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EQuad News

Winter 2016
Volume 27, Number 2

BUILDING

PRINCETON
School of Engineering
and Applied Science

NEW BEGINNINGS BUILT ON DEDICATION AND GENEROSITY

This issue of EQuad News marks my last as dean, having announced last June that I will step down at the end of this academic year. A search for my successor is well underway and I am confident that the school is primed to move forward in spectacular ways under new leadership.

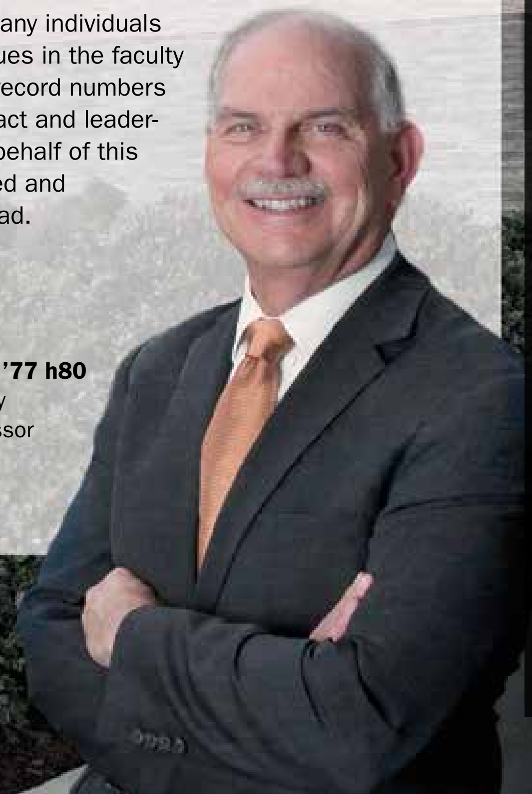
It is appropriate that this issue also celebrates the opening of the striking new building for the Andlinger Center for Energy and the Environment, a beginning built on years of dedicated work and the generosity of donors. The Andlinger Center, founded in 2008, epitomizes the strength and promise of engineering and applied science at Princeton. It brings together students, postdoctoral researchers and faculty from across the campus in pursuit of solutions to one of society's most pressing and complex challenges. It demands technical expertise and creativity but also a collaborative spirit that links to the social sciences, public policy and the humanities as well as to industry and government.

This ethic of bridging disciplines – harnessing science in the service of society – has been the driving idea behind the school's remarkable growth over the last decade. The Center for Information Technology Policy, the Keller Center and numerous other initiatives link students and faculty across the University and already have greatly enriched the Princeton experience for thousands of students.

As I reflect on these developments, I want to thank the many individuals who have so generously supported our mission, my colleagues in the faculty and administration who have advanced our vision, and the record numbers of students who are choosing engineering as a path to impact and leadership. It has been great working with all of these people on behalf of this wonderful engineering school, and because of your combined and continuing support, I am very optimistic about the road ahead.

Warmest regards,

H. Vincent Poor Ph.D. '77 h80
Dean and Michael Henry
Strater University Professor
of Electrical Engineering



(Photo by Denise Applewhite)

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Dean
H. Vincent Poor, Ph.D. '77 h80

Vice Dean
N. Jeremy Kasdin BSE '85

Associate Dean, Undergraduate Affairs
Peter Bogucki

Associate Dean, Graduate Affairs
Brandi Jones

Associate Dean, Development
Jane Maggard

Director of Engineering Communications
Steven Schultz

Senior New Media Editor
Teresa Riordan

Staff Writer
John Sullivan

Contributors
Sharon Adarlo
Stacey Huang '16
Angela Page
Catherine Shen
Anna Windemuth '17

Graphic Designer
Matilda Luk

Additional editing
Morgan Kelly

Web Designer
Neil Adelantar

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EQuad News
C-222, EQuad
Princeton University
Princeton, NJ 08544

T 609 258 4597
F 609 258 6744
eqn@princeton.edu

www.princeton.edu/engineering/eqnews

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CREATIVITY, TENACITY, CRITICAL THINKING URGED AT KELLER CENTER SYMPOSIUM

It takes more than just a good idea to begin an entrepreneurial venture, Tom Leighton, a Princeton alumnus and CEO of the Internet infrastructure company Akamai Technologies, told a Princeton audience Oct. 13.

To pursue entrepreneurship is to take risks, to work hard and not be afraid of making mistakes, he said. "You have to operate with a sense of urgency. Once you have an idea, you have to do something about it fast because if you don't, someone else will."

