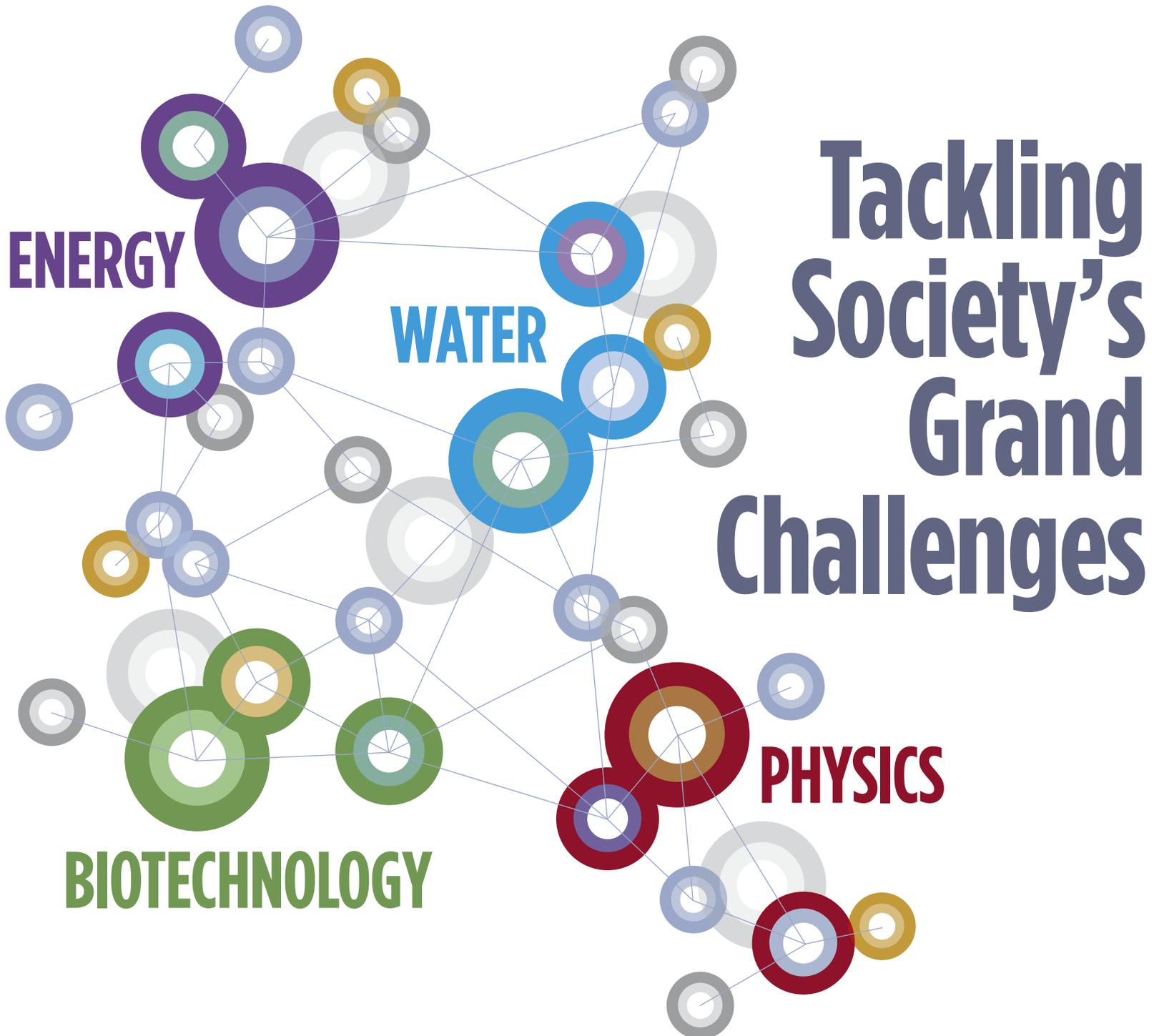


# ENERGY & EARTH

 **COLORADO SCHOOL OF MINES** RESEARCH 2014-15



## Tackling Society's Grand Challenges



# Tackling society's grand challenges

**COLORADO**SCHOOL**OF MINES**

**M**ines has a special place in the scientific and engineering world. There are many examples from our history of major technological impacts from the earliest days of gold and silver mining and smelting in the development of Colorado to the more recent environmental remediation of the Rocky Flats plutonium facility. Two advances in the past year demonstrate our continuing prowess. The Department of Energy launched a major research initiative focusing on the supply and role that strategic and critical minerals, such as the rare earths, play in the energy world. The importance of this initiative is described in the editorial by its director, Alex King of Ames National Laboratory (page 42). Mines is the lead university partnering with Ames and other major national laboratories. President Obama announced this year the formation of three national manufacturing centers with one focusing on light-weight metal manufacturing. Mines will lead a key part of the ferrous metallurgy research where the fabrication of high-strength light-weight steels has the promise of substantially reducing automobile fuel consumption.

This issue of our research magazine focuses on thematic or grand challenge areas of science and technology where Mines is at the forefront or developing a strong position. The grand challenges identified at last year's U.S., U.K. and China engineering summit, held in London, were the energy-environmental nexus and synthetic biology. Our progress in these areas is discussed as well as some of the intriguing developments in the fundamental physics world.

## **ENERGY AND THE SUBSURFACE WORLD**

Developments in unconventional oil and gas exploration and production have transformed the nation's energy and manufacturing landscape. Moreover, the impact on the environment and climate is substantial with the growth in shale gas usage leading to CO<sub>2</sub> reduction. Mines is definitely one of the nation's leading universities in this sector in terms of research and education. Research is needed to determine the impact of these developments on renewable energy, not only in the economics, but also in new technologies. Will, for example, the technologies used in horizontal drilling lead to a resurgence in enhanced geothermal energy production, an ultimate renewable source?

## ENVIRONMENT AND WATER

Understanding the future and role of water resources in the changing global environment is clearly a grand challenge and the increasing demand for water in energy production has to be factored into the equation. Mines has campus wide research addressing these issues. Significantly, ConocoPhillips has just funded a major center at Mines to address the energy-water nexus in the arid western region.

## SYNTHETIC BIOLOGY

Synthetic biology is loosely defined as the intersection of biology and the engineering and physical sciences to produce new structures. We have vigorous programs at this intersection ranging from arterial clot busting devices to the engineering of the genomes of algae. This junction plays to Mines' strengths and is important in the essential development of our biology programs.

## PHYSICS

Physics always seems to stay at the forefront of the fundamental grand challenges and the discipline is now at a particularly exciting time. At the lowest energies ( $10^{-10}$  electron-volts, eV) some of the mysterious properties of quantum mechanics are being probed and manipulated. At the cosmological or highest energies ( $10^{20}$  eV) many fundamental questions are being raised. Our physicists are working across this whole spectrum.

I am confident that the articles and news items in the magazine will give you a sense of the vitality of research at Mines, which is largely due to our talented faculty and students. The new faculty appointments show that we are attracting the best and brightest. This is in large measure due to our research opportunities but there are clear challenges. To maintain this momentum we need sustained research growth and productivity. We are a small school without the benefit of the infrastructure of the large public research universities. Growth will be maintained by focusing on the grand challenges across our mission space.

Finally, let me not question that authoritative voice from the BBC that Mines is "America's best engineering school" (as featured in the BBC News story "The Numbers of the Year," cited by Dr. Pippa Malmgren of Pincipalis Asset Management, ([bbc.com/news/magazine-25421916](http://bbc.com/news/magazine-25421916))). That is good enough for me.

Mines continues to punch above its weight.



Dr. John Poate  
Vice President for Research and Technology Transfer



**JOHN POATE**  
Vice President for Research  
and Technology Transfer,  
Colorado School of Mines

- Fellow of the American Physical Society and the Materials Research Society
- Editor of *Applied Physics Reviews*
- Earned a PhD in Nuclear Physics from the Australian National University
- Headed the Silicon Processing Research Department at Bell Laboratories
- Former dean of the College of Science and Liberal Arts at New Jersey Institute of Technology
- Served as president of the Materials Research Society and chair of the NATO Physical Sciences and Engineering Panel
- Chairs Lawrence Livermore National Laboratory review committees and is on the board of the National Renewable Energy Laboratory

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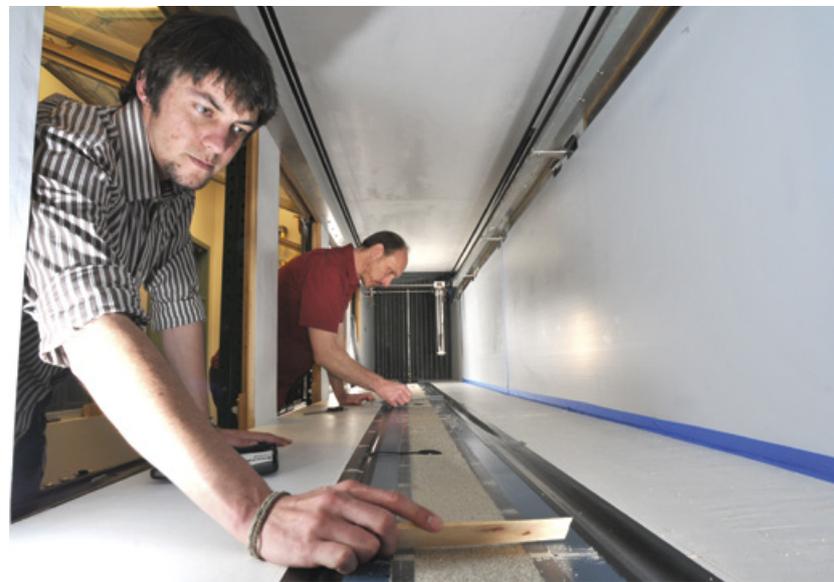
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## A MESSAGE FROM THE PRESIDENT



The faculty, students and staff at Colorado School of Mines are empowered to achieve excellence—we are working to address the needs and aspirations of the world's growing population.

The innovative and award-winning faculty members here at Mines continue to receive prestigious fellowships, high profile research grants and other local and international accolades. Our experts are relied upon time and again by media outlets spanning the globe to help make sense of science, explain technical issues and discuss groundbreaking research with the potential to create positive change in the world.

Colorado School of Mines students are academically exceptional and are recognized for their leadership and professional talents, showcasing why they are so highly sought after by our industrial partners and other world-class universities.

As noted in the achievements through this magazine, Mines is clearly up to the challenge.

—M.W. Scoggins, President, Colorado School of Mines

In “Numbers of the Year” story by *BBC News*, Mines touted as “America’s best engineering school.”

Physics Professor Jeff Squier '84, MS '86, was awarded the 2014 Harold E. Edgerton Award by the International Society for Optics and Photonics.

Mines placed first for both the Overall Conference award and the Steel Bridge competition at the American Society of Civil Engineering Rocky Mountain Student Conference.

Corinne Packard, assistant professor in the George S. Ansell Department of Metallurgical and Materials Engineering was awarded National Science Foundation Faculty Early Career Development (NSF CAREER) Award.

The Mines student section of the Society of Women Engineers is the largest collegiate section in the nation.



# COLORADO SCHOOL OF MINES

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CPM Number #40065056

ISSN 2150-377X

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**Mines ranks #1 in 2014 PayScale ranking of public universities by ROI.**

Roel Snieder, the W.M. Keck Distinguished Professor of Basic Exploration Science, received the prestigious 2014 Humboldt Research Award from the Alexander von Humboldt Foundation.

Chemistry and Geochemistry Assistant Professor Jenifer Braley received a U.S. Department of Energy Early Career Research award.

Chemical and Biological Engineering Assistant Professor Keith Neeves received the "Educator of the Year" award from the Colorado BioScience Association.

Grad student Elena Finley is a finalist for Mars One project.

The *Denver Post* profiled Mines student Johnny Briones, Grand Master of Memory.

Marcelo Simoes, an associate professor in the Electrical Engineering and Computer Science Department, was awarded the Green Energy and Technology Award and will conduct research at Aalborg University in Denmark as a Fulbright Fellow.

Mines Ranks 3rd in PayScale's 2014 ranking of starting salary for state schools with \$66,700.

Mines' supercomputer 'BlueM' is mentioned in "Top Supercomputing Discoveries of 2013."

Keith Neeves, assistant professor in the Department of Chemical and Biological Engineering, has been awarded a National Science Foundation Faculty Early Career Development (NSF CAREER) Award.

The *Denver Post* gave front-page coverage to food-waste-to-glass research at Mines.

Stephen Liu, a professor in the George S. Ansell Department of Metallurgical and Materials Engineering, was named by the J. William Fulbright Foreign Scholarship Board as the Distinguished Chair for Oil and Gas to Brazil.

Mines Ranks 40th in *U.S. News and World Report's* Top Public Schools.

Melissa Krebs, assistant professor of chemical and biological engineering, was selected as a 2013 Boettcher Investigator joining seven other early-career scientists in the Webb-Waring Biomedical Research Program.

Ivar Reimanis, Herman F. Coors Distinguished Professor of Ceramic Engineering, has been appointed as a Fellow of the American Ceramic Society.

Tissa Illangasekare, AMAX Distinguished Chair of Environmental Sciences and Engineering, has been appointed to the Nuclear and Radiation Studies Board in the Division on Earth & Life Studies of the National Academies.

Gavin Hayes, adjunct assistant professor in the Geophysics Department and U.S. Geological Survey research seismologist, received the Presidential Early Career Award for Scientists and Engineers (PECASE).

Moises Carreon, associate professor in the Chemical and Biological Engineering Department, received the Presidential Early Career Award for Scientists and Engineers (PECASE).

## Mines, Children's Hospital Colorado announce second round of research grants



Chemical and biological engineering student Rima Baliga, left, works with Mechanical Engineering Assistant Professor Anne Silverman.

A 2013 pilot program funding research collaboration between Children's Hospital Colorado-University of Colorado and Mines has been so successful over the past year, the institutions have announced funding for four projects in 2014.

The recipients and their projects are:

- Brian Trewyn (Mines) - Colm Collins (CU School of Medicine), "Development of a novel copolymer delivery system for the treatment of Inflammatory Bowel Diseases"
- Cecilia Diniz Behn (Mines) - Melanie Cree Green (Pediatric Endocrinology – Children's Colorado), "Hepatic and Adipose Insulin Resistance in Polycystic Ovarian Syndrome"
- Ozkan Celik (Mines) - Richard Weir (Bioengineering CU-Denver, Children's Colorado), "A Novel Finger Joint Employing High Speed Low Torque Transfer for use in a Powered Finger Prosthesis"
- Anne Silverman (Mines) - Travis Heare (Orthopedics – Children's Colorado), "Evaluating the Functional Muscle Units in Van Ness Rotationplasties"

The 2013 research has already led to further funding and the intent to collaborate further.

Melissa Krebs, from Mines, and Karin Payne, from CU, worked on "Dual Delivery Biomaterial System for the Treatment of Growth Plate Injuries."

"Growth plate cartilage injuries have devastating consequences to the growth of young children. The overall goal of this proposal was to engineer a novel delivery system that can

regenerate the growth plate and prevent significant life long orthopedic problems," said Krebs, noting the success of such a therapy would not only be beneficial to growth plate injuries due to trauma, but could be further applied to growth plate disruptions due to osteosarcoma or infection as well as other clinical applications.

"The funding provided by this program was very valuable for us in establishing a strong collaboration and allowing us to obtain substantial preliminary data," said Krebs.

Krebs was awarded an NSF Broadening Participation Research Initiation Grants in Engineering (BRIGE) grant (\$175,000 total for two years) to further pursue a variation of this delivery system.

Stephen Boyes, from Mines, and Sven-Olrik Streubel, of Children's Colorado, collaborated on "Bone Regeneration Using Biodegradable Polymer Scaffolds."

Bone is one of the most transplanted tissues, second to blood, but current treatment options have significant drawbacks. The research by Boyes and Streubel aims to bridge the gap between the need for, and the current lack of, ideal bone grafting materials using polymers.

