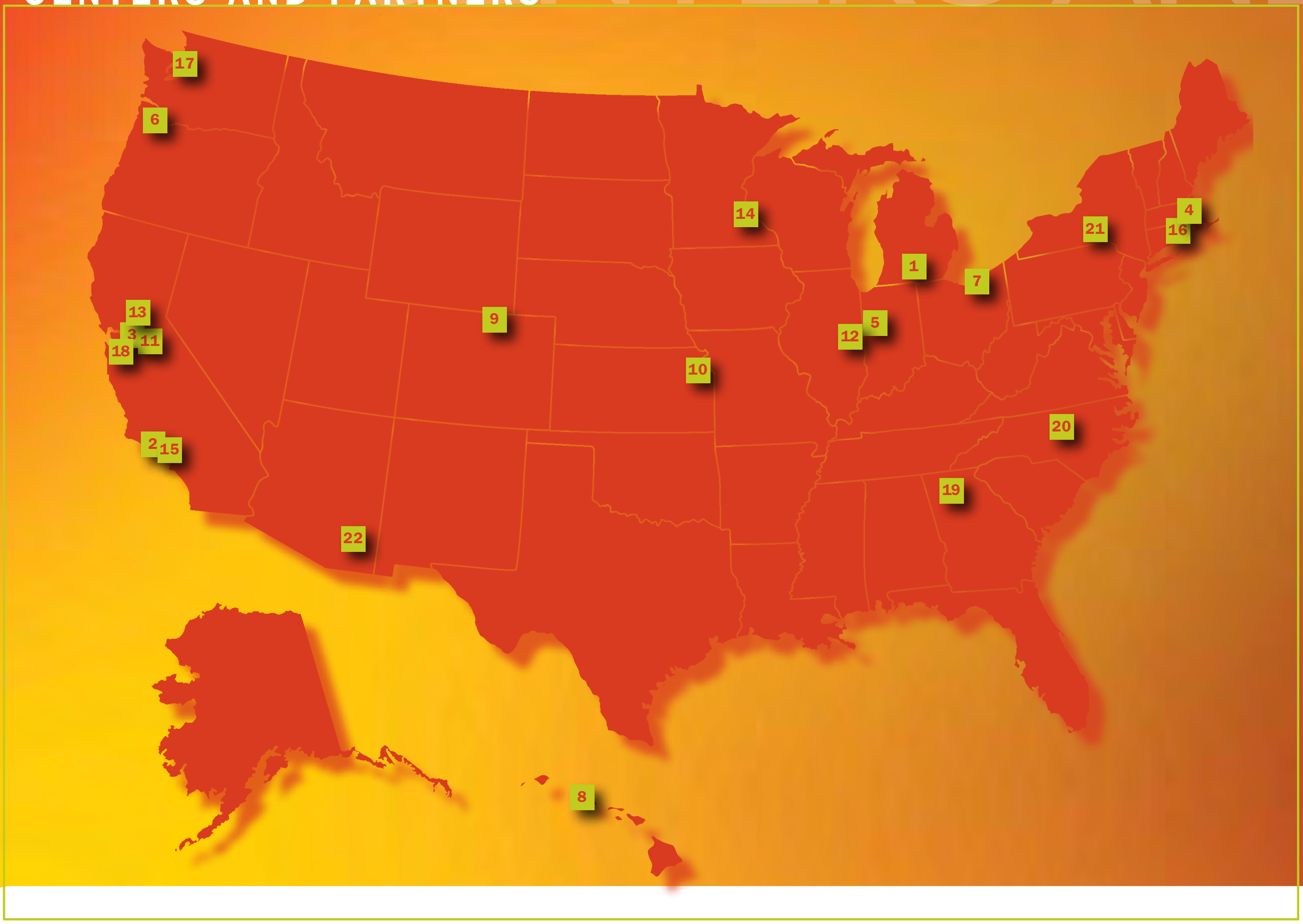
Outreach and education are a major emphasis of SAHRA, with notable efforts in classroom learning from primary school through university and other publications for water professionals.