Leighton joined educators, entrepreneurs and students at the Keller Center's 10th Anniversary Symposium, celebrating the center's decade-long mission of fostering innovation in education and entrepreneurship. Leighton, who earned a bachelor's degree in engineering from Princeton in 1978, described the development of Akamai in the keynote address. The company, which helps speed delivery of websites and video through the Internet, is now the world's largest distributed computing platform. In his address, Leighton emphasized that the key to a successful business is not just working with great people to come up with a great product; it is to be "tenacious as hell."

"My team and I were not going to give up," he said.

In addition to Leighton's talk, the Keller Center symposium included two panel discussions. One panel included conversations on the goals of higher education as well as discussions of the pros and cons of online classes, the importance of preparing students with real-life skills, and the challenges of implementing cross-disciplinary curricula.

Panelist Janet Vertesi, an assistant professor of sociology, said a Princeton education offers key skills such as critical thinking and the ability to make connections across disciplines. "It's about taking the knowledge and processing it," Vertesi said. ▶

A daylong celebration of the 10th anniversary of the Keller Center featured talks on innovation in education and entrepreneurship and honored Dennis and Constance Keller for the center's foundational gift. (Photos by Sameer Kahn/Fotobuddy; photo of the Andlinger Center by Denise Applewhite)

CREATIVITY, TENACITY, CRITICAL THINKING AT KELLER SYMPOSIUM *(continued from page 1)*

"It's important to think critically about the information and being able to discuss it with other people. This is a skill that is transferable to any environment and it gives students the ability to move comfortably anywhere."

The University also can give students the environment to be surrounded by inspiring minds in a way that nowhere else can, she said.

"It doesn't take one person to come up with new ideas, it takes a small group of people who can work together effectively," Vertesi said. "If students can work and think outside the box and listen to each other, it enables them to be able to create something amazing." **–by Catherine Shen**

KELLER CENTER: A DECADE OF 'BROADENING PATHWAYS' TO POSITIVE IMPACT

The Keller Center supported seniors Jack Hudson (left) and Evan Corden (right), who founded SignSchool, an online platform for teaching American Sign Language.

Ten years ago, the founding director of Princeton's new Keller Center for Innovation in Engineering Education set a simple goal: "To inject more engineering into the liberal arts and inject more of the liberal arts into engineering."

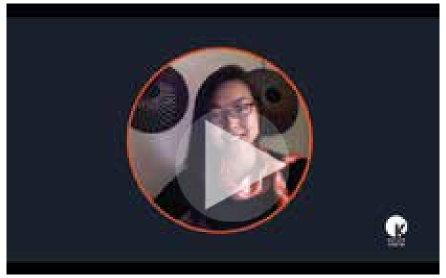
"We saw technology affecting nearly every aspect of public and private life and knew we needed to broaden engineering education far beyond its traditional borders," said H. Vincent Poor, now dean of the School of Engineering and Applied Science. "Our vision was to teach technology more broadly in a societal context and also to engage with the community outside the University."

As the center celebrated its 10th anniversary in 2015, current Keller Center director Mung Chiang said, "This is about planning the future decades that will continue to broaden Princetonians' pathways to make a positive impact in society."

In an article and video, the Keller Center and engineering school collected reflections of students who benefited from the center as its activities blossomed over the last decade. Watch the video at http://ow.ly/Ulmrf

"The Keller Center really embraces any ideas you have," said Jack Hudson, a senior who developed a venture to teach American Sign Language online. "They do everything they can to help you develop it."

"The Keller Center provides a space for students and faculty to come together and … think," recalled Jane Yang BSE '11. "The Keller Center was a place where it didn't matter what degree – A.B. or BSE – you were getting. It only mattered what were you trying to do to make the world a better place."



MORE RAIN LEADS TO FEWER TREES IN THE AFRICAN SAVANNA

In 2011, satellite images of the African savannas revealed a mystery: these rolling grasslands, with their heavy rainfalls and spells of drought, were home to significantly fewer trees than researchers had expected. Scientists supposed that the ecosystem's high annual precipitation would result in greater tree growth. Yet a study found that the more instances of heavy rainfall a savanna received, the fewer trees it had.

In a collaboration of environmental engineers and geoscientists, Princeton researchers may have found a solution to this ecological riddle. In a study published in the Proceedings of the National Academy of Sciences, researchers use mathematical equations to show that physiological differences between trees and grasses are enough to explain the curious phenomenon.

The researchers found that under very wet conditions, grasses have an advantage because they can quickly absorb water and support high rates of photosynthesis, the process by which plants convert sunlight into energy. Trees, with their tougher leaves and roots, are able to survive better in dry periods because of their ability to withstand water stress. But this amounts to a disadvantage for trees in periods of intense rainfall, as they are comparatively less effective at using the newly abundant water.