"I am currently on sabbatical at the University of Colorado Anschutz Medical Campus, and know firsthand there is much potential for collaboration, but finding money to get the project started and generating preliminary results can be very difficult. Programs like the Mines-Children's Colorado seed grant enable researchers with good ideas the ability to start new projects and generate results that will hopefully lead to more substantial funding in the future," Boyes said.

Keith Neeves, from Mines, and Shama Ahmad, from CU, worked on "Air Flow-dependent Modifications of Airway Epithelial Basal/Progenitor Cell Phenotype: Implications in Cystic Fibrosis Disease Pathogenesis."

"The ultimate goal of this collaboration is to use microfluidic models of pulmonary airways to test therapeutic strategies," said Neeves.

The lung-on-a-chip device developed by Neeves and Ahmad could help the medical community identify better treatment options for those afflicted with cystic fibrosis; a chronic, inherited disease that affects the lungs and digestive systems of more than 70,000 people worldwide.



## Supercomputer BlueM amps up Mines' energy research

Colorado School of Mines' 155 teraflop supercomputer, dubbed "BlueM," has allowed researchers to run large simulations related to energy research, climate and seismic modeling.

Mines outgrew the 23 teraflops of BlueM's predecessor, a supercomputer named "RA" after the Egyptian sun god. The additional number of flops allow researchers to run higher fidelity simulations.

"BlueM provides Mines with a revolution and evolution in high performance computing capabilities with more than six times the capability we had with RA. Its dual-natured hybrid architecture allows for types of simulations that cannot be done on a homogeneous machine," said Timothy Kaiser, director of research and high performance computing and the Golden Energy Computing Organization at Mines. "Housing the machine at the National Center for Atmospheric Research (NCAR) is the beginning of a partnership that will promote additional collaborations, both in algorithm development and in environmental science."

NCAR, which is managed by the University Corporation of Atmospheric Research, (UCAR) is housing the unique machine at its Mesa Laboratory located in Boulder, but the system is operating on Mines' computing network. It features a dual architecture system that combines the IBM BlueGene Q and IBM iDataplex platforms. Since the two computer partitions are optimized for different calculations, Mines and NCAR will conduct research on ways to combine the two to perform multi-physics modeling mostly focused on climate and the Earth.

"The Mines-UCAR relationship on Blue M is a win-win for both institutions. By leveraging this relationship we can more efficiently deliver high-end supercomputing capabilities for our researchers who need these capabilities to conduct-cutting edge science," said Tom Bogdan, president of UCAR.

Mines research professors have touted BlueM as an excellent computing platform for the university.

"With a mix of traditional and forward-looking low power/highly scalable configurations, BlueM serves the campus science needs well. My own group has used it to understand such science questions as the scaling of physical and chemical heterogeneity in reactive transport floodplain simulations and hydrologic impacts and feedbacks from the mountain pine beetle infestation," said Reed Maxwell, associate professor of hydrology.

### BlueM technical specs:

- 85kW of electrical power requirement
- 20 by 8-foot footprint
- Five racks (three computer racks, a management rack and a file system rack)
- Two partitions: MC2 (pronounced "Energy") runs on an IBM Blue Gene0 and AuN (pronounced "Golden") is based on the IBM iDataplex platform
- 155 teraflops (more than 104 in MC2 and 50 in AuN)
- 17.4 terabytes of memory, 10,496 cores in 656 nodes and 480 terabytes of disk
- Water-cooled

NCAR's Mesa Laboratory was designed by modernist architect I.M. Pei in 1961.



## Braley awarded DOE Early Career grant

Colorado School of Mines Chemistry and Geochemistry Assistant Professor Jenifer Braley is among 35 scientists from across the nation to receive significant funding for research as part of the U.S. Department of Energy's Early Career Research Program.

Under the program, Braley will receive \$150,000 per year for five years to cover summer salary and expenses related to her research. Awardees include 18 researchers from U.S. universities and 17 from DOE laboratories.

Her project, "Actinide N-Donor Thermodynamics: Expanding the f-Element Covalency Dialogue," was selected for funding by the Office of Basic Energy Sciences. The research aims to improve management of used nuclear fuel.

"As nuclear power becomes increasingly attractive to mitigate concerns relevant to global climate change, understanding the chemistry of the actinide elements, especially the heavier actinides, becomes increasingly important to improve peaceful nuclear fuel recycling technologies, select appropriate used nuclear fuel geological disposal sites and further develop our nation's nuclear forensics capabilities," Braley said. "The unique research and educational access Mines has to the USGS nuclear research reactor in the Denver Federal Center catalyzed the development of this exciting project that examines the extreme edge of the periodic table."

## Alumnus, Kiewit CEO establishes underground construction and tunneling endowed chair

Civil and Environmental Engineering Professor Mike Mooney has been appointed as the Grewcock University Endowed Chair in Underground Construction & Tunneling at Colorado School of Mines.

Mooney will lead the university-wide Center of Excellence in Underground Construction & Tunneling (UC&T). The UC&T center is an interdisciplinary effort across civil, geological and mining engineering, and includes mechanical and electrical engineering, geophysics and computer science. The mission of the center is to educate engineers to join the UC&T industry and to advance knowledge that benefits industry through research.

The Grewcock University Endowed Chair in Underground Construction & Tunneling was established through a generous gift from 1976 Mines alumnus Bruce E. Grewcock, chairman and CEO of Kiewit Corporation.

"Colorado School of Mines equipped me with the technical expertise and training that our industry demands," said Grewcock. "The UC&T Center at Mines will serve as a valuable training and research resource."

Grewcock sees a clear need for strong



MIKE MOONEY



BRUCE E. GREWCOCK

university focus nationally in UC&T, both to prepare the engineering workforce of the future and to solve challenging problems through interdisciplinary research.

"Underground infrastructure is being built in increasingly complex geologic environments, so the demand for highly skilled professionals is growing," said Grewcock. "Through partnerships with educational institutions like Mines, we can meet the demands of our growing industry."

A registered professional engineer, Mooney brings 18 years of academic and consulting experience in heavy civil engineering and construction to this position. He received a

bachelor's degree in civil engineering from Washington University in St. Louis, a master's degree in civil-structural engineering from the University of California-Irvine and a doctorate in civil-geotechnical engineering from Northwestern University.

His expertise lies in soft ground tunnel design and construction, ground improvement, instrumentation/monitoring of construction systems, nondestructive imaging techniques and intelligent geoconstruction processes.

He has been the principal investigator for more than 30 geoconstruction-related research projects and has authored more than 100 technical publications. At Mines, Mooney teaches courses in tunnel design and construction, support of excavations/earth retaining structures, instrumentation and monitoring, nondestructive evaluation and intelligent geosystems. He advises numerous graduate and undergraduate students pursuing industry-applied research projects in UC&T.

"Mines is a natural fit for a Center of Excellence in UC&T given the collective strength of the civil, geological and mining engineering departments, the industry-focused nature of Mines and a university mission that is strongly tied to earth engineering," said Mooney.

He and his colleagues are eager to help grow the output of talented engineers and provide value to the industry through research.

"Some of the most sophisticated engineering in extremely challenging environments is being carried out underground around the world. The more UC&T courses our students take, seminars they attend, and projects they participate in, the more they gravitate toward this challenging field," Mooney said. "Our mission is to advance and help grow the UC&T industry. Industry involvement and engagement is critically important to our efforts."

## Center for Underground Construction & Tunneling takes students on subterranean field trip



Photo courtesy of Washington State Department of Transportation

Nineteen Mines students, including undergraduate and graduates from the civil, geological, mining and mechanical engineering departments traveled to Seattle to visit the largest tunnel boring machine tunnel project in the world.

The 17.5-meter diameter tunnel-boring machine is carving a two-mile-long tunnel through downtown Seattle as part of the SR 99 Alaskan Way Viaduct Replacement project site.

Many of the graduate students who traveled with the group participated in the Analysis and Design of Tunnels in Soft Ground course taught by Mike Mooney in the fall of 2013 at Mines, in which they completed academic designs of many aspects of the enormous double-decker traffic tunnel. The tour provided a unique and valuable experience for them to compare what they had analyzed and developed in the classroom with the actual, implemented design.

## Professors named Fulbright scholars

Stephen Liu, a professor in the George S. Ansell Department of Metallurgical and Materials Engineering at Colorado School of Mines, has been named by the J. William Fulbright Foreign Scholarship Board (FSB) as the Distinguished Chair for Oil and Gas to Brazil. Marcelo Simoes, an associate professor in the Electrical Engineering and Computer Science Department, has been awarded the Green Energy and Technology Award and will conduct research at Aalborg University in Denmark as a Fulbright Fellow.

“For the past few years, there have been significant discussions between the presidents of the U.S. and Brazil on the production and supply of ethanol to the U.S. that would require a significant expansion of shipbuilding activities of ‘blue-water’ fleets in Brazil to meet the demand,” said Liu. “This Fulbright program proposes to prepare high-level researchers with advanced knowledge in shipbuilding and structural fabrication to support the intense level of production and development experienced by the Brazilian oil and gas industry.”

Simoes research, “Integration of more distributed generation in a power electronics based power system,” will be a collaborative effort with researchers at the



Institute of Energy Technology at Aalborg University. Simoes will investigate adopting power electronic converters and control challenges to stabilize the grid system with a higher penetration of renewable energy sources.

“I will work on Aalborg projects in the Center of Reliable Power Electronics as well as on a technology

platform project on Intelligent and Efficient Power Electronics, with funding on the order of €30 million,” said Simoes, noting the university often collaborates with major Danish power electronic companies like Danfoss, Grundfos, Vestas and KK-Electronics. Simoes will also learn new pedagogical techniques, as Aalborg is known for its unique problem-based, project-organized model of teaching and learning.

As Fulbright grantees, Liu and Simoes will join the ranks of many distinguished participants in the program. Grantees are expected to “establish open communication and long-term cooperative relationships.”

MARCELO SIMOES



## Managing mass amounts of data



A Colorado School of Mines-led research team has been funded by the U.S. Department of Energy’s Advanced Scientific Computing Research program to improve the capabilities of data-intensive physical simulations such as climate modeling, groundwater flow and renewable energy applications.

The \$1.05 million award disbursed over three years will allow principal investigator Paul Constantine, the Ben L. Fryrear Assistant Professor of Applied Mathematics and Statistics at Mines, along with Youssef Marzouk and Qiqi Wang of MIT and Tan Bui-Thanh of the University of Texas at Austin, to develop methods to reduce tremendous data streams into more meaningful and manageable parcels.

“One of the most important challenges is the inverse or calibration problem: find the inputs of a simulation such that its outputs agree with a given set of measurements,” said Constantine. “As both the cost of the complex simulations and the volume of measurement data sets increase, intuition-driven trial-and-error methods for calibration quickly become untenable. Scientists need more computationally efficient and mathematically rigorous methods.”

Constantine’s team will apply the methods they develop to real inverse problems in chemical kinetics and turbulent flame modeling.

“We think that newly developed active subspace methods can provide the necessary dimension reduction to help cutting-edge methods find solutions for a large class of otherwise intractable statistical inverse problems,” Constantine said.

## Undergraduate biology course a collaborative experience



Successfully manipulating the DNA of bacteria so they fluoresce under ultraviolet light would have rocked the bioscience community a few decades ago. Today, it's an intriguing, though straightforward, procedure built into an innovative freshman biology course recently launched at Mines.

The Department of Chemical and Biological Engineering's new Studio Biology I course (soon to be complemented by Studio Biology II) takes lessons from the highly successful studio physics courses pioneered by the Department of Physics over the last decade.

Studies conducted at Mines and elsewhere demonstrate that, by requiring students to collaborate

in groups on carefully structured experiments and activities, outcomes for retention, critical thinking, problem solving, teamwork and initiative are all improved over conventional teaching approaches.

The *Chronicle of Higher Education* has also reported that undergraduate gains in science are tied to this sort of hands-on lab experience. Citing a study published in *mBio*, an online open access journal of the *American Society for Microbiology*, the *Chronicle*, noted first-year science undergraduates who continued to a second year increased by nearly 10 percent when they took part in a lab program.

"We give students meaningful, real-world problems and ask them to form hypotheses and develop procedures for testing them," said Teaching Associate Professor Judy Schoonmaker, who has played the lead role in creating the studio biology course and designing the new lab at Mines.

With studies of this instructional model suggesting that social interaction is one of the keys to success, the lab is configured so the 21 workstations, which each accommodate three students, are in close proximity to two other workstations, forming a pod of nine. Groups are encouraged to ask

questions, share ideas and compare results with their neighbors.

Workstations are equipped with computers, dual monitors, video microscopes, digital cameras, and digital balances, as well as more specialized equipment like micropipettes and oxygen, pH and temperature sensors.

Tony Dean, a longtime veteran of the Department of Chemical and Biological Engineering who now heads the College of Applied Science and Engineering, is excited about the potential impact of the new course, both on the department and the rest of campus. "In addition to strengthening chemical and biological engineering programs, we also envision that Studio Biology I and II can pave the way for the creation of new bio minors in other disciplines," said Dean. "Students would take these as foundational prerequisites and then move on to specialized coursework in their own departments."

As Schoonmaker put it, "If I can demonstrate engineering concepts in the context of biology, such as biomimicry, it becomes much more interesting. This is not a plain biology course—it's a biology course with an engineering backstory."

*—First published in Mines magazine, fall/winter 2013*

### Squier receives Edgerton Award

Physics Professor Jeff Squier '84, MS '86, was awarded the 2014 Harold E. Edgerton Award by the International Society for Optics and Photonics for his outstanding contributions to optical or photonic techniques in the application and understanding of high-speed physical phenomena. In particular, the award honors his work with femtosecond lasers and amplifiers, laser filamentation, ultrafast spectroscopy, femtosecond micromachining, ophthalmic procedures with ultrafast lasers, and high-speed nonlinear optical microscope.



Prof. Jeff Squier is pictured with photographs by Harold Edgerton, "Tennis Serve" (1952) and "Pole Vaulter, David Tork" (1964), on display in the Arthur Lakes Library at Colorado School of Mines.

## NSF recognizes Mines professors with CAREER Awards



Corinne Packard, assistant professor in the George S. Ansell Department of Metallurgical and Materials Engineering and Keith Neeves, associate professor in the Department of Chemical and Biological Engineering, have been awarded National Science Foundation Faculty Early Career Development (NSF CAREER) Awards.

Packard's study, "Controlling Pressure-Induced Transformation in Rare Earth Orthophosphates," examines how to improve the properties of high temperature ceramic components such as combustors, nozzles and thermal insulation in aircraft engines, turbines and rockets.

Some unique ceramics undergo a change in shape and volume when they are deformed; researchers want to harness this crystal structure change to increase a material's toughness by absorbing energy caused by an impact or propagating crack. Researchers will determine how to use chemistry to control the point at which this change occurs.

Information and new materials discovered through this research could be useful in designing coatings to improve the performance of ceramic components used in high temperature aerospace applications.

Mines undergraduate and graduate students studying materials science and engineering will be involved in the research. The project also will develop science-learning modules for local elementary school teachers and the Rocky Mountain Camp for the Dyslexic.

Neeves' research, "An integrated research and education program on the biomechanics of blood clot growth," examines blood clot formation and could lead to more effective treatment of thrombosis, one of the leading causes of death.

The abstract states: "The conventional models of clot formation focus primarily on the kinetic processes involved in coagulation reactions and platelet signaling. The proposed studies build upon previous models by incorporating interstitial solute transport as a key mechanism of clot growth. With more capable predictive methods available, better drugs and drug delivery strategies can be developed ... Results will be used to assess how known risk factors for thrombosis lead to uncontrolled clot growth and how this process can be physically impeded."

Additionally, the study will create K-12 outreach programs and undergraduate research opportunities focused on the connection between engineering and biology.

The NSF CAREER award is the most prestigious recognition in support of junior faculty who exemplify the role of teacher-scholars through outstanding research, excellent education and the integration of education and research within the context of the mission of their organizations.