For example, *Southwest Hydrology* was a full-color, trade magazine published bimonthly and distributed free of charge to water professionals throughout the Southwest. The magazine promoted communication with a broad spectrum of water experts—ranging from university and federal researchers to regulators, consultants, policy-makers, and local water managers—to foster the sustainable management of water resources in the semi-arid Southwest. The publication received numerous awards over the years and was an extremely valuable resource to stakeholders and mechanism to rapidly transfer research to a broader audience.

CENTERS AND

CENTERS AND PARTNERS

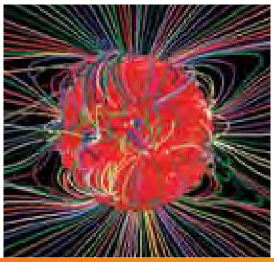


1 BEACON CENTER FOR THE STUDY OF EVOLUTION IN ACTION

WEBSITE – www.beacon-center.org
CENTER DIRECTOR – Erik D. Goodman
LEAD INSTITUTION – Michigan State University
PARTNER INSTITUTIONS
North Carolina A&T State University
University of Idaho
University of Texas at Austin
University of Washington

2 CENTER FOR DARK ENERGY BIOSPHERE INVESTIGATIONS

WEBSITE – www.darkenergybiosphere.org
CENTER DIRECTOR – Katrina J. Edwards
LEAD INSTITUTION – University of Southern California
PARTNER INSTITUTIONS
University of Alaska, Fairbanks
University of California, Santa Cruz
University of Hawaii
University of Rhode Island



3 CENTER FOR ENERGY EFFICIENT ELECTRONICS SCIENCE

WEBSITE – www.e3s-center.org
CENTER DIRECTOR – Eli Yablonovitch
LEAD INSTITUTION – University of California Berkeley
PARTNER INSTITUTIONS
Massachusetts Institute of Technology
Stanford University
Tuskegee University
Contra Costa College
Los Angeles Trade Technical College

4 EMERGENT BEHAVIORS OF INTEGRATED CELLULAR SYSTEMS

WEBSITE – www.ebics.net
CENTER DIRECTOR – Roger D. Kamm
LEAD INSTITUTION – Massachusetts Institute of Technology
PARTNER INSTITUTIONS
City College of New York
Columbia University
Georgia Institute of Technology
Morehouse College
University of California, Merced
University of Georgia
University of Illinois at Urbana-Champaign

5 EMERGING FRONTIERS OF SCIENCE OF INFORMATION

WEBSITE – http://soihub.org/
CENTER DIRECTOR – Wojciech Szpankowski
LEAD INSTITUTION – Purdue University
PARTNER INSTITUTIONS
Bryn Mawr College
Howard University
Massachusetts Institute of Technology
Princeton University
Stanford University
University of California, Berkeley
University of California, San Diego
University of Illinois at Urbana-Champaign

6 CENTER FOR COASTAL MARGIN OBSERVATION & PREDICTION

WEBSITE – www.stccmop.org
CENTER DIRECTOR – Antonio M. Baptista
LEAD INSTITUTION – Oregon Health & Science University
PARTNER INSTITUTIONS
Oregon State University
University of Washington
Saturday Academy
University of Maryland Center for Environmental Science
University of Utah

PARTNERS

7 CENTER FOR LAYERED POLYMERIC SYSTEMS

WEBSITE – http://stc-clips.org
CENTER DIRECTOR – Eric Baer
LEAD INSTITUTION – Case Western Reserve University
PARTNER INSTITUTIONS
Cleveland Metropolitan School District
Fisk University
Kent State University
Naval Research Laboratory
Northwestern University
University of Southern Mississippi
University of Texas at Austin

8 CENTER FOR MICROBIAL OCEANOGRAPHY

WEBSITE – www.cmore.soest.hawaii.edu
CENTER DIRECTOR – David M. Karl
LEAD INSTITUTION – University of Hawaii
PARTNER INSTITUTIONS
Massachusetts Institute of Technology
Monterey Bay Aquarium Research Institute
Monterey Peninsula College
Oregon State University
University of California-Santa Cruz
Woods Hole Oceanographic Institution