"A simple way to view this is to think of rainfall as annual income," said Xiangtao Xu, a graduate student in geosciences and the study's lead author. "Trees and grasses are competing over the amount of money the savanna gets every year and it matters how they use their funds."

Xu explained that when the "bank" is full with rain, grasses, which build relatively cheap structures, thrive. When there is a deficit of rain, the trees suffer less than grasses and therefore win out.

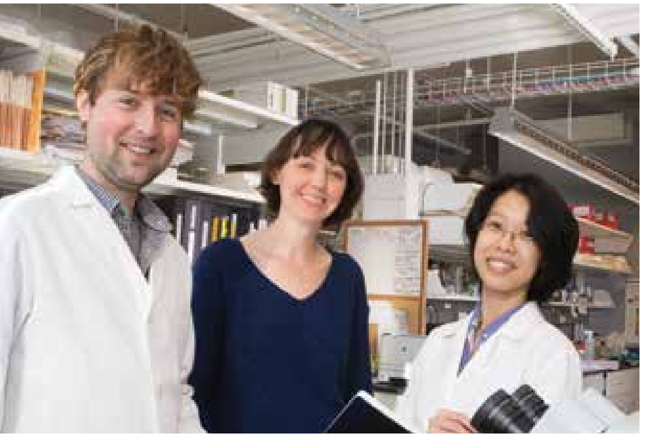
The problem is that several high-profile papers over the past decade have predicted that periods of intense rainfall will become more frequent around the globe, especially in tropical areas, Xu said. The Princeton research suggests that these global climate changes will eventually lead to a reduced abundance of trees on the savannas.

The study highlights the importance of understanding the pattern and intensity of rainfall, not just the total annual precipitation, which is where most research in this area has focused, Xu said. "Because the savanna takes up a large area, which is home to an abundance of both wild animals and livestock, this will influence many people who live in those areas," Xu said. "It's important to understand how the biome would change under global climate change."

The study's senior authors include Ignacio Rodríguez-Iturbe, the James S. McDonnell Distinguished University Professor of Civil and Environmental Engineering, and David Medvigy, assistant professor of geosciences. It was funded by the Andlinger Center for Energy and the Environment and the Princeton Environmental Institute. **–by Angela Page**

Princeton researchers found that the ability of grasses to more efficiently absorb and process water gives them an advantage over trees such as the acacia (pictured) on African savannahs. The research, funded by the Andlinger Center, helps reveal emerging impacts of new rainfall patterns due to climate change. (Photo by Kev Moses, Licensed under CC BY 2.0.)

BRANCHING OUT: ENGINEERS REVEAL MECHANISMS OF COMPLEX ORGAN STRUCTURES



Celeste Nelson (center), associate professor of chemical and biological engineering, works with postdoctoral researchers Victor Varner and Mei Fong Pang to study the development of branching tissues found in lungs and other organs. (Photo by Denise Applewhite)

With its twisting branches and delicate curls, the lung seems as much a natural work of art as a functioning organ.

Now Princeton researchers have observed the artistry unfold in a petri dish and have arrived at a surprising conclusion about the forces that help shape it.

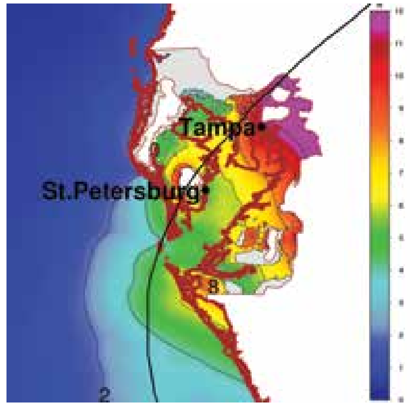
In a series of recent experiments, researchers in the lab of Celeste Nelson, an associate professor of chemical and biological engineering, have found that airway branching in the developing lung is regulated in part by the mechanical forces experienced by these embryonic tissues. This insight adds a previously unexpected mechanism to the standard theory that the airway branching pattern is controlled by a closed genetic program, hardwired in our DNA.

"Our work indicates that physical forces can determine the locations where new branches form within the developing lung," said Victor Varner, a postdoctoral researcher in chemical and biological engineering and the lead author of one of two papers recently written on the subject.

The results have long-term implications for understanding developmental disorders in babies or treating later-stage growth disorders such as cancer, or in developing lab-grown replacements for human organs.