## Mines contributes to Critical Materials Institute mission

Since the Critical Materials Institute (CMI) launched in 2013, researchers have begun more than 30 projects focused on improving and diversifying sources for rare earths and other critical elements, identifying substitute materials and improving efficiency of the use of existing resources. The CMI, an Energy Innovation Hub of the U.S. Department of Energy, has established a number of new facilities and has made 10 invention disclosures.

Mines Economics and Business Professor Rod Eggert serves as the deputy director of the CMI. He notes that "CMI is focused on innovation to help assure supply chains for materials that provide essential properties to energy materials. At Mines, faculty members and students in the Kroll Institute of Extractive Metallurgy aim to improve engineering processes for separations and further processing of rare earths. Researchers in the Division of Economics and Business aim to improve our ability to anticipate which materials may become subject to supply-chain risks in the future."

The institute is led by the Ames Laboratory, Iowa, and consists of scientists and engineers from the Idaho National Laboratory, Lawrence Livermore National Laboratory, Oak Ridge National Laboratory, Brown University, Mines, Florida Industrial and Phosphate Research Institute, Iowa State University, Purdue University, Rutgers University, University of California at Davis and industry partners Advanced Recovery, Cytec, GE Global Research, Molycorp, OLI Systems and Simbol Materials.



## NSF grant to aid research on wildfire impact on water quality



An NSF Rapid Response Research (RAPID) proposal was awarded to Colorado School of Mines researchers to investigate the potential impacts on water quality in the Rim Fire area near Yosemite National Park.

The Rim Fire, the third largest fire in California history, started Aug. 17, 2013, and burned for nearly 10 weeks destroying 402 square miles of forest and wildlife habitat. It is the largest fire in the recorded Sierra Nevada history and cost more than \$127 million to fight—\$4.3 million will be used toward watershed treatment to mitigate potential downstream impacts.

The research, led by Terri Hogue, Mines civil and environmental engineering associate professor and director of the new ConocoPhillips Center for a Sustainable WE<sup>2</sup>ST, along with her colleagues John McCray, Richard Luthy, Alexis Stichler, Chris Higgins, and Alicia M. Kinoshita, will involve monitoring reservoir and regional stream system water quality as well as alterations in snow patterns and associated spring runoff.

The Rim Fire threatened the O’Shaughnessy Dam and reservoir in the Hetch Hetchy Valley, which supplies water for the San Francisco Bay Area. It also has the potential to impact the Tuolumne River water system, which supplies water to San Francisco and 29 other wholesale buyers in San Mateo, Santa Clara and Alameda counties.

RAPID proposals allow quick-response research on natural or anthropogenic disasters and similar unanticipated events. The project also is supported by funds from the NSF Engineering Research Center on Urban Water Infrastructure ReNUWI.

## Next-gen fuel cell research boosted by U.S. DOE investment

The U.S. Department of Energy announced a \$4.5 million investment in two projects—led by Colorado School of Mines and Minnesota-based 3M—to lower the cost, improve the durability and increase the efficiency of next-generation fuel cell systems.

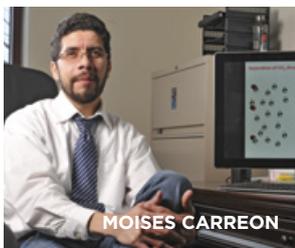
Mines will receive \$1.5 million to develop advanced hybrid membranes for cutting-edge, next-generation fuel cells that are simpler, more affordable and able to operate at higher temperatures. Associate professor of chemical and biological engineering Andrew Herring is leading the project at Mines, with partners at NREL, Nissan USA and 3M.

“We are extremely excited to be continuing our work on advanced membranes for fuel cells,” said Herring. “This project began as a basic science effort, but we now have the opportunity to demonstrate the materials in actual fuel cells. If successful, these fuel cells will help drive down the cost and increase the efficiency and durability of the fuel cell cars that are currently being commercialized.”

3M will receive \$3 million to focus on developing innovative fuel cell membranes with improved durability and performance using processes, that are easily scalable to commercial size.

“Fuel cell technologies have an important role to play in diversifying America’s transportation sector, reducing our dependence on foreign oil, and curbing harmful carbon pollution,” said Assistant Secretary for Energy Efficiency and Renewable Energy David Danielson. “By partnering with private industry and universities, we can help advance affordable fuel cell technologies that save consumers money and give drivers more options while creating jobs in this growing global industry.”

## Mines faculty members earn Presidential Early Career Awards



Moises Carreon, an associate professor who holds the Coors Developmental Chair in the Department of Chemical and Biological Engineering at Colorado School of Mines, and Gavin Hayes, of the U.S. Geological Survey's National Earthquake Information Center and a member of the Mines geophysics adjunct faculty, are among 102 researchers to receive the highest honor bestowed by the U.S. Government on science and engineering professionals in the early stages of their independent research careers: The Presidential Early Career Award (PECASE).

"The impressive achievements of these early-stage scientists and engineers are promising indicators of even greater successes ahead," President Barack Obama said of the PECASE award winners. "We are grateful for their commitment to generating the scientific and technical advancements that will ensure America's global leadership for many years to come."

The awards were established by former President Bill Clinton in 1996, and are coordinated by the Office of Science and Technology Policy within the Executive Office of the President. Awardees are selected for their pursuit of innovative research at the frontiers of science and technology and their commitment to community service as demonstrated through scientific leadership, public education or community outreach.

## Mines tests world's first geothermic fuel cell

Researchers at the Colorado Fuel Cell Center at Mines have been working with the world's first geothermic fuel cell (GFC)—a technology with the potential for positive economic and environmental impact on oil-producing nations.

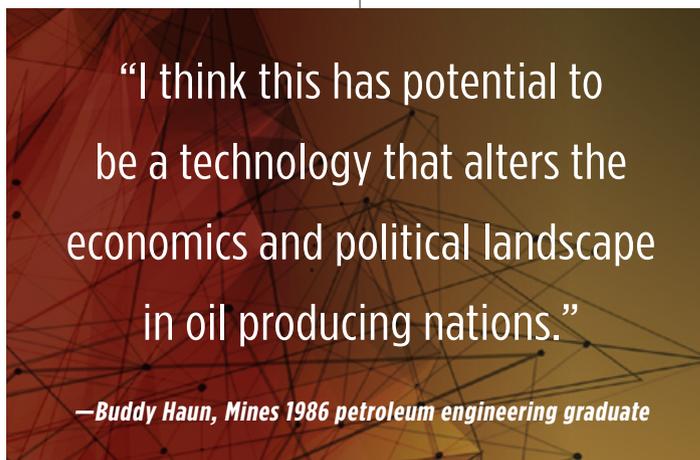
Colorado Fuel Cell Center Director Neal Sullivan and his research team are testing the GFC for a new application of solid-oxide fuel cell technology: heat

generation. Designed and built by Rochester, NY-based Delphi for IEP Technology, of Parker, Colo., the GFC will efficiently generate 4.5 kW of electricity from natural gas fuel.

When placed underground within oil-shale formations, the heat naturally generated from the 750 °C fuel cells is harnessed to liberate oil from the shale, known as "in situ oil shale processing." The electricity generated by the fuel cells comes as a useful and valuable byproduct of the oil-recovery process.

The GFC arrived on campus in fall 2013 and operated continuously for five days. During that time, the 6-foot by 1-foot diameter GFC generated 3 kilowatts of electricity (kWe) and 6 kW of heat. Follow-up testing in November reached power levels of 4.3 kWe. Both startup and operation of the GFC was thermally self-sustained.

Sullivan, who is a mechanical engineering associate professor at Mines, hopes to build on this laboratory-scale success through



outdoor GFC operation scheduled for summer 2014. The outdoor tests will be on the Mines campus, and will utilize a significantly larger GFC measuring approximately 28-feet by one-foot. It is expected to generate around 15 kWe of electricity and up to 25 kW of heat.

Sullivan explained that the GFC he and his team tested could currently power one or two American homes. However, even a small oil production facility would require thousands of much

larger GFCs. The target GFC size during deployment could reach nearly 500 feet in length. IEP Technologies estimates an 80,000 barrel-per-day oil field would require nearly 3,400 GFCs distributed in a network throughout the oil shale formation.

A field of GFCs of this magnitude would generate approximately 700 megawatts of electricity that could be sold back to the utility and put on the grid or provide power for operation of the oil field.

Research engineer Buddy Haun designed and built the extensive data-acquisition systems for the project, building test stands and taking advanced measurements to quantify GFC performance and behavior. Haun graduated from Mines in 1986 with a degree in petroleum engineering.

"I think this has potential to be a technology that alters the economics and political landscape in oil producing nations," Haun said. "We are using green technology to produce a product that is more easily refined."

## Mines joins lightweight and modern metals manufacturing institute

Colorado School of Mines will serve as one of four core facilities in a newly formed institute focused on lightweight and modern metals manufacturing.

The American Lightweight Materials Innovation Institute will be headquartered in Michigan and led by Ohio-based EWI, the University of Michigan and The Ohio State University. It will expand the market for and create new consumers of products and systems to utilize advanced, lightweight, high performing metals and alloys—titanium, aluminum and high-strength steels—by removing technological barriers in manufacturing. The institute will consist of a pilot-plant facility with capabilities for manufacturing process development and prototype characterization, as well as research and development laboratories at partner locations.

The Colorado Office of Economic Development and International Trade will provide \$1 million per year for the next five years toward Mines research program, which will be matched at least one-to-one by the federal government.

“This outstanding partnership will not only bring about real improvements in the creation of advanced, lightweight, high-strength materials, but will drive critical innovation and collaboration between industry and academia, which is a hallmark of research at Mines,” said John Poate, vice president for research and technology transfer at Mines.

Mines will develop thermomechanical process improvements and technologies,

which will have broad application to Colorado’s key industries including military and defense, aerospace, energy and natural resources, advanced manufacturing, infrastructure engineering and transportation, and logistics.

“Thermomechanical processing refers to simultaneous control of deformation and temperature during the production of metals leading to materials in final product forms with enhanced properties,” said David Matlock, university emeritus professor of the George S. Ansell Metallurgical and Materials Engineering Department. “For example, the production of new lightweight metals, such as advanced, high-strength steels which are essential for many applications including lighter, more fuel-efficient and safe automobiles, benefit from controlled processing.”

The 30-year success of the Advanced Steel Processing and Products Research Center, an industry/university cooperative research center formed at Mines in 1984, and the newly developed Center for Advanced Non-Ferrous Structural Alloys, played a role in landing the partnership.

In addition to technical expertise, Mines possesses a unique thermomechanical processing simulator (the Gleeble 3500), which can be used to economically assess potential processing histories on various metals prior to committing to full-scale production. As the institute evolves, the research opportunities at Mines will expand beyond those in the Metallurgy and Materials Engineering Department.

## American Bureau of Shipping creates Metallurgical and Materials Engineering endowed chair

The American Bureau of Shipping (ABS) has established an endowed faculty chair in metallurgical and materials engineering at Colorado School of Mines. ABS, founded in 1862, is a leading international classification society devoted to promoting the security of life, property and the marine environment through the development and verification of standards for the design, construction and operational maintenance of marine-related facilities.

The ABS Endowed Chair in Metallurgical and Materials Engineering will provide resources for attracting and retaining a world-renowned expert in materials engineering who will further bolster the research and educational offerings of Mines’ George S. Ansell Metallurgical and Materials Engineering Department and its affiliated research centers.

Professor Stephen Liu, who has been at Mines since 1987, has accepted an appointment as interim chair. Liu has been engaged in the research of marine materials and offshore engineering for the shipbuilding, and oil and gas industries for many years.

“The ABS Chair will be a highly visible position in one of the nation’s most comprehensive materials engineering departments, not only advancing Mines’ intellectual leadership role in the field, but also helping to ensure the industry’s vitality by building a pipeline of future engineers,” said Mines President M. W. Scoggins. “ABS’ establishment of this position builds on a collaborative partnership with Mines that spans more than three decades, and it will have a significant impact in furthering Mines’ research and educational endeavors in this important discipline.”

ABS has sustained a 30-year relationship with the university by providing funding for student scholarships, sponsoring technical workshops and engaging in joint research programs.

“Colorado School of Mines is a leader of research and academic training in the areas of materials and metallurgy, and ABS is proud of the strong collaborative relationship we have had for a number of years,” said ABS Chairman, President and CEO Christopher J. Wiernicki. “As we look to the future, I believe that Colorado School of Mines and the ABS Chair in Metallurgical and Materials Engineering will extend the reach of our global R&D network that is conducting cutting-edge research into the most pressing challenges impacting the marine and offshore energy industries.”



## Engineering across disciplines

It was a first for Mines when Linda Battalora, associate teaching professor in the Department of Petroleum Engineering, presented her research on bone density and fracture risk in HIV-infected adults at the Joint Session of the 14th European AIDS Conference and the 15th International Workshop on Co-morbidities and Adverse Drug Reactions in HIV in October 2013 in Brussels.

As a Young Investigator Scholarship awardee, she presented her research at the Conference on Retroviruses and Opportunistic Infections in March 2014 in Boston – another first for Mines.

Breaking new research ground for Mines has been part of her pursuit toward a doctorate degree in Environmental Science and Engineering, but it was Battalora's career in the oil and gas industry that sparked her interest in studying a health-related topic.

During her career in the oil and gas industry, she served as engineer, attorney and negotiator for international oil and gas project development. Her interest in the health of people stricken by infectious diseases like malaria, tuberculosis and human immunodeficiency virus (HIV) in resource-limited countries led her to pursue cross-discipline, cross-college research with her PhD advisors, John Spear in Mines' Civil and Environmental Engineering Department, and Benjamin Young, of the International Association of Providers in AIDS Care; APEX Research, in collaboration with the U.S. Centers for Disease Control and Prevention (CDC).

She earned her bachelor's and master's

degrees in petroleum engineering from Mines, in 1987 and 1988 respectively, and then a Juris Doctor degree from Loyola University New Orleans College of Law in 1993. She is licensed to practice law in Colorado and Louisiana, and is a registered patent attorney.

"I grew up on the Gulf Coast, so I was familiar with offshore oil and gas development. I was good in math and science, and I wanted to see the world," Battalora said of her decision to study petroleum engineering.

In addition to her teaching role, Battalora has been a part-time graduate student at



LINDA BATTALORA

It becomes a teachable moment," Battalora said. "The short answer is that corporate social responsibility is an integral part of every oil and gas project. When we enter a location for project development, we

have a social responsibility to the community. Depending on where we are in the world, this may include building roads, health clinics, risk-prevention programs, schools or addressing other community needs."

Asked how her PhD will inform her teaching at Mines, she explained, "Every engineering project involves the human workforce and regulatory frameworks. Understanding

the integration of health, safety, security, environment and social responsibility (HSSE-SR) is essential to maintain a healthy workforce and a safe, cost-effective engineering project. Students must understand these elements, integrate them in project development and be able to communicate effectively with representatives from the community, government agencies and other stakeholders."

Battalora incorporates HSSE-SR in the undergraduate and graduate courses she teaches at Mines.

She is a member of the Society of Petroleum Engineers (SPE) HSSE-SR Advisory Board and recently was awarded the 2014 SPE Rocky Mountain Regional Award for her work in HSSE-SR.

Battalora plans to continue her research with the CDC, and her collaboration with Spear and Young, on HIV-related topics and HSSE-SR.



Mines since 2009. She earned her PhD in Environmental Science and Engineering in May 2014. The title of her thesis was, "Bones, Fractures, Antiretroviral Therapy and HIV."

"When I'm asked about my research, and I explain that it's a public health topic, the typical response is another question: What does this have to do with petroleum engineering?"

The background of the entire page is a photograph of a modern, multi-story building with large glass windows and a brick base. A person is sitting on a ledge in the foreground, looking down at a book. The sky is clear and blue. On the left side, there is a vertical white bar with a blue geometric pattern at the top.

# NEW Faculty

Led by extraordinary faculty members, the collaborative research conducted at Mines enhances the educational experience and the advancement of technology. Thirty-four named faculty positions at all levels have been established at Mines through the support of the Colorado School of Mines Foundation.