9 CENTER FOR MULTI-SCALE MODELING OF ATMOSPHERIC PROCESSES

WEBSITE – www.cmmap.colostate.edu
CENTER DIRECTOR – David A. Randall
LEAD INSTITUTION – Colorado State University
PARTNER INSTITUTIONS
Colorado College
Columbia University
Hampton University
Lawrence Livermore National Laboratory
National Center for Atmospheric Research
Pacific Northwest National Laboratories
The Catamount Institute
University of California, Los Angeles
University of California, San Diego
University of Colorado at Boulder
University of Maryland
University of Utah
University of Washington

10 CENTER FOR REMOTE SENSING OF ICE SHEETS

WEBSITE – www.cresis.ku.edu
CENTER DIRECTOR – S. Prasad Gogineni
LEAD INSTITUTION – University of Kansas
PARTNER INSTITUTIONS
Elizabeth City State University
Pennsylvania State University
Indiana University
University of Washington
Los Alamos National Laboratory
Association of Computer and Information Sciences and Engineering Departments at Minority Institutions

11 TEAM FOR RESEARCH IN UBIQUITOUS SECURE TECHNOLOGY

WEBSITE – www.truststc.org
CENTER DIRECTOR – S. Shankar Sastry
LEAD INSTITUTION – University of California at Berkeley
PARTNER INSTITUTIONS
Carnegie Mellon University
Cornell University
San Jose State University
Stanford University
University of California, Berkeley
Vanderbilt University

12 CENTER OF ADVANCED MATERIALS FOR WATER PURIFICATION

WEBSITE – www.watercampws.uiuc.edu
CENTER DIRECTOR – Mark Shannon
LEAD INSTITUTION – University of Illinois
PARTNER INSTITUTIONS
Clark Atlanta University
Massachusetts Institute of Technology
National Risk Management Research Laboratory
Rose Hulman Institute
Rutgers University
Sandia National Laboratories
University of California at Berkeley
University of Notre Dame
Yale University

13 CENTER FOR BIOPHOTONICS SCIENCE & TECHNOLOGY

WEBSITE – www.cbst.ucdavis.edu
CENTER DIRECTOR – Dennis Matthews
LEAD INSTITUTION – University of California at Davis
PARTNER INSTITUTIONS
Alabama A&M University
Fisk University
Lawrence Livermore National Laboratory
Mills College
Stanford University
University of California at Berkeley
University of California at San Francisco
University of Texas at San Antonio

14 NATIONAL CENTER FOR EARTH-SURFACE DYNAMICS

WEBSITE – www.nced.umn.edu
CENTER DIRECTOR – Efi Foufoula-Georgiou
LEAD INSTITUTION – University of Minnesota
PARTNER INSTITUTIONS
Johns Hopkins University
Louisiana State University
Science Museum of Minnesota
Southern Illinois University Carbondale
St. Anthony Falls Laboratory
University of California at Berkeley
University of Colorado at Boulder
University of Illinois at Urbana-Champaign
University of Texas at Austin

15 CENTER FOR EMBEDDED NETWORKED SENSING

WEBSITE – http://research.cens.ucla.edu/
CENTER DIRECTOR – Deborah Estrin
LEAD INSTITUTION – University of California at Los Angeles
PARTNER INSTITUTIONS
California Institute of Technology
University of California, Merced
University of California, Riverside
University of Southern California

16 CENTER FOR INTEGRATED SPACE WEATHER MODELING

WEBSITE – www.bu.edu/cism
CENTER DIRECTOR – W. Jeffrey Hughes
LEAD INSTITUTION – Boston University
PARTNER INSTITUTIONS
Alabama A&M University
Dartmouth College
National Center for Atmospheric Research
Predictive Science Inc.
Rice University
Stanford University
University of California at Berkeley
University of Colorado at Boulder
University of Maryland
University of Texas, Arlington

17 CENTER FOR MATERIALS AND DEVICES FOR INFORMATION TECHNOLOGY RESEARCH

WEBSITE – www.stc-mditr.org
CENTER DIRECTOR – Philip Reid
LEAD INSTITUTION – University of Washington
PARTNER INSTITUTIONS
California Institute of Technology
Cornell University
Georgia Institute of Technology
New Mexico Highlands University
Norfolk State University
University of Arizona
University of Central Florida
University of Maryland, Baltimore County

LEGACY CENTERS...