"Our work underlines the fact that tissues and organs are physical objects that are sculpted in the embryo by mechanical forces," Nelson said. **–John Sullivan**

GRAY SWANS: RARE BUT PREDICTABLE STORMS COULD POSE BIG HAZARDS



In the years 2068 to 2098, the possibility of storm surges up to 36 feet increases significantly in cities not usually expected to be vulnerable to tropical storms, such as Tampa, Florida, according to recent research at Princeton. (Image adapted from Ning Lin)

Researchers at Princeton and the Massachusetts Institute of Technology have used computer models to show that severe tropical cyclones could hit a number of coastal cities worldwide that are widely seen as unthreatened by such powerful storms.

The researchers call these potentially devastating storms Gray Swans in comparison with the term Black Swan, which has come to mean truly unpredicted events that have a major impact. Gray Swans are highly unlikely, the researchers said, but they can be predicted with a degree of confidence.

"We are considering extreme cases," said Ning Lin Ph.D. '10, an assistant professor of civil and environmental engineering at Princeton. "These are relevant for policy-making and planning, especially for critical infrastructure and nuclear power plants."

In an article published in Nature Climate Change, Lin and her co-author Kerry Emanuel, a professor of atmospheric science at MIT, examined potential storm hazards for three cities: Tampa, Florida; Cairns, Australia; and Dubai, United Arab Emirates.

The researchers concluded that powerful storms could generate dangerous storm-surge waters in all three cities. They estimated the levels of devastating storm surges occurring in these cities with odds of 1 in 10,000 in an average year, under current climate conditions. Their simulations showed possible storm surges in Tampa reaching 18 feet, a third more than previous records.

"With climate change, these probabilities can increase significantly over the 21st century," the researchers said. In Tampa, the current storm surge likelihood of 1 in 10,000 is projected to increase to somewhere between 1 in 2,500 and 1 in 700 by the end of the century. **–JS**

BUILDING
our energy and environmental future

by Emily Carter

(Photo by Denise Applewhite)

"If you're going to build a center for energy and the environment, then the architecture should be about nature and the landscape." That was the core idea that architects Tod Williams A.B. '65, MFA '67 and Billie Tsien presented as they started work on the spectacular building that is now home to the Andlinger Center for Energy and the Environment.

I say "spectacular" not in the sense of a dazzling edifice; I use that word because of how superbly the building manifests that original vision and how strongly it supports the ambitious and urgent mission of the Andlinger Center. That mission is to develop solutions that provide the world with the energy systems it needs while protecting this planet and preserving its resources for future generations.

As with the architecture, we are taking an integrative approach. We recognize the enormous and wonderful complexity of both nature and humanity. That complexity demands solutions that draw together expertise from multiple disciplines, institutions, industries, governments and nations. We must develop not only technical solutions but also policy, behavioral and economic solutions – all within an environmental context that continuously questions how our solutions stack up against the realities of nature. We work closely with the Woodrow Wilson School of Public and International Affairs, the School of Architecture and other colleagues across the University. ▶

(Photos by Denise Applewhite)

In the five years since I became founding director of the center, we have been pursuing this broad agenda along several fronts. First we have been recruiting faculty members in key areas of research that hold promise across a range of timeframes, from the near to long term. So far we have brought to Princeton six faculty members with expertise spanning solar cells, biofuels, energy storage, sustainable building materials, energy-efficient architecture and nuclear fusion. I have been enormously gratified and excited to see their individual initiatives and spontaneous collaborations. At the same time we are awarding funding to these and other faculty members through a competitive grant process that encourages bold ideas and collaborations that would be difficult to fund through conventional government grants.

To build a dynamic dialogue across departments we run a seminar series that brings in guest speakers from around the world.

And extending that dialogue beyond academia, we have created a corporate affiliates program called the Princeton E-ffiliates Partnership, which allows companies to harness Princeton expertise while providing a practical, market-based perspective on emerging technologies.

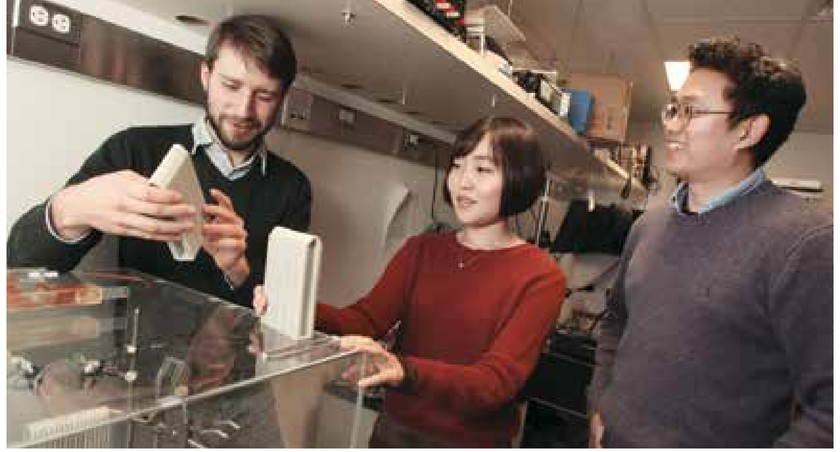
Together these activities create a vibrant environment for learning, which is critical as we prepare the next generation of leaders who will continue to find creative solutions and make wise decisions related to energy and the environment. Our educational efforts include two new undergraduate certificate programs, one a rigorous technical introduction to energy systems and the other a broad examination of energy technologies aimed at engaging students from the social sciences and humanities. We also offer research internships and fellowships for our students.