The following pages highlight a selection of new faculty.



**ATEF ELSHERBENI**  
Professor and Dobelman Chair  
**Electrical Engineering and  
Computer Sciences**

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Atef Elsherbeni's research interests include the scattering and diffraction of electromagnetic waves by simple and composite objects, the finite difference time domain analysis of antennas and microwave devices, field visualization and software development for electromagnetics education, interactions of waves with the human body, radio frequency identification (RFID) and sensors in integrated RFID systems, reflector and printed antennas and antenna arrays for radars, personal communication systems, unmanned vehicles, and measurements of antenna characteristics and material properties.

**NEW FACULTY 2013-14**



**Ozkan Celik**, Mechanical Engineering  
Assistant Professor

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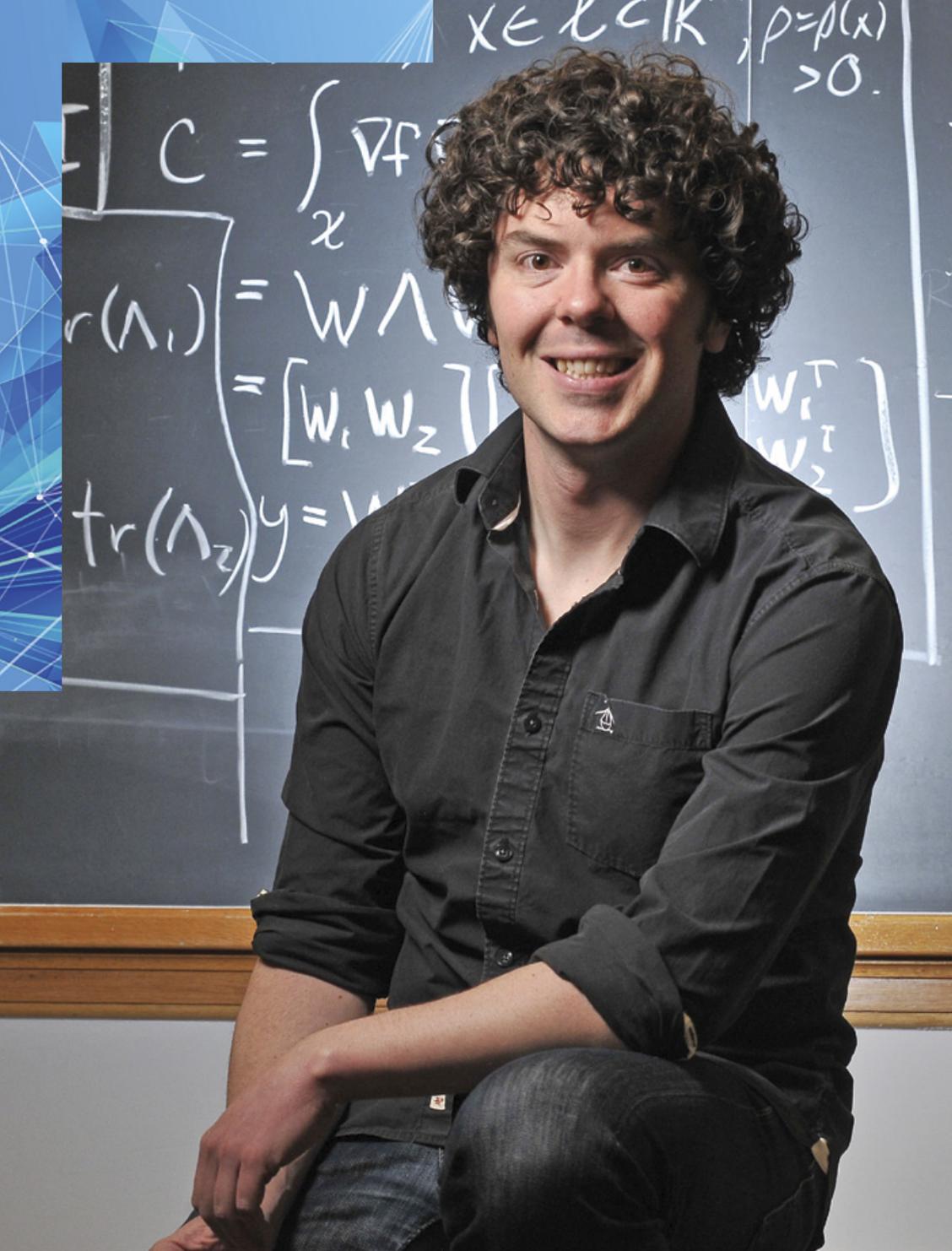
Celik's research focuses on problems at the intersection of robotics and human sensorimotor control system. His group designs and implements mechatronic and haptic interfaces that physically interact with humans. They have applications in rehabilitation, augmentation and modeling of human movement.



**Cecilia Diniz Behn**, Applied Mathematics  
and Statistics Assistant Professor

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Diniz Behn's research interests lie in differential equations with applications to mathematical biology. More specifically, she focuses on developing mathematical modeling and analytical techniques to investigate the neurophysiology of sleep/wake regulation, glucose-insulin dynamics, and viral dynamics in HIV.



## PAUL CONSTANTINE

Ben L. Fryrear Assistant Professor

**Applied Mathematics and Statistics**

Paul Constantine's research falls in the category of uncertainty quantification, which attempts to formulate and compute measures of confidence for physics and engineering simulations - analogous to confidence measures from physical experiments. In this context, he has developed algorithms for sensitivity analysis and dimension reduction to help manage the tremendous amounts of data that costly computer simulations generate. He has applied these algorithms to models in aerospace and geoscience.

## NEW FACULTY 2013-14



**Peter Maniloff**, Economics and Business Assistant Professor

Maniloff studies energy policy and the interactions between the energy sector, agriculture and the environment. He particularly focuses on uncertainty and volatility and their implications for policy design.



**Shiling Pei**, Civil and Environmental Engineering Assistant Professor

Building hazard resilient communities with sustainable materials, Pei is leading a National Science Foundation collaborative research project to enable wood buildings higher than 10 stories for high seismic regions in the U.S.

## Global Smartphone Users



### DEJUN YANG

Ben L. Fryrear Assistant Professor  
**Electrical Engineering and Computer Sciences**

Dejun Yang's research interest lies at the intersections of game theory, optimization, algorithm design and networks. He strives to find the best solutions to the resource allocation and management problem in networks to optimize the network performance. To prove the efficacy of these solutions, he uses rigorous mathematical proofs, such as combinatorics, convex optimization and probability. When independent individual decision-makers are involved, he models, analyzes and addresses the problem using game theory, a resourceful mathematical framework originally from economics. Recently, his research has focused on how to take advantage of the pervasive smartphones to revolutionize our way of life.



**Ronny Pini**, Petroleum Engineering Assistant Professor

Pini develops experimental techniques to study the flow of fluids through rocks by combining conventional core-flooding experiments with multidimensional imaging tools that allow for real-time visualization of flow pathways. His research interests range from the recovery of oil and gas from deep sedimentary formations to hydrogeological flows in the shallow subsurface.



**Aaron Stebner**, Mechanical Engineering Assistant Professor

Stebner's research encompasses multiscale characterization and modeling of advanced behaviors exhibited by crystalline materials. He is working to inform and advance the chemistry, processing, engineering and design of new materials and applications including shape memory alloys for morphing aircraft structures, biological implants, core metals for use in nuclear energy containment, and creating clean energy via laser fusion.



## NANETTE BOYLE

William K. Coors Developmental Chair and Assistant Professor  
**Chemical and Biological Engineering**

The petroleum products we use for energy today were produced by photosynthetic organisms millions of years ago. Nanette Boyle's laboratory focuses on using single cellular aquatic photosynthetic organisms, such as algae and cyanobacteria, to produce the next generation of biofuel. She and her research team use advanced techniques in systems and synthetic biology to design and engineer organisms to produce hydrocarbons that can replace petroleum. Traditionally, chemical engineers design and operate large-scale chemical plants for industrial chemical and petroleum processing; Boyle's group employs the same design principles to redesign cellular metabolism to produce products of interest.

## NEW FACULTY 2013-14



**Andrei Swidinsky**, Geophysics Assistant Professor

Swidinsky specializes in electrical and electromagnetic exploration for natural resources such as oil, gas, gas-hydrates and mineral deposits. His research interests range from the theoretical development of novel exploration technology to applied geophysical field studies.



**Douglas Van Bossuyt**, Mechanical Engineering Assistant Professor

Van Bossuyt focuses his research efforts on complex system design where he specializes in risk and reliability engineering, design for additive manufacturing (3D printing), the psychology of engineering decision-making, early-phase conceptual design, prognostics and health management, and design for the developing world. He is active in the aerospace, civilian nuclear power, automotive, consumer product and space mission arenas.



## **MOISES CARREON**

William K. Coors  
Developmental Chair and  
Assistant Professor  
**Chemical and Biological  
Engineering**

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Moises Carreon's research interests focus on the rational design of advanced functional porous materials at different length scales, including zeolites, mixed metal oxides and metal organic frameworks for applications in molecular gas separations, heterogeneous catalysis and natural gas storage. His research group aims to have a better understanding of the formation mechanisms of these materials and to establish its fundamental structure/separation and structure/catalytic relationships. Other research areas include rational design of heterogeneous catalysts, carbon dioxide conversion to chemicals and synthesis/catalytic transformations of biodiesels/biofuels.



**Xiaoli Zhang**, Mechanical Engineering  
Assistant Professor

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Zhang's research expertise lies in medical robotics including surgical robotics, medical devices design, intelligent human-robot cooperation, smart health care and well-being, and medical cyber-physical systems.



**Luis Zerpa**, Petroleum Engineering Assistant  
Professor

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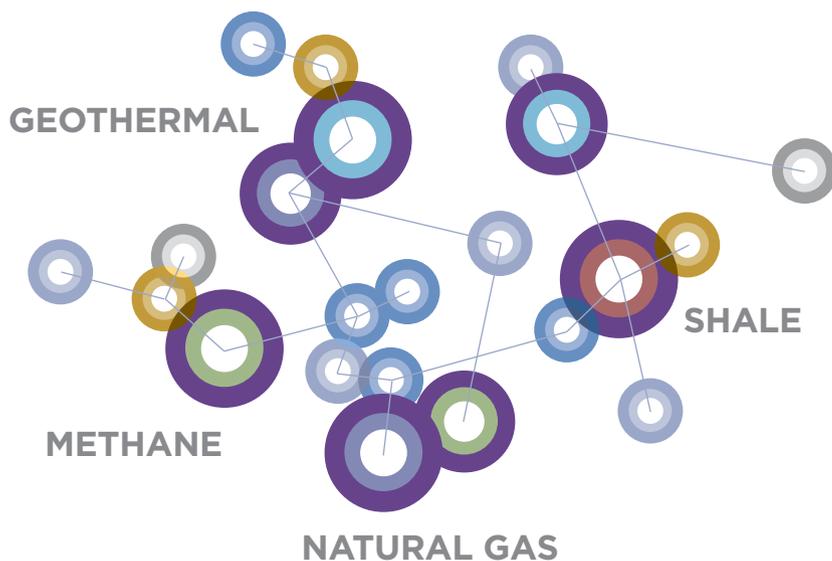
Zerpa's research focuses on the application of numerical modeling techniques for the characterization of oil and gas reservoirs and the analysis of geothermal energy extraction from sedimentary basins. Other areas of research involve deep-water flow assurance with the purpose of understanding the formation mechanisms of solid phases such as gas hydrates, waxes and asphaltenes in subsea oil and gas pipelines and the effects on multiphase flow.



# Sustainability and the Subsurface World

PhD student Ariel Esposito works on a small wind tunnel to investigate the fundamental processes that dictate natural gas transport and leakage through the subsurface to the atmosphere. In the background is the large-scale wind tunnel that is part of the porous media wind tunnel test facility.





## GRAND CHALLENGES

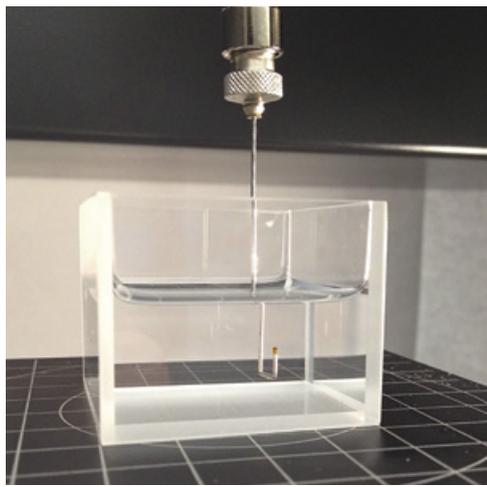
## ENERGY

For those of us residing on the planet's surface, the term "shale" evokes visions of flaking layers of rock you can all but peel away by hand. Oil and gas shale is nothing like this. Pick up a cylindrical core brought up from a reservoir two miles below—from the Bakken in North Dakota, the Niobrara in Colorado, the Vaca Muerta in Argentina, it doesn't matter—and it's heavy and solid like a hunk of marble. The hydrocarbons are locked inside, perhaps 100,000 times more tightly than would be the case were it merely mixed into concrete.

This is the stuff, though, of the American—and, increasingly, global—boom in unconventional oil and gas. You can't just drop a well bore into rock like this and watch hydrocarbons gush out. You must use advanced horizontal drilling and hydraulic fracturing technologies to release the oil and gas. Roughly one-third of the U.S. natural gas production heating our homes and fueling our factories is won this way. Two-thirds of all rigs are drilling horizontal wells. Unconventional energy, at least as applies to shale oil and gas, has become conventional.

Hydraulic fracturing has been around for decades, but we're still learning about it. What are the true environmental impacts? How can we increase yields to bring more output per well and so have fewer wells, lower costs, cut trade imbalances and lessen the impact on the planet? Can these same techniques be applied to renewable geothermal technologies? Researchers at Colorado School of Mines are working to answer these and other questions via a broad set of disciplines and several noteworthy vehicles. Among them include the Marathon Center of Excellence for Reservoir Studies (MCERS); the new ConocoPhillips Center for a Sustainable WE<sup>2</sup>ST (Water-Energy Education, Science and Technology); and a new National Science Foundation (NSF)-sponsored program to understand the risks of natural gas development to the Rocky Mountain region's air and water.

As Dag Nummedal, who directs the Colorado Energy Research Institute, put it, "We really focus on making fossil energy more sustainable. That means reducing carbon dioxide emissions, reducing methane emissions, and doing energy development in ways that allow the fossil energy industry to coexist with clean water, agriculture, breathable air and optimal temperatures."



Courtesy of Younki Cho



From left, graduate students Younki Cho, Somayeh Karimi and Professor Hossein Kazemi examine a Drop Shape Analyzer (DSA 100) chamber (top photo) to determine the contact angle between oil and a shale sample in the brine-oil environment.

As part of a five-year, multi-institution NSF project, Mines researchers will focus on quantifying what those risks actually are, said Professor Will Fleckenstein. In the public arena in particular, assertions about the environmental and public health impacts of hydraulic fracturing have frequently outstripped their scientific basis, he added.

The projects include a study of the stresses in the cement sheaths and well casings for a better sense of what they can actually handle, he said. Fleckenstein is at the forefront of such work, having invented a technology, now ready for market, that uses a pressure test to ensure a sound hydraulic seal at depths of 300 to 2,000 feet, the zone of freshwater aquifers. The team also will examine databases relating to hydrocarbon migration for a better sense of if, how, and how often it happens.

Elsewhere at Mines, researchers will use a wind tunnel, filling what used to be the Volk Gymnasium pool, to better grasp how methane from natural gas production migrates through surface soils. Ground

and aircraft-based sensors sometimes find methane hot spots with no obvious methane sources. That ground-based and air-based sensors tend to disagree on the volume of methane leaking has made the work all the more urgent, said Kathleen Smits, an assistant professor. PhD student Ariel Esposito was at work on a small-scale version of the experiment at the pool's edge. She would feed methane into the bottom of a tank of fine gravel, sand and water and detect it through sensors on top at a rate of 500 samples per second.