18 ADAPTIVE OPTICS

WEBSITE – http://cfao.ucolick.org/
CENTER DIRECTOR – Claire Max
LEAD INSTITUTION – University of California at Santa Cruz

19 BEHAVIORAL NEUROSCIENCE

WEBSITE – http://www.cbn-atl.org/
CENTER DIRECTOR – Elliott Albers
LEAD INSTITUTION – Georgia State University

20 ENVIRONMENTALLY RESPONSIBLE SOLVENTS AND PROCESSES

WEBSITE – http://www.nsfstc.unc.edu/
CENTER DIRECTOR – Joseph DeSimone
LEAD INSTITUTION – University of North Carolina at Chapel Hill

21 NANOBIOTECHNOLOGY

WEBSITE – http://www.nbtc.cornell.edu/
CENTER DIRECTOR – Harold Craighead
LEAD INSTITUTION – Cornell University

22 SUSTAINABILITY OF SEMI-ARID HYDROLOGY AND RIPARIAN AREAS

WEBSITE – http://www.sahra.arizona.edu/
CENTER DIRECTOR – Paul Brooks
LEAD INSTITUTION – University of Arizona

FOR MORE INFORMATION ABOUT THE NATIONAL SCIENCE FOUNDATION SCIENCE AND TECHNOLOGY CENTERS AND/OR THE NSF OFFICE OF INTEGRATIVE ACTIVITIES, PLEASE CONTACT:

Joan Frye, jfrye@nsf.gov

http://www.nsf.gov/dir/index.jsp?org=OIA

OTHER RESOURCES ON TEAM SCIENCE

"Visibility of Team Science: A Case Study of Media Coverage of NSF Science and Technology Centers," Deborah L. Illman and Fiona Clark, *Science Communication,* 30(1), 48-76 (September 2008).

"Coverage of Team Science by Public Information Officers: Content Analysis of Press Releases about the National Science Foundation Science and Technology Centers," Marita Graube, Fiona Clark, and Deborah L. Illman, *J.Tech.Writing & Communication,* 40(2), 143-159 (March 2010).

"The Increasing Dominance of Teams in Production of Knowledge," Stefan Wuchty, Benjamin F. Jones, and Brian Uzzi, *Science,* 316, 1036-1039 (May 18, 2007).

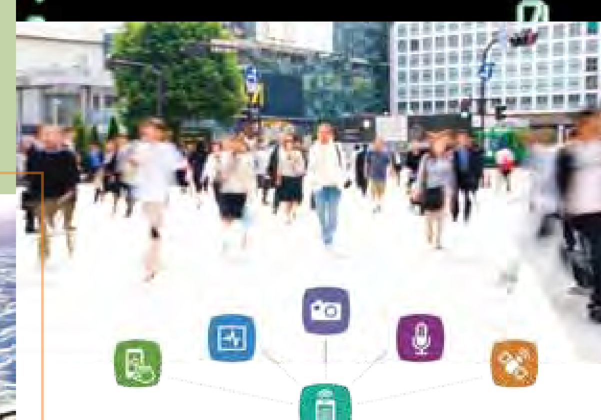
"Interdisciplinary Research," National Science Foundation (2011). http://www.nsf.gov/od/oia/additional_resources/interdisciplinary_research/

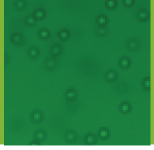
Facilitating Interdisciplinary Research, National Academy of Sciences, Washington D.C, National Academies Press (2004).

"Risks and rewards of an interdisciplinary research path," Diana Rhoten, and Andrew Parker, *Science,* 306(5704), 2046-2046 (December 17, 2004).

"The Dawn of Networked Science," Diana Rhoten, *The Chronicle Review,* 54,(2), B12 (September 7, 2007).

"Team science," Lynn E. Elfner, Holly J.Falk-Krzesinski, Kelly Sullivan, Andrew Velkey, Deborah L. Illman, Jerry Baker, and Antonio Pita-Szczesniewski, *American Scientist,* 99(6), s1-8 (Nov.-Dec. 2011).





PROFILES IN TEAM SCIENCE 2012

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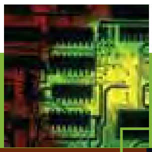
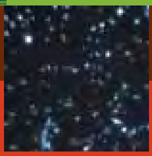


2012



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ONLINE

http://depts.washington.edu/teamsci