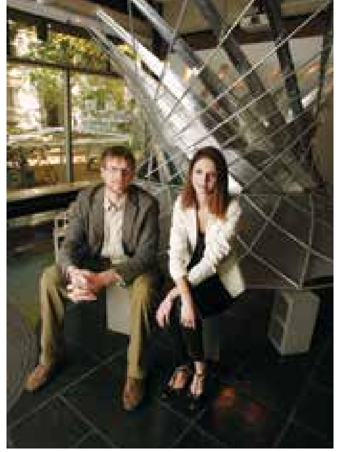
Extending our educational outreach beyond the University, we have developed a series of publications called Energy Technology Distillates, which analyze emerging areas of technology and distill them to their essential concepts. These publications – aimed at policymakers in both the public and private sector as well as educators and the general public – serve as a framework for non-experts to quickly familiarize themselves with key ideas and make their own judgments.

Our wonderful new building accelerates all these efforts. Its spaces range from the super high-tech (labs with ultralow dust and vibration for atomic-level fabrication and analysis of materials) to collaborative spaces and gardens. The architects ensured that even labs rooted deep in bedrock have ample natural light flowing from above and open to garden courtyards. Science and engineering offer us many exciting possibilities to provide sustainable energy and to preserve the environment, but through our engagement with policy and the broader University we seek never to lose sight of the human and natural contexts that drive our pursuit. **E**

Emily Carter is the Gerhard R. Andlinger Professor in Energy and the Environment and professor of mechanical and aerospace engineering and applied and computational mathematics. She is the founding director of the Andlinger Center for Energy and the Environment as well as the associate director of the Program in Technology and Society.

(Photo by Ricardo Barros)





WATER MAY BE KEY TO COUNTERING SUMMER HEAT IN BUILDINGS

by Sharon Adarlo

As the world's climate heats up, buildings in tomorrow's cities will need innovative solutions to keep cool.

Channeling streams of water on a building's skin or spraying a water mist around a structure could be unique ways to solve this issue with minimal use of energy. A team of Princeton researchers spanning two engineering departments and architecture is exploring the cooling effect of water on architecture – from small-scale prototypes to full-size structures.

"Urban surfaces are dry and dark. They absorb a lot of heat," said Elie Bou-Zeid, associate professor of civil and environmental engineering. In a series of studies, Bou-Zeid found that spraying water on buildings could dramatically cool the surface temperature and may combat the urban heat island effect that makes cities warmer than rural areas. Having a wall with a water-flowing feature, which Bou-Zeid calls evaporative walls, or "e-walls," would be a good alternative to green walls and roofs, which serve much the same purpose but require soil and frequent maintenance.

To better analyze the idea, Bou-Zeid turned to the fluid dynamics expertise of Howard Stone, the Donald R. Dixon '69 and Elizabeth W. Dixon Professor of Mechanical and Aerospace Engineering. Suin Shim, a graduate student, and Sangwoo Shin, a postdoctoral researcher, both in Stone's group, built experimental models of specially treated aluminum, called boehmite, to test the effectiveness of an e-wall. Water already likes to hug the surface of aluminum – boehmite makes it do so even more. Built with thin rails and staggered together to increase the surface area, the e-wall model was a success.

"The temperature drop between inside and outside was five degrees," said Shim.

The e-walls work more effectively with as little water as possible, according to tests. Bou-Zeid also calculated that a south-facing e-wall would use less water than a typical four-person household. Future e-walls could also use gray water (household waste water not from toilets), further cutting down water usage.

The work meshed with the research interests of Forrest Meggers, assistant professor of architecture and the Andlinger Center for Energy and the Environment. Megger's group built Cool Oculus, a tower prototype that sprays a water mist to decrease a building's interior temperature. Meggers and students had also built the Thermoheliodome, a pavilion that creates a feeling of coolness inside by using tubes of water embedded within the structure's walls. Reflective mylar covers the structure's walls, which "radiate" the water's coolness onto occupants. These projects could inform what a future e-wall could look like, Meggers said.