"It's a really important field because there's a lot of uncertainty about the amount of gas that's leaking," Esposito said. "We're trying to lend some insights into the underlying processes."

Meanwhile, Mines is applying its renowned strengths in reservoir characterization to boost the production of hydraulically fractured wells, which makes both economic and environmental sense. There's a big potential upside, said Professor Hossein Kazemi, who co-directs MCERS: current production techniques only yield about 10 percent of unconventional oil, compared to 30 to 40 percent for conventional reservoirs. The work ranges from major field studies of the Bakken, Niobrara and Vaca Muerte led by Professor Steve Sonnenberg to lab experiments focusing on the nanoscale properties of reservoir rock.

As with much of the work at Mines, the research involves both experimentation and computer modeling. In one of Kazemi's Marquez Hall labs, Mines PhD student Younki Cho has spent two years building a core flooding experiment to measure shale permeability at the nanoscale. The experiment also can inject surfactants or carbon dioxide to simulate enhanced oil recovery, he said. The stainless-steel setup was forcing pressurized brine into a 1.5-inch by 2-inch cylindrical rock core at confining stress of 2,600 pounds per square inch (psi) and pressure differential of 2,100 psi, producing a flow of 0.003 cubic centimeter per minute.

"It's a very slow rate because permeability is so small," Cho said. "You have to be very patient."

Downstairs, PhD student Somayeh Karimi was spinning cores in an ultracentrifuge humming at 13,000 rpm.

"Right now we have not seen any published data on direct measurement of capillary pressure with reservoir fluids in tight shale rocks," she said. The results will feed into modeling of how much oil and gas might be recoverable, how fast, and how long that recovery might take, Karimi added.

Over in Professor Marte Gutierrez's Brown Hall lab, PhD student Luke Frash was fracturing rocks of his own, but larger ones of about a cubic foot. Using a black-steel cell of his own design, Frash applies heat and pressure in three dimensions, and then drills into and hydraulically



Professor Steve Sonnenberg stands in the Mines core laboratory with a core of the Vaca Muerta shale from the Neuquén basin of Argentina.

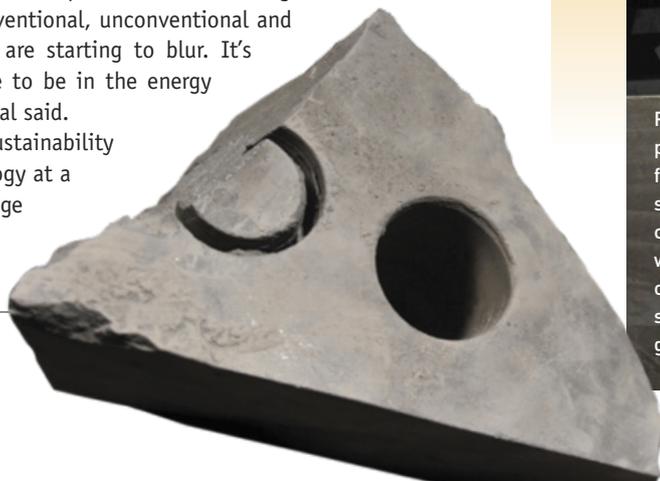
fractures cubes of shale, high-strength cement and granite, testing for strain, temperature, pressure, sound, even micro-earthquakes. The idea is to understand the rock-mechanical behavior of underground formations, Gutierrez said.

"It's a scale model of what's going on in the field," Gutierrez said.

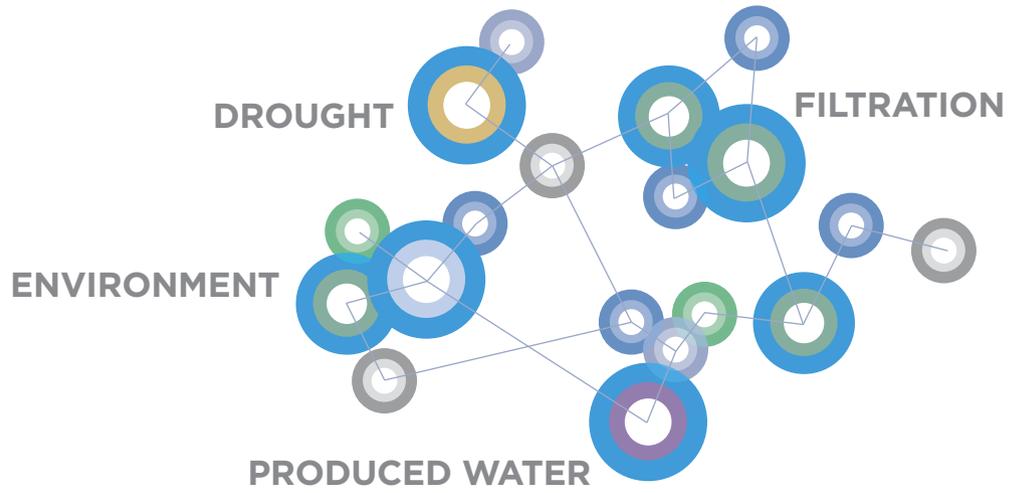
The granite cubes in Frash's lab are for studies of hydraulic fracturing for renewable geothermal applications, an active field of study at Mines, said Associate Professor Bill Eustes. He and Fleckenstein are working on a project with the National Renewable Energy Laboratory to see if multi-stage hydraulic fracturing technology used in unconventional shale can be applied to geothermal energy. There are many challenges, Eustes said—among them, thicker geothermal well bores and much more heat.

These and other efforts, including work to characterize possible reservoirs for carbon sequestration and storage, illustrate how the definitions of conventional, unconventional and renewable energy are starting to blur. It's a fascinating time to be in the energy business, Nummedal said.

"The push for sustainability is driving technology at a faster rate of change than ever before," he said.



PhD student Luke Frash is pictured with two hydraulic fractured laboratory specimens: a clear acrylic cylinder that was fractured with high-pressure injection of liquid epoxy and a cross-section from a fractured granite specimen.



# Worth its weight: Water in the West

Graduate students Skuyler Herzog (standing) and Kyle Knipper work with Associate Professor Terri Hogue analyzing snow properties and water content in the burned areas of the Rio Grande headwaters.



**W**ater and oil don't mix. With oil and gas production and water, it's quite the opposite.

Getting at the unconventional oil and gas reserves at the heart of America's energy boom can take millions of gallons of water per well before the first hydrocarbons emerge. One estimate puts the hydrologic demands of the 80,000 wells in 17 states drilled since 2005 at more than 250 billion gallons. That's three times the volume of Denver Water's Dillon Reservoir.

Yet in the western U.S. and elsewhere, geologic "accidents" have placed some of the most promising unconventional oil and gas reserves below parched landscapes.

Mines researchers are at the forefront of enhancing our still-nascent understanding of this modern story of oil and water, and more broadly in the development of new ways to boost freshwater resources in an era of rising demand and growing scarcity.

ConocoPhillips' recent \$3 million gift to establish the new Center for a Sustainable WE<sup>2</sup>ST (Water-Energy Education, Science and Technology) is the latest testament to Mines' strengths in water.

The idea is to focus on a single formation such as the Niobrara, taking a comprehensive look at the complex technical and social interdependencies of oil and gas development and limited water resources. Professor John McCray, head of Mines' Civil and Environmental Engineering Department, describes a wide-ranging effort, involving remote sensing and hydrological models to map out water sources and the tools of geochemistry, hydrology, microbiology and environmental engineering to develop ways to clean up the water that emerges from the depths during oil and gas operations. The work also will involve a strong social-sciences component led by Mines anthropologist Assistant Professor Jessica Rolston, McCray said, to help define ways to communicate the actual risks of unconventional energy development and get energy companies, regulators and the public on the same factual page.

"It's a partnership with ConocoPhillips that can break new ground, and one that doesn't exist outside of this center," McCray said. "We want to come out and be the honest broker."



Education is a key component of the ConocoPhillips center, said Associate Professor Terri Hogue, who is directing the new center. A big part of the budget will go to fellowships for 15 to 20 master's and PhD students, she said, in addition to 10 undergraduate fellowships each year. The center will attract top-notch talent all focusing on the nexus of water resources and energy development.

Associate Professor Tzahi Cath is among those at Mines already at work at that confluence. Cath directs Mines' Advanced Water Technology Center (AQWATEC), which is developing a range of water-treatment technologies. This spring, the master's students in Cath's Environmental Engineering Pilot Lab course were studying if adding an inky slurry of activated charcoal to the city of Golden's water treatment process might help remove the organics that have spiked in reservoirs along Colorado's Front Range after the 2013 flood. A green garden hose snaked from a tank in the bed of the AQWATEC pickup parked on the sidewalk outside Coolbaugh Hall. It fed a bench-scale model of Golden's water treatment plant, its upper tanks full of fluid like curdling apple cider. If it worked here, they would test the activated charcoal in a Mines pilot plant housed in the treatment facility itself and, assuming the city adopts the approach, would help with the transition to the full-scale plant.

"Usually, the city adopts our recommendations," Cath said.

A bit downhill, in AQWATEC's space in Mines' General Research Laboratory, PhD student Bryan Coday was working near several hip-high plastic drums, some encrusted with salt (they're for a project testing new ways to extract valuable potassium sulfate from the Great Salt Lake).

Others contained produced water from hydraulic fracturing operations, and Coday was working on a system to cleanse it using low-pressure osmosis and flat-sheet polymeric membranes. To the touch, the membranes felt like high-end wrapping paper, but in practice they are very sophisticated materials. The system uses salt water to attract clean water from the deep-brown produced water across the membrane, which retains contaminants.

"Produced water is difficult to treat because of the hydrocarbons and complex organic compounds, plus high salinity," Cath said. Mines environmental chemistry Associate Professor Christopher Higgins is working with Cath to identify just what chemicals from the different samples of produced water cross the membranes, and how they can improve the process to produce even drinking-quality water from produced water.

A test system had performed well enough that Coday and research associate Mike Veres were now in the midst of building a pilot-scale system. "Harnessing the natural chemical energy of brine as the driving force for wastewater treatment has its advantages," Cath said. "Such systems are mechanically simpler, take less energy, and are easier to clean because the grime hasn't been rammed into filter pores as happens with high-pressure systems."

If some combination of low-pressure filtration and microbial treatment (another AQWATEC project being tested across the lab in columns of activated carbon next to the AQWATEC aluminum boat) can economically bring produced water to the high standards of municipal wastewater treatment, the benefits are hard to miss. Water locked up two miles



THE GREAT SALT LAKE



From left, graduate students Bryan Coday, Daniel Freedman and Stephanie Riley work with Associate Professor Tzahi Cath in his lab where they study biological, chemical and physical wastewater treatment processes that can transform contaminated produced water and fracturing flowback wastewater from oil and gas wells to highly purified water suitable for reuse in a broad range of applications.

below could be released into streams in drought-prone regions, actually boosting the water budget. And oil and gas operations could reuse some portion of this new resource in their hydraulic fracturing operations. Coday is enthusiastic.

"It's a great opportunity to work on a project where industry is moving at such a quick pace on the energy side, on the water side and on the regulatory side," he said.

Another major project has a similarly sweeping purview, but pertains to urban water use. Since 2011, Mines has teamed with Stanford University, the University of California at Berkeley and New Mexico State University on a 10-year, \$40 million effort that aims to transform how cities in the arid West use and reuse water. The program, called Re-Inventing the Nation's Urban Water Infrastructure (ReNUWIt), is the first National Science Foundation-funded Engineering Research Center to focus on water issues.

McCray, who leads the Mines effort, said a dozen Mines faculty are leading or working on some 20 ReNUWIt projects. Hogue is spearheading an effort involving several Mines colleagues to determine the potential impact of August 2013's 257,000-acre Sierra Nevada Rim Fire on water supplies to San Francisco and surrounding counties. Cath's team is refining a portable, commercial-scale sequence batch membrane bioreactor that has proven its mettle with the wastewater

from the apartments at Mines Park—capable of producing drinking water from domestic wastewater. Mines professors Tissa Illangasekare and Kate Smits lead a project that is developing technology to allow underground aquifers to treat and store water and then reuse it rather than letting it escape downstream. They are researching the use of sensors that provide real-time feedback on system performance, so decisions can be made to improve operation efficiency. Mines Associate Professor Linda Figueroa is working with the Plum Creek Wastewater Authority south of Denver on a pilot-scale system using anaerobic wastewater treatment. The system has been in operation for 1.5 years and has reduced more than 40 percent of the influent organic matter without the expense of oxygen (unlike traditional aerobic methods) and, as a bonus, produces energy while it cleans wastewater.

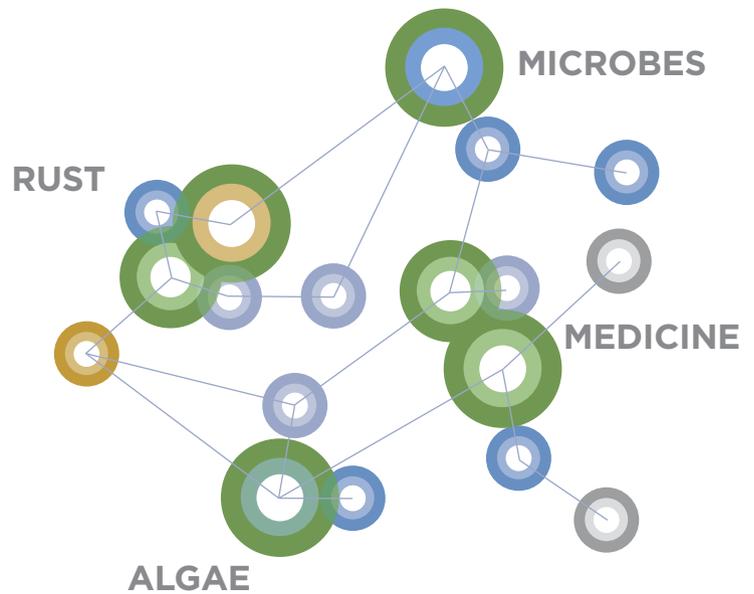
As with the ConocoPhillips center, ReNUWIt involves a heavy social science component. That's because, for all the technological capabilities on display at Mines, the biggest challenges facing smarter water systems may reside between our ears. People just don't like the idea of drinking reclaimed water (in Singapore they call it NeWater), McCray said, even though that's what the South Platte River really is. Collectively, such apprehensions coalesce into powerful social and political barriers.

"They're by far the biggest hurdles to clear if we're going to have any change in the way we develop our infrastructure," McCray said.

Where **Biology**  
and **Engineering**  
**Meet**







## GRAND CHALLENGES | BIOTECHNOLOGY

Colorado School of Mines has been known for its prowess in geology since about 1874. Its reputation in biotechnology has taken just a little bit longer to develop – about 130 years longer, give or take.