"You can have a closed loop of water inside the wall," said Meggers. "You take evaporative cooling and deploy it into the structure of a wall." **E**

Graduate students Eric Teitelbaum and Suin Shim and postdoctoral researcher Sangwoo Shin (from left in left photo) are part of a multidisciplinary group examining low-energy methods of cooling buildings. At right, Assistant Professor Forrest Meggers and Dorit Aviv, who earned a master's in architecture in 2014, created Cool Oculus, a study in passive cooling. (Photos by Frank Wojciechowski)

Built firmly into bedrock, the new building for the Andlinger Center for Energy and the Environment is more than half below street level. Three sections of the building project upward, indicating the main areas of activity within the building.

+ The rear portion, closest to the Engineering Quadrangle on the left, contains the most technically sophisticated laboratories. This space includes cleanrooms and microscopy labs with ultralow dust and vibration levels for atomic-scale fabrication and analysis of materials.

+ The middle section includes administrative offices as well as teaching labs and a light-filled space for graduate students.

+ The front section, closest to Olden Street and Prospect Avenue, is called Maeder Hall and includes an auditorium, classroom and meeting spaces for events that engage the broader campus and community.

(Illustration by Matilda Luk)

NEW ANDLINGER BUILDING 'DEFINED BY GARDENS'

Meandering paths, sunken courtyards and gardens weave through the sculptural complex of gray brick and glass that has risen at the eastern edge of Princeton University.

by Sharon Adarlo

After three years of construction, the Andlinger Center for Energy and the Environment has opened its doors, ushering in a new phase for the center's goal of developing solutions to ensure our energy and environmental future.

Laboratories, finely tuned for atomic-level investigations, are beginning to hum with the collaborative work of researchers from across the University and industrial partners. Specialized spaces are filling with faculty, students, postdoctoral researchers and visitors creating materials that will help power cities, fuels that propel vehicles, and technologies that prevent and repair environmental damage.

"It's an extraordinarily beautiful building," said Emily Carter, the center's founding director and the Gerhard R. Andlinger Professor in Energy and the Environment. "What it offers is absolutely state-of-the-art facilities where people want to come and work, and work together."

Princeton created the center in 2008 following a $100 million gift from international business leader Gerhard Andlinger, Class of 1952. The center's mission, Carter said, is to preserve the planet through education and research on energy-related environmental issues and sustainable-energy technologies such as batteries, building design, solar cells and biofuels.

Gerhard Andlinger, Carter said, has long been a believer in investing in sustainability and alternative-energy technologies.

"We are incredibly grateful he had the vision to establish this center," she said.

Carter is positioning the center to be a research hotbed and think tank through its labs, educational certificates for students, publications and events that bring together policymakers, researchers and students.

The center's new building, designed by New York architects Tod Williams (A.B. '65 MFA '67) and Billie Tsien, has 129,000 square feet of labs, offices, instructional spaces, meetings areas and a lecture hall. ▶

(Photos by Denise Applewhite)

NEW ANDLINGER BUILDING 'DEFINED BY GARDENS' *(continued from page 9)*

Designed to avoid a monolithic presence, the center appears to be several buildings. But it is actually one contiguous structure in its lowest level, much like an iceberg. While the building hunkers low in the landscape, its towers rise above the complex. Despite more than 60 percent of the building being below street level, light infuses the structure. Various spaces connect to gardens and three courtyards, which echo the University's plazas.

A key feature of the building is the interweaving between the architecture and the gardens.

"All of the spaces of the building are defined by the gardens. They are the source of light, orientation and identity," said University Architect Ronald McCoy M.Arch. '80.

Also important, McCoy said, is the materiality of the architecture – the gray brick, the sandblasted concrete and the felt wall coverings, which show enlarged images from scientists' notebooks such as those of Albert Einstein and Marie Curie.

In the complex's lower spaces, an imaging and analysis center contains electron microscopes, which are situated on bedrock to minimize vibration. These instruments require shielding from electromagnetic interference and are thus cocooned in aluminum armor.

The Andlinger Center has 27,000 square feet of cleanrooms – spaces that have stainless steel ductwork that will filter and reduce airborne dust 1,000-fold. These ultraclean conditions are required for nanotechnology research and the creation of materials and devices such as plastic-based solar cells or superconducting materials. These spaces roughly double the amount of cleanroom space at Princeton.

Research and teaching labs intersperse the building. In a lower level, the research commons provide working space for 42 students and postdoctoral scholars.

The lecture hall is named in recognition of a gift from Paul A. Maeder, Class of 1975. It seats 208 and is shaped inside like a crystalline geode.

The building's mechanics also reflect the center's mission to preserve the planet. An air-handling system relies mostly on the natural flow of air. To warm the building, a heat recovery system harvests heat from exhaust air and reduces energy consumption. Green roofs filled with plants filter and retain rainwater. Built on bedrock, the ground also insulates the complex.

Perhaps most important, the building offers a space for collaboration among researchers who were previously scattered across campus. Among those who will be working in the lab are four recently hired faculty members who last year began a joint project to design long-lasting, inexpensive and environmentally friendly structures. Coming from the fields of architecture and mechanical, electrical and civil engineering, they had met after joining the Andlinger Center.

"The problems we face – both technologically and in terms of policy and economics – are not going to be solved just by one expert in one discipline," Carter said. "They are all complex problems and they require a team effort."

The new building should accelerate this kind of fruitful, cross-fertilization of research and lead to a better future, she said.

"We are working to make the world a better place," Carter said. "It's very meaningful, it's incredibly important, and it gives you a real sense of satisfaction and reward knowing you are doing something good for the rest of the world." **E**

FLIPPED WIND MILLS FIND POWER IN NUMBERS

by John Sullivan

With wind power emerging as a key energy source around the world, Princeton researchers are exploring a new idea to squeeze more energy out of the whirling devices: flip them.

Love them or hate them, the silhouettes of turbine farms are becoming a fixture of the modern landscape – the stalk of a metal tower topped by a giant propeller turning slowly in the wind. These standard turbines, in which the shaft runs horizontal to the ground, have benefited from decades of research into aircraft propellers, resulting in high efficiency.

But research teams led by associate professors Elie Bou-Zeid and Luigi Martinelli Ph.D. '87, and Alexander Smits, the Eugene Higgins Professor of Mechanical and Aerospace Engineeing, are asking whether engineers can create more efficient turbine arrays using vertical turbines. Turning the shaft vertically – like mixer beaters rather than airplane propellers – has some advantages. For one, builders can place the turbine's generator at the base of the tower instead of mounting it on the top. The vertical turbines are also easier to use underwater and offshore. And unlike horizontal turbines, vertical turbines do not have to change direction to follow the wind direction.

Lastly, following a proposal originally developed by John Dabiri BSE '01, now a professor at Stanford University, the researchers are seeking more efficient ways to group multiple turbines.

"You can fit more of them in an area," said Martinelli, an associate professor of mechanical and aerospace engineering. "Also, it might be possible to arrange a set of vertical turbines to increase their overall efficiency."

That said, vertical turbines come with their own drawbacks. Foremost among those is that current vertical turbines are only about 80 percent as efficient as horizontal ones. The blades create complex swirls on the downwind side of the turbine, which creates a pocket of dead air behind the blades, slowing the rotation and decreasing power production.

"The process is called dynamic stall," Martinelli said. On a computer simulator in his office, the critical area looks like a tiny hurricane's eye behind the turbine blade.

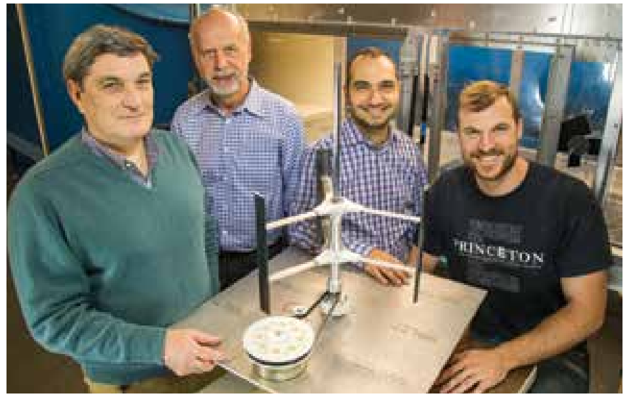
To approach this problem, the researchers have developed a model that simulates airflow through vertical turbines and are designing blades that decrease dynamic stall as they move through the air. As they refine their model, the researchers also are exploring whether it would be possible to use the flow created by the turbines to increase the overall efficiency of an array of turbines (rather than increasing the efficiency of each one).

To address this issue, they teamed up with Bou-Zeid, whose research group studies wind patterns in the lower atmosphere. Bou-Zeid studies microclimates such as cities but in this case, he applied his expertise to wind farms.

"Typically, turbines are arranged to make sure that one turbine is not in the wake of another," said Bou-Zeid, an associate professor of civil and environmental engineering.