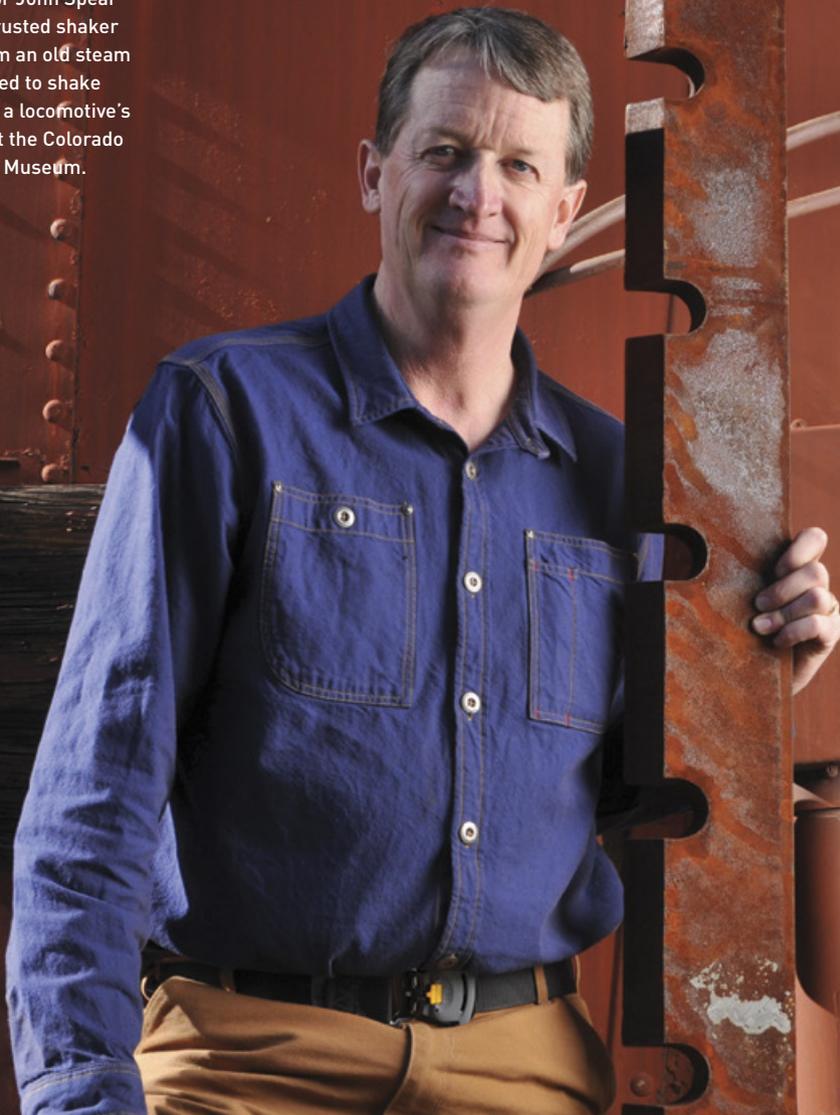
Mines is making up for lost time. The school's faculty, researchers and students have shed new light on areas as diverse as the nature of blood clots and the microbial role in rust. They have helped make better artificial limbs and developed laser microscopes capable of capturing video of the inner working of cells. They have reengineered algae to produce biofuels and developed scaffolding that could one day give new cartilage a foothold in creaky knees. In short, biological sciences and engineering have arrived at Mines, and in a big way.

The work is diverse, but there are common threads, said David Marr, who heads Mines' Department of Chemical and Biological Engineering.

"We are an engineering and technology-focused institution—that's really where our niche is," Marr said. "It's in areas of bioengineering, broadly interpreted, that we have a strong role to play." Those areas, he added, encompass biomedical applications, biomechanics, biomaterials, environmental biotechnology and biofuels.

Assistant Professor Nanette Boyle looks at one type of photosynthetic organism used in her lab for metabolic engineering. In the flask is a model green algae, *Chlamydomonas reinhardtii*, that has been extensively used for algal-based biodiesel research.

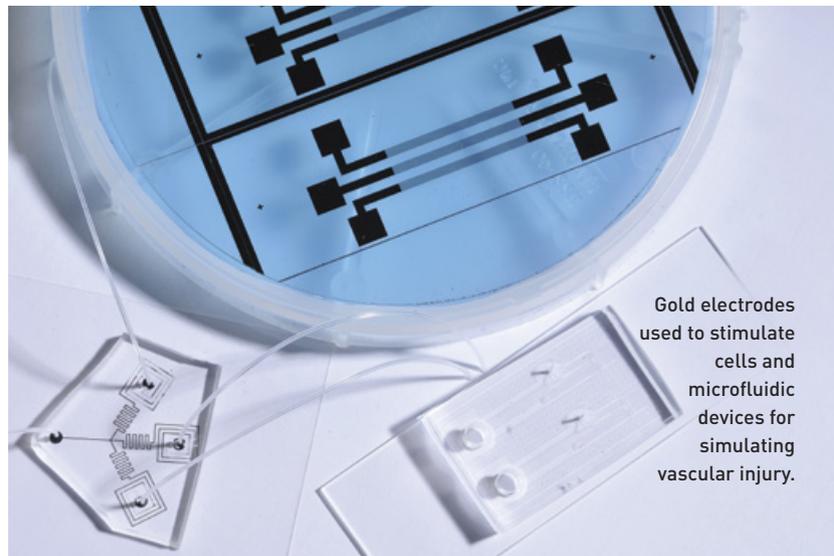
Professor John Spear holds a rusted shaker rack from an old steam train (used to shake coal into a locomotive's boiler) at the Colorado Railroad Museum.



Recent hires have bolstered several of these research areas, and curriculum has changed in kind, with courses covering a range of biomedical engineering, biomaterials, environmental biotechnology and biophysics available to undergraduate as well as graduate students. In fall 2013, Mines' freshman biology course moved to a studio format, where small teams of students sit at workstations equipped with computers, dual monitors, video microscopes, digital cameras and digital balances, as well as with more specialized equipment like micropipettes and oxygen, pH and temperature sensors.

Mines Assistant Professor Nanette Boyle is among the recent arrivals, having signed on in August 2013. Like many at Mines, Boyle considers herself an engineer. But she engineers the genomes of algae and cyanobacteria, microscopic plants using the tools of synthetic biology, systems biology and metabolic engineering.

"The overall goal of my research is to make products that replace petroleum using these photosynthetic organisms," Boyle said.



Gold electrodes used to stimulate cells and microfluidic devices for simulating vascular injury.

In her new Alderson Hall lab, stacked incubator shakers swirled the contents of four beakers, their sloshing fluid of varying light-green hues under the bright multispectral light. They were filed with the algae *Chlamydomonas* and the cyanobacteria *Synechococcus*. Boyle's work differs from most algae-based biofuel efforts, which aim to fatten up the algae and then harvest them. Rather, she wants to engineer the algae to produce short chain alcohols, isoprene or other hydrocarbons while they keep photosynthesizing away.

"You can get them to create whatever you want if you can find the genes to do it," Boyle said.

Mines Professor John Spear, a microbiologist, also focuses on the genomics of tiny creatures. The driving questions of his work, though, are big.

"What are the possible benefits of microbes to make human life and/or the environment better?" Spear asked. "How can we put microbes to work in ways we haven't done before?"

Genetic sequencing has fostered an explosion in what is known of the tree of life, and Spear and colleagues are discovering new organisms at a dizzying pace. In the mid-1980s, there were perhaps 12 known phyla, or kingdoms, of bacteria. Now there are 130 and counting.

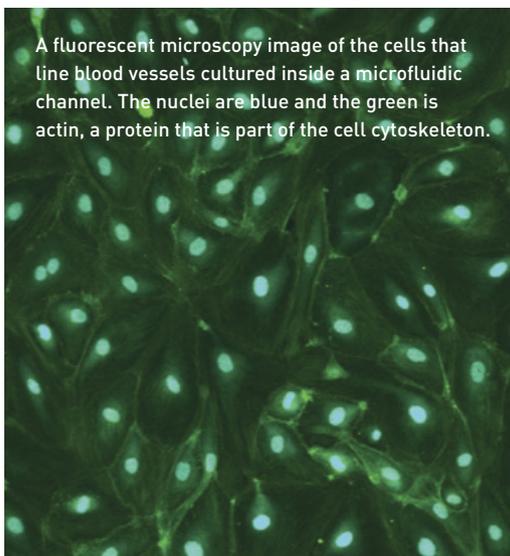
"So when you find 10 or 20 phyla of bacteria as we have found in some environments, that's like walking out your door and discovering plants for the first time," Spear said.

On the applied side, Spear has focused on a couple of areas, including wastewater treatment and corrosion. Some corrosion is chemical, but microbes, which feed on the electrons metal has to offer, also contribute, to the point that the oil and gas industry has considered flushing wells with antibiotics. Across industry, the

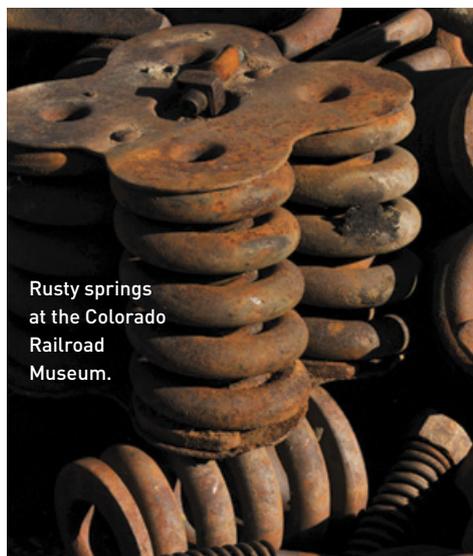
Professor David Marr is developing a microfluidic cell sorter.



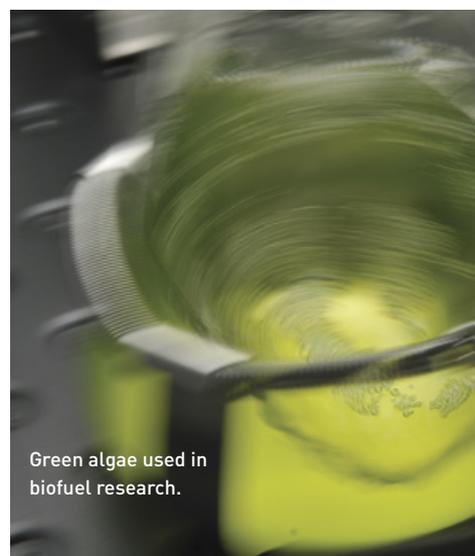
A fluorescent microscopy image of the cells that line blood vessels cultured inside a microfluidic channel. The nuclei are blue and the green is actin, a protein that is part of the cell cytoskeleton.

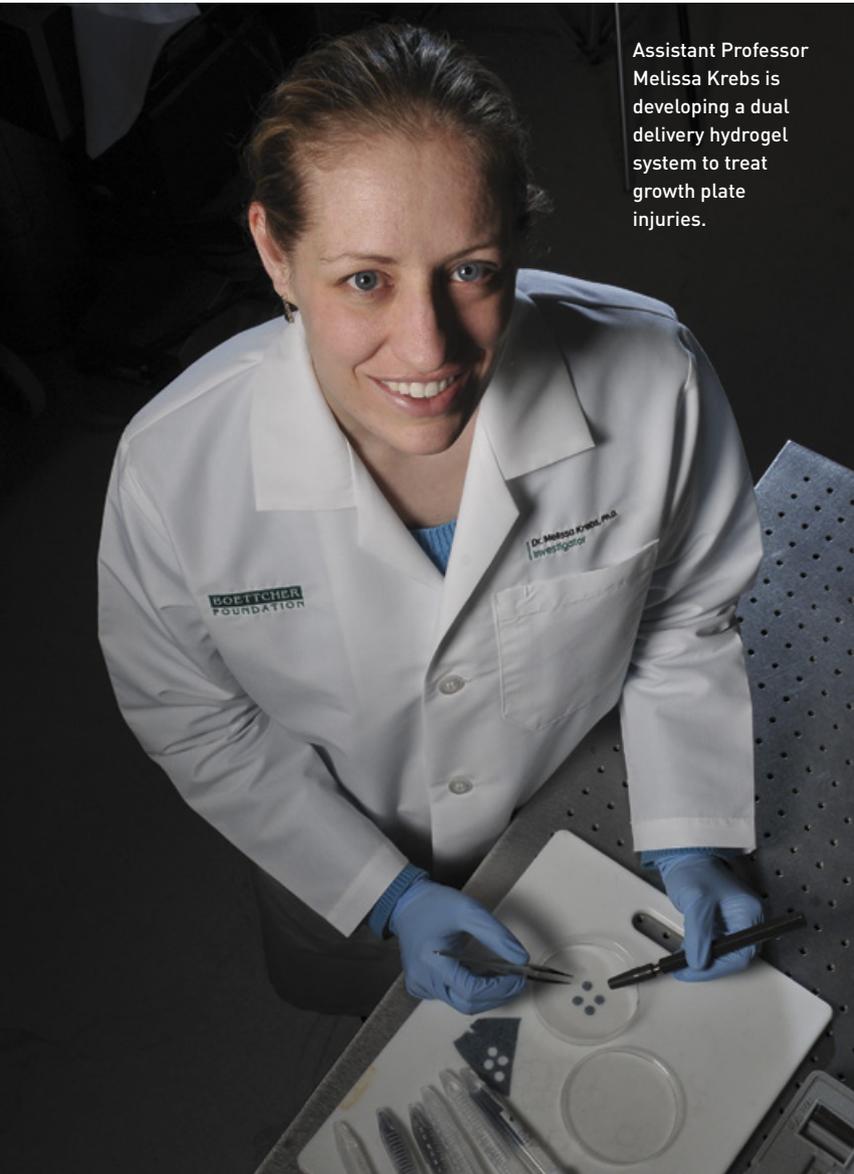


Rusty springs at the Colorado Railroad Museum.



Green algae used in biofuel research.



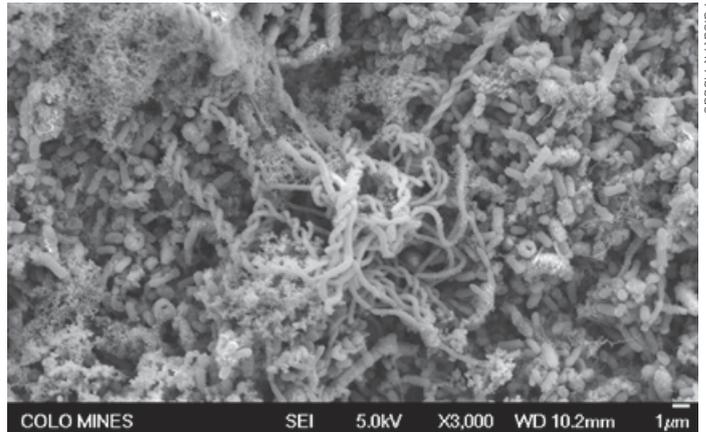


Assistant Professor Melissa Krebs is developing a dual delivery hydrogel system to treat growth plate injuries.

failures and replacement costs associated with corrosion cost tens of billions of dollars annually. More precisely understanding the composition and habits of such microbes can help industry develop better countermeasures and lower costs, Spear said.

Much of Mines' biology-related work involves the biomedical field. A longstanding collaboration involving Marr and Associate Professor Keith Neeves, recently landed a National Institutes of Health grant to study how microbots – tiny spherical machines each about one-twentieth the diameter of a human hair – might be used to deliver clot-busting drugs straight to the blockage in stroke patients. The idea, Marr said, is to inject a swarm of microbots and steer them to clots using magnets outside the body, "A sort of 'Fantastic Voyage' kind of thing," Marr said.

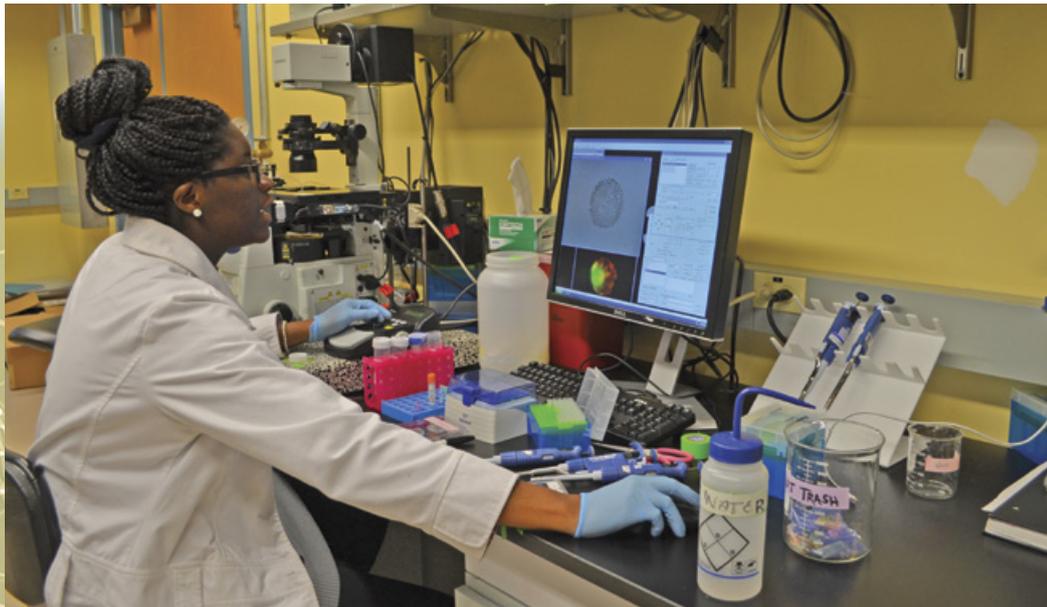
Marr's Alderson lab has the markings of an experimental physicist's haunts, with stainless-steel-topped laser tables rife with grids of screw holes, many anchoring lenses and mirrors. The work there focuses on using light and magnetism to, among other things, test the mechanical properties of cells. A floor below, Neeves' PhD student Abimbola Jarvis bounced between making microfluidic devices of rubbery silicone and adjusting an Olympus microscope where the



Faisal Al-Abbas

A scanning electron micrograph of a microbial biofilm on the surface of pipeline steel.

PhD student Abimbola Jarvis looks at blood clots formed in vascular injury models.



screen displayed a fluorescence-enhanced time-lapse of a blood clot forming. Neeves' main interest is in how blood clots form and dissolve, work that has piqued the interest of clinicians at places such as Children's Hospital Colorado, where Neeves has helped study hemophilia patients.

"We work where physics and hematology meet," Neeves said.

Down the hall, Assistant Professor Melissa Krebs is working on where joints meet, among other things. She and her students create biopolymers with applications ranging from tissue regeneration (cartilage being one target) to cancer fighting. The trick, she said, is to create polymers that support cell growth or drug delivery for a prescribed amount of time and then dissolve away.

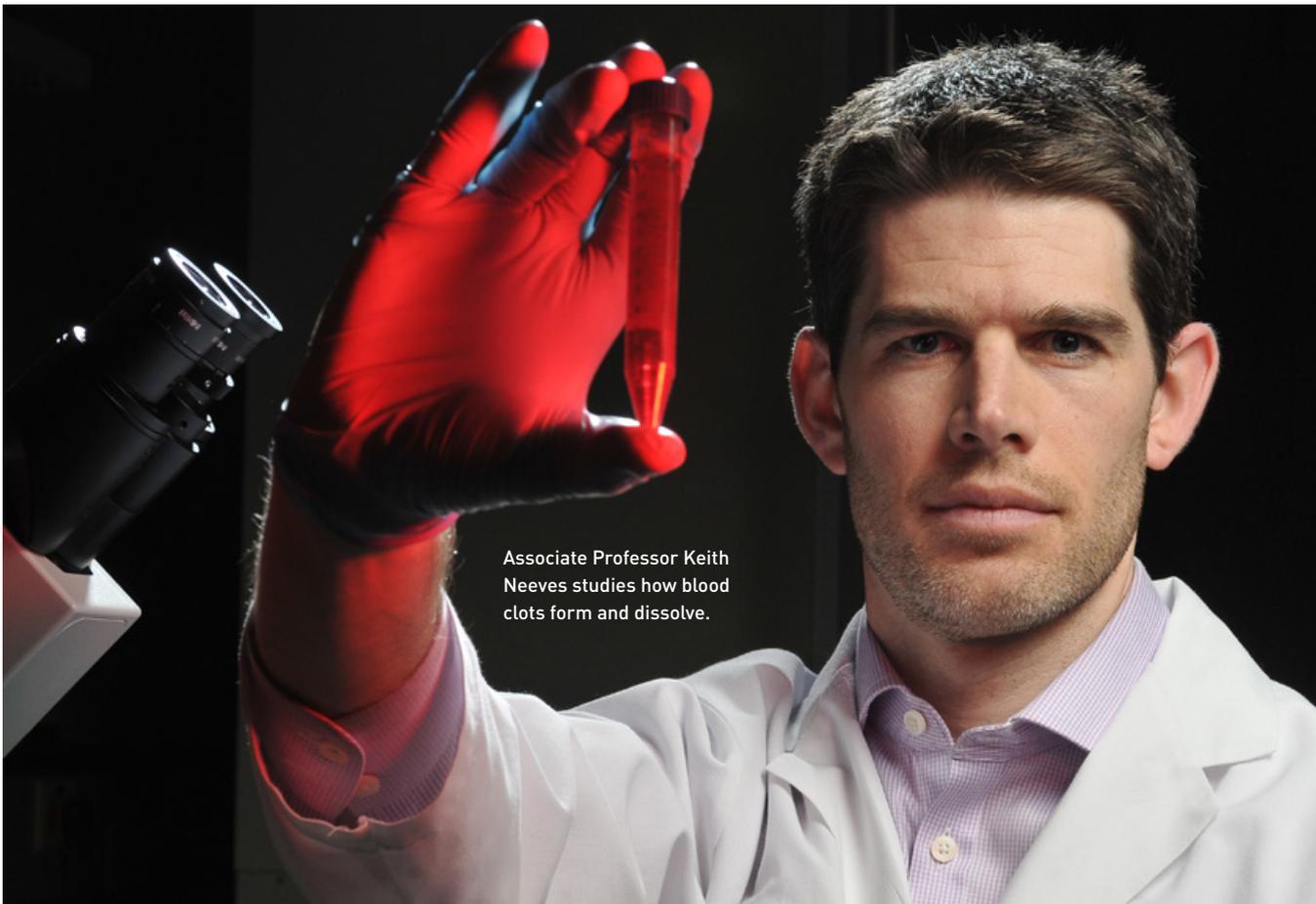
In Krebs's lab, PhD student Michael Riederer was creating microspheres for use on the drug-delivery side. Among the inputs were genipin, a chemical derived from gardenias, and chitosan from shrimp shells. As the research progresses, he will work on releasing proteins from the microspheres, controlling the pace and volume of release, Krebs said. These proteins might include growth factors for tissue regeneration or growth inhibitors for cancer treatment, she said.

Mines Assistant Professor Anne Silverman works on joints, too, but from a different perspective. With Mines associate professors Anthony Petrella and Joel Bach, she leads Mines' Center for Biomechanics & Rehabilitation Research.

"The overall theme is improving walking ability in people who have movement disorders," Silverman said.

Her team takes experimental measurements on patients using near-infrared cameras, voltage sensors to measure muscle excitations and force plates to measure external loads (such as the heel hitting the ground). They then use this data to develop computer simulations of movement. Amputations below the knee have been a focus, but her team also works with patients who have Parkinson's disease and cerebral palsy. Collaboration partners have ranged from the Center for the Intrepid at Brooke Army Medical Center and the Colorado Neurological Institute at Denver's Swedish Medical Center.

"We're creating complex models and simulations of movement to estimate in vivo muscular and joint behavior," Silverman said. "We're using an engineering approach to solve biological problems."

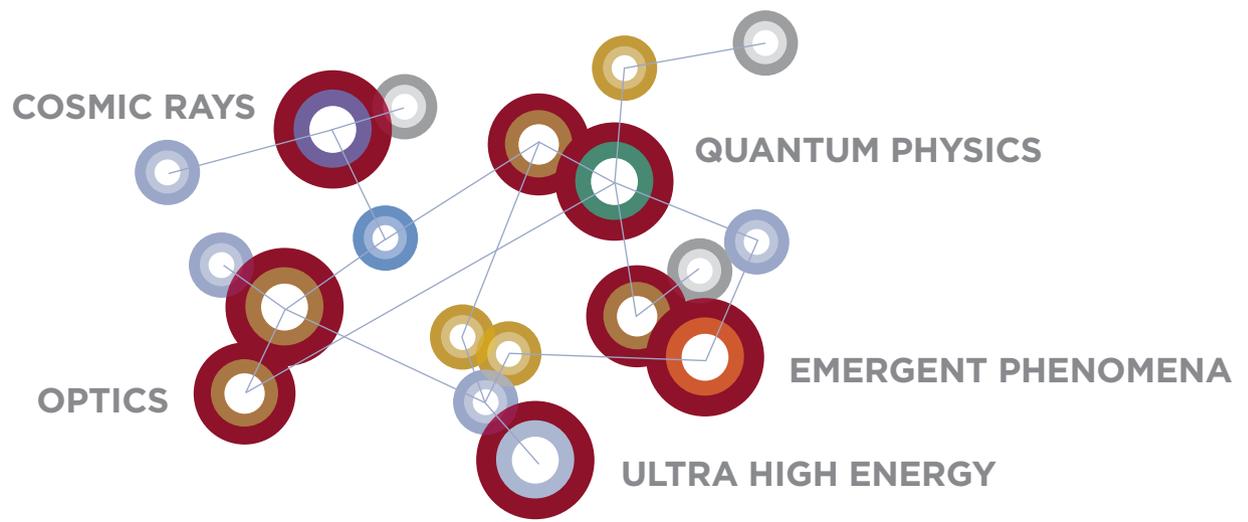


Associate Professor Keith Neeves studies how blood clots form and dissolve.

# Exploring the Unknown



From left, PhD student Johannes Eser and Associate Professor Lawrence Wiencke stand in front of the mirror of a cosmic ray detector located near Two Buttes, Colorado.



## GRAND CHALLENGES **PHYSICS**

**P**hysics is the broadest of all studies, sweeping from the universe’s grandest creations down to the particles that form particles that make up atoms. Given such a large vista, the physicists at the Colorado School of Mines have research agendas that are surprisingly close. As Mark Lusk, a Mines physics professor put it: “We’re all interested in the properties of very small particles, where the quirky nature of quantum mechanics is in full force.”

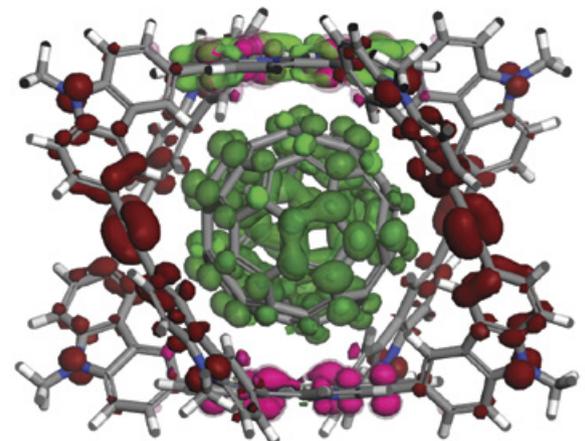
It’s just that what these particles have to say about nature covers a huge range of topics. Lusk is most interested in how electrons move around in, say, solar cells or the proteins of microbes. His colleague Jeff Squier crafts photons to illuminate the black gearboxes of living machines. Lawrence Wiencke and Fred Sarazin are interested in individual charged particles carrying as much energy as a tennis ball smashed at 50 miles per hour. In the lingo of particle energy, Mines physicists study a range from  $10^{-10}$  to  $10^{20}$  electron-volts (eV). That’s 30 orders of magnitude, or roughly the difference between something happening once in the history of the universe and something happening a trillion times each second.

Like Lusk, Lincoln Carr focuses on the low-energy side – on atoms and molecules a million times colder than outer space, specifically their quantum behavior. Carr, too, is a theoretical physicist, a conceptual designer of the foundations for technologies we can’t yet imagine. His Meyer Hall office sports an orange-leather couch above which are festooned the prayer-flag-like results of a student project.

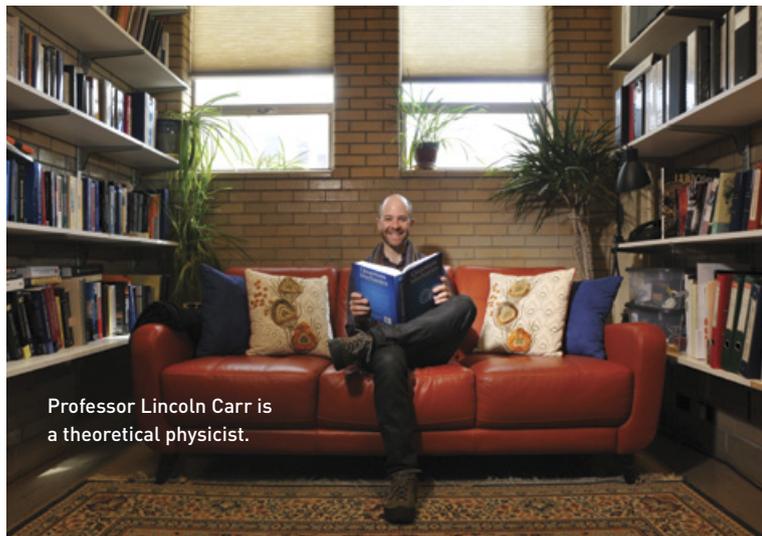
When Carr arrived at Mines in 2005 from the University of Colorado at Boulder’s JILA – one of the world’s top atomic, molecular and optical physics institutions – Mines had a very limited theoretical physics program. That has changed quickly; now there are several highly research-active theoretical physics faculty members and as many as 20 graduate students doing theoretical physics work, some of it at the highest levels. For instance, recent Mines PhD graduate Michael Wall won the 2014 Nicholas Metropolis Award for Outstanding Doctoral Work in Computational Physics from the American Physical Society, the top such award in the world.

Carr’s philosophy echoes that of the growing theoretical physics team: “I want to create great students and colleagues.”

Using high performance computing, Physics Professor Mark Lusk is exploring structures such as C70 fullerenes (below), molecules consisting of 70 carbon atoms, as all-organic solar cell materials. C70 fullerenes can be encapsulated within a framework of linked carbon-based molecules and when exposed to light, excited electrons (dark green) jump to the fullerene leaving positively charged regions on the framework (brown and magenta). The quantum mechanical motion of the photons and electrons can be mapped out in detail, allowing researchers to relate sunlight intensity to the resulting electrical current before creating a material in the laboratory. Projects like this are always team efforts involving theoretical physicists and synthetic chemists.



Across the hall is the Carr lab. Its hardware is comprised of a dozen desks, coffee and espresso machines, a microwave, white boards plastered with equations and a roll-call of history's greatest physicists, black-and-white on standard office paper, looking down from on high. Here some of Carr's group works on a widely used open-source code to model quantum states of many-body systems over time – Matrix Product State, or MPS, it's called, and it has been used for hundreds of studies around the world, Carr said.



Professor Lincoln Carr is a theoretical physicist.

A key research thrust is the development of a theory of many-body systems of ultracold molecules. In the 1920s, Satyendra Nath Bose and Albert Einstein hypothesized that a cloud of millions of atoms could, if cooled to temperatures close to absolute zero, congeal into a single “superatom” exhibiting strange quantum properties at a macroscopic scale. Carr's group is now trying to predict how a cloud of ultracold molecules might interact – a much more complicated task, given that electron and nuclear spin states of each atom in the molecule as well as the overall rotational, vibrational and other degrees of freedom come into play. Carr has calculated that an ultracold cloud of methyl fluoride (CH<sub>3</sub>F) trapped in a crystal of light could lead to quantum magnets with properties much different than those hanging on refrigerators.

“I spend a lot of time on this couch just dreaming where it can go,” Carr said.

Lusk, who frequently collaborates with Carr, uses supercomputers to understand the quantum behavior of materials. He is the lead theorist of the Renewable Energy Materials Research Science and Engineering

Center (REMRSEC) as well as lead scientist of the Golden Energy Computing Organization (GECO).

Lusk's work focuses on quantum transport – “the way in which energy and charge can be scooted around in these very small domains,” as he put it. Recent work in collaboration with Alan Sellinger, an associate professor of chemistry and geochemistry, modeled – and then created – “fuzzy looking” quantum dots made by linking organic molecules to the photovoltaic particles. Lusk

and Sellinger had hypothesized that something along these lines with very small (1-2 nanometer) silicon-carbon dots would change the sort of light they absorb, making them better candidates for future high-efficiency solar cells. In less than a year, Lusk's group had worked out the theoretical design and Sellinger had created them.

“And it works,” Lusk said. “What a rush.”

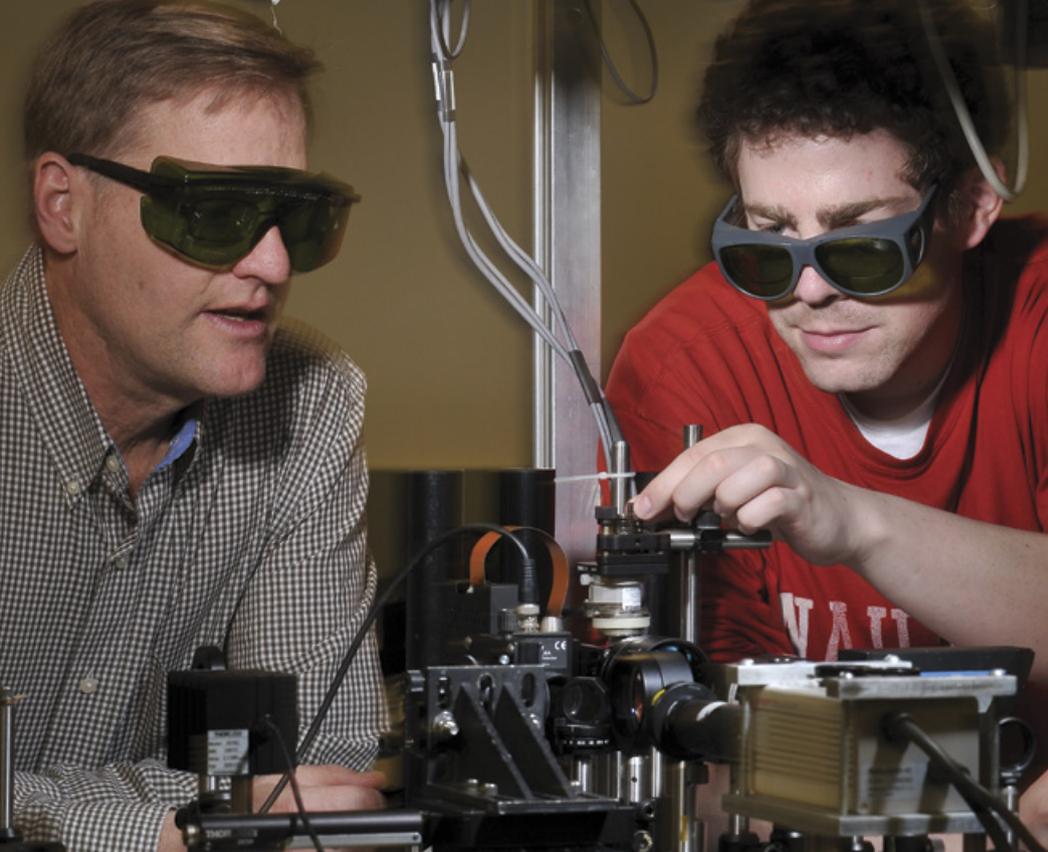
While energy applications are interesting to Lusk, his programs run on Mines' BlueM supercomputer, he also models things like the motion of energy and electrons in biological systems such as the green algae at Yellowstone National Park.

“At first, we thought their proteins were just structural units holding things in place. But it turns out that they also guide the transport of energy and charge and use a whole grab bag of complex tricks to influence the environment in which the charges and energy find themselves,” Lusk said. “We're learning a lot about how to design systems where all the pieces conspire to produce surprising results, called emergent phenonema by those in the business.”

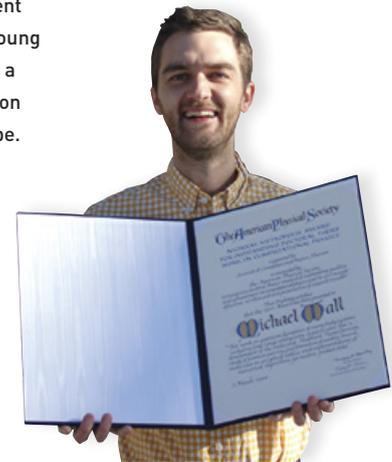
Below left, the Caihueco Fluorescence Detector building at the Pierre Auger Observatory. The bay doors are open, so the detector is in operation. The Milky Way can be seen in the background together with the Magellanic clouds (top right). Lower on the horizon is the background light from nearby towns and the (green) airglow of the atmosphere.







Professor  
Jeff Squier  
(left) and  
PhD student  
Michael Young  
work with a  
multiphoton  
microscope.



Michael Wall PhD '12 was awarded the American Physical Society's 2014 Nicholas Metropolis Award for Outstanding Doctoral Thesis Work in Computational Physics for his work on the quantum dynamics of many-body systems.

Mines Physics Professor Jeff Squier, in contrast, is an experimentalist. The optics expert recognized that microscopy was full of tools offering two-dimensional views of a three-dimensional world. What could he do about it? His answer, an array of lasers, mirrors and lenses called the Multifocal Multiphoton Video-Rate 3D Imaging System.

The system is an enhancement of one he co-invented in 1992. Like the original system, it uses femtosecond (a thousandth of a trillionth of a second) pulses of laser light to capture the action of the inner workings of a living cell, and in ways that present a narrow focal plane and don't damage the target. The new system, first demonstrated 20 years after the original, creates images in six planes of depth at once, offering scientists a view into multiple tiers of cellular activity at the same instant.

Collaborators at the University of California, San Diego, have used it to look at the inner workings of the brains of fruit flies. Keith Neeves, associate professor of biological engineering at Mines, would like to take closer looks at blood clots. The National Renewable Energy laboratory is interested in using multiphoton imaging to see exactly what happens as an electron is produced in solar cells. A Squier-group PhD student is working on a version 10 times smaller.

"Once it's there, it'll be manageable enough for a biology lab," Squier says.

Sarazin and Wiencke are members of the International Pierre Auger Observatory, a collaboration of more than 500 scientists and engineers. They study the nature and origins of ultra high energy cosmic rays, the most energetic particles ever observed. Reaching these energies with a man-made particle accelerator would require supersizing CERN's Large Hadron Collider ring to the scale of Mercury's orbit around the sun. Measurements of high energy cosmic rays represent a unique view of the extreme universe beyond our galaxy. The most energetic of these atomic nuclei, packing  $10^{20}$  eV, crash down less than once a century per square kilometer. The Pierre Auger Observatory in Argentina, completed

in 2008, ups its odds by covering an area of 1,200 square miles (almost exactly the size of Rhode Island), and so giving its dual-detector system a few chances per year to witness such power in action.

The observatory's two detection systems are comprised of many, many detectors. One system encompasses more than 1,600 tanks spaced at 1.5-kilometer intervals, each filled with 3,000 gallons of purified water (for the curious on campus, there's one parked on the south side of Meyer Hall, a stout brown cylinder custom-made in Brazil). Pitch dark inside, solar-powered photomultipliers detect a fraction of the multibillion-particle "air showers" created when cosmic rays smash atmospheric molecules. Analysis of the data collected by these water tanks is Sarazin's area of expertise.

"This array of detectors is the statistical engine of the observatory. This is how most of the air showers occurring over the observatory are detected," said Sarazin.

A second system, comprised of 27 fluorescence telescopes at four sites view the sky above the surface detector array. These optical detectors collect data on moonless, clear nights. They capture the ultraviolet emissions of nitrogen when a cosmic ray particle cascade sweeps across the atmosphere. The effect, though invisible to the human eye, is like a 100-watt lightbulb turning on and off while traveling through the sky at almost the speed of light.

Wiencke led the design and installation of the two automated laser stations near the middle of the observatory. These solar powered systems fire thousands of calibrated light bursts at night into the sky. "We use the atmosphere as the world's largest calorimeter to measure cosmic rays. The atmosphere is a complex dynamic system. To measure the cosmic rays accurately, the observatory measures our laser traces every night. Combining fundamental astrophysics, applied earth science and engineering as a physicist at Mines is fascinating."

"It's fundamental science," Sarazin said. "Fundamental science is part of the foundation that lets you do a lot of other things."

# Alpha Bet

It may have been the most famous public wager of the 20th Century. In 1980, Paul Ehrlich bet Julian Simon that the prices of metals would be higher in 10 years. (You can read all of the details in “The Bet,” by Paul Sabin, Yale University Press, 2013.)

Ehrlich was a celebrity because of his 1968 book, “The Population Bomb,” and he took the view that world population growth would place huge demands on all commodities, including metals, so prices would inevitably rise. Simon was an economist, and he believed that technology would develop in response to demand, to improve the supply of the commodities that we need, or alternatives would be found for metals that truly could not be extracted from the earth.

In 1990, the prices of the representative metals selected by Ehrlich and Simon were lower – significantly lower. Technology won, as Simon had predicted. Lesson learned: Never make a cash bet against an economist.

You might think that the story ends with the result of the bet.

The Ehrlich-Simon bet was really about rates of change. Simon overestimated the rate at which demand would increase, partly because most of the growth in the world’s population was in the ranks of the extremely poor, who don’t buy many commodities. He also underestimated the rate of improvement in extractive technology. He may have even thought there was no improvement in the technology, but data collected by *The Economist* show that worldwide prices of metals

declined fairly steadily (excluding wars, depressions and such) from the middle of the 19th Century, all the way through the 20th. ([economist.com/node/3651836](http://economist.com/node/3651836)) Technology improvements outpaced the impact of demand increases for more than 150 years. No wonder Julian Simon was confident.

Past behavior may be the best predictor of future success, but it is not infallible. There are a few new things to take into account as we look to the future:

- According to the Organization for Economic Cooperation and Development, overall population growth is expected to slow, but the world’s middle class is going to grow from 1.8 billion in 2012 to 4.9 billion in 2030. That means that the poor decline from about 74 percent of the world’s population to about 31 percent, and we will more than double the number of consumers who want cellphones, appliances, vehicles, etc. and the energy to run them.
- Energy production has to grow to meet the needs of the growing middle class, and the growth will be organic, diverse, partly-to-mostly off-grid in emerging economies, and hopefully it will include a healthy component of clean energy systems such as wind, solar and geothermal. These systems call for increasingly specialized materials: neodymium and dysprosium for magnets; gallium, selenium, indium, tellurium, and cadmium for photovoltaics; lithium for batteries, and many others for other emerging technologies.

# CRITICAL MATERIALS INSTITUTE

- All of our technologies are becoming more complex. It takes about 65 of the elements to make a smartphone today, compared to only 30 for the best mobile phones of just 10 years ago. That has two effects – it makes manufacturing more vulnerable to supply disruptions, and it makes phones harder to recycle for recovery of their raw materials. Similar developments apply to almost every technology that we use in our daily lives.
- This is hardly new, but it is accelerating: it is getting harder to obtain metals from mining. Primary extraction for basic metals, like iron and copper, is coming from poorer and poorer grades of ore. ArcelorMittal, for example, estimates that it is extracting iron from ores that have about 5 percent lower iron concentration than just 10 years ago.

Demand is rising for energy, and for materials to make the devices that deliver it and use it most cleanly. Supplies of these materials are increasingly challenged, resulting in the emergence of the idea of “critical materials” – stuff we really, really need but cannot reliably obtain. Without sustained investment in extractive technology development we will have rising commodity prices in general, and there will be increasingly frequent disruptions caused by shortages of specific critical elements.

Colorado School of Mines contributes to solving these problems, both through technology development, and with advanced economic and supply-chain analyses. I am very happy that it is a partner in the Critical Materials Institute.

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## ALEX KING, DIRECTOR OF THE U.S. DEPARTMENT OF ENERGY'S CRITICAL MATERIALS INSTITUTE

King is the former director of the Ames Laboratory, in Ames, Iowa. He has been a Visiting Fellow of the Japan Society for the Promotion of Science and a U.S. Department of State Jefferson Science Fellow. He is a Fellow of the Institute of Mining Minerals and Materials, ASM International and the Materials Research Society. King also has served as the president of the Materials Research Society, chair of the University Materials Council and chair of the American Physical Society's Group on Energy Research and Applications.

He attended the University of Sheffield as an undergraduate and earned his doctorate from Oxford. He was a postdoc at Oxford and then MIT before joining the faculty at the State University of New York at Stony Brook, where he also served as the vice provost for graduate studies. Previously, he was head of the School of Materials Engineering at Purdue University.

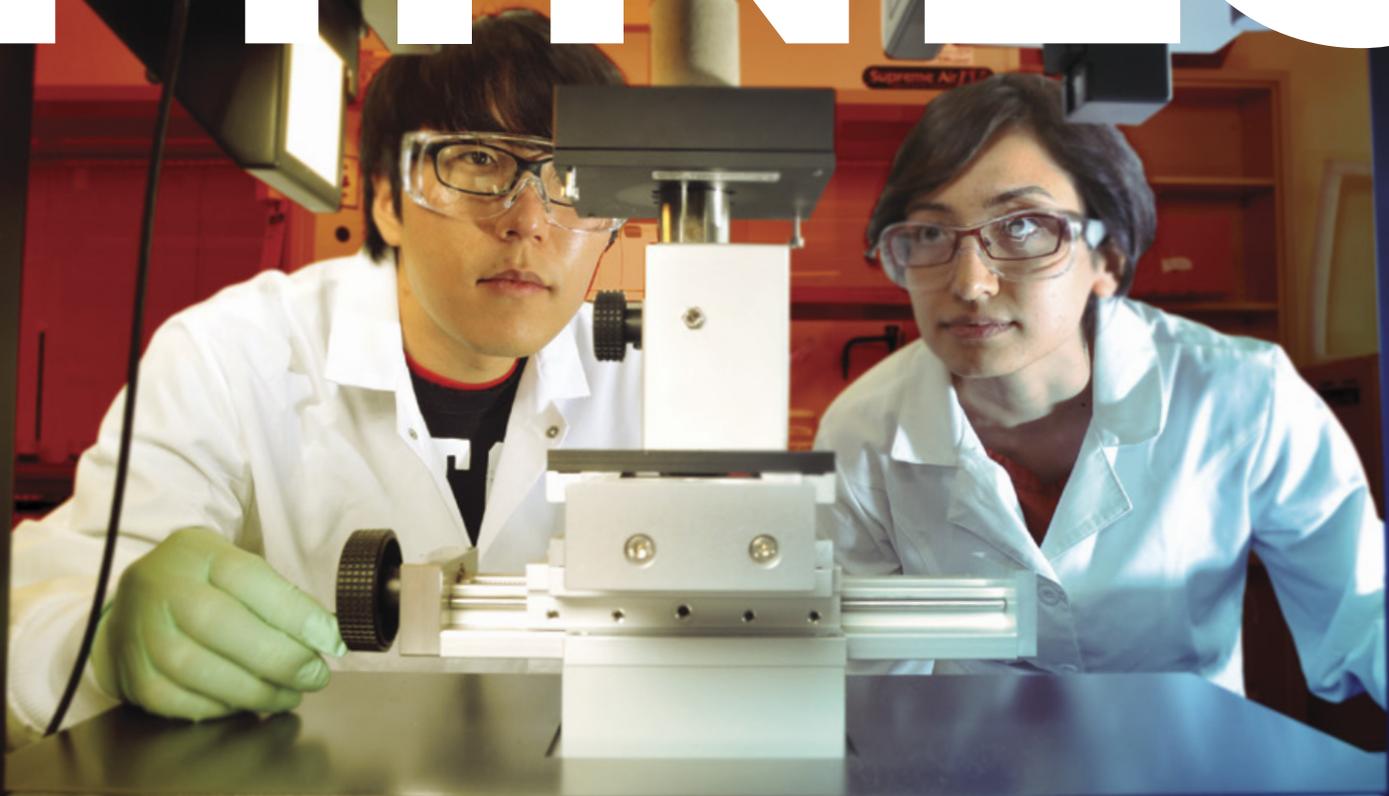




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