However, unlike standard turbines, vertical turbines can be arranged so the wake from one turbine boosts others nearby. The researchers are working with clusters of three turbines and believe they can use the arrangement to markedly increase their efficiency.

"The beauty of it is not only that you can pack more turbines into an area, but that the efficiency of each turbine is not less, it is actually greater than a single turbine," Bou-Zeid said.



From left, professors Luigi Martinelli, Alexander Smits and Elie Bou-Zeid and graduate student Tristen Hohman have collaborated to investigate a new type of wind turbine that, when used in groups, creates greater efficiency and flexibility than conventional windmills. (Photo by David Kelly Crow)

ALTERNATIVE FUELS COULD POWER VEHICLES WITH 'NEGATIVE' EMISSIONS

by Sharon Adarlo

From left, Senior Research Engineer Eric Larson, professors Michael Celia and Lynn Loo, graduate student Anna Hailey, and postdoctoral researcher Hans Meerman: The five have collaborated on a method to make transportation fuels that lower rather than raise greenhouse gas levels. (Photo by Frank Wojciechowski)

In the future, cars could run on fuel that started as a tree branch – part of a virtuous cycle that begins in the woods and ends with cleaner air and decreasing levels of greenhouse gases in the atmosphere.

In a collaboration between chemical and environmental engineers, Princeton researchers are designing processes to create fuels from twigs and branches left after a lumber harvest. These fuels would serve as an alternative to petroleum fuels and to biofuels grown on valuable cropland.

"We will likely need energy options with negative greenhouse gas emissions down the road to deal with global warming," said Eric Larson, senior research engineer at the Andlinger Center.

Larson worked with Lynn Loo Ph.D. '01, the Theodora D. '78 and William H. Walton III '74 Professor in Engineering and chemical and biological engineering, Anna Hailey, a graduate student, and Hans Meerman, a postdoctoral researcher, to analyze how such systems would work and what they might cost.

Creating these fuels does produce the greenhouse gas carbon dioxide as a byproduct, but Michael Celia Ph.D. '83, the Theodora Shelton Pitney Professor of Environmental Studies and professor of civil and environmental engineering, said the system can greatly reduce CO_2 emissions by pumping the gas, via depleted natural gas wells, into geological formations deep underground.

"Instead of venting into the atmosphere, which we don't want to do, we push the CO_2 underground, where we expect it will stay for thousands of years," said Celia, who worked with graduate student Ryan Edwards and undergraduate student Cynthia Kanno on the project.

The team's projections show that locking CO_2 underground could make the process "carbon negative," meaning that the trees used to create the fuel absorb more carbon than the fuel releases into the atmosphere.

To reduce transportation costs, the plants that create the fuels should be built close to natural gas wells, Loo said. There are many possible locations near the Marcellus Shale Formation, an area being tapped for natural gas in Pennsylvania and West Virginia.

Some of the earliest wells drilled into the Marcellus will go out of production within a decade and could be ready for greenhouse gas storage, Celia said.

Because the region also is rich with forests, the team says the process is feasible, if the right economic and policy conditions are in place.

"The individual technologies exist," Loo said, "but they haven't been pieced together into a system. Our work provides a kind of roadmap for doing this."

SO COOL: LOW-TEMPERATURE FLAMES COULD BRING LOW EMISSIONS

by John Sullivan

Researchers at Princeton have created a flame so cool that it would be possible to run your hand through it without getting burned.

This may seem like a great magic trick, but cool flames are providing important insights into engine efficiency and pollution control. "We are developing a diagnostic process to optimize combustion at a very low temperature," said Yiguang Ju, the Robert Porter Patterson Professor of Mechanical and Aerospace Engineering and the project's lead researcher. "If we can better understand cool flames we can better understand the process by which future advanced combustion engines will work."

Burning as low as 300 degrees Celsius, cool flames have fascinated scientists for hundreds of years. Sir Humphrey Davy first discovered the phenomenon in 1817, when he reported an unusual flame that he could run his fingers through without getting burned. That would not be possible with a standard visible fire, which burns between 1,200 and 1,700 degrees Celsius. But, Davy noted, the cool flame could change without warning into a standard flame when pressure or mixture conditions changed.

Since then, cool flames have been of great interest to scientists and engine designers. This unusual form of combustion causes knocking in gasoline engines and plays an important role in diesel operation. But because of their unusual slow-burning properties, cool flames have been extremely difficult to produce in a laboratory. In a series of experiments on the International Space Station in 2013, astronauts were astonished to learn that something like cool flames were formed after the extinction of a hot droplet flame in zero gravity.

Those zero-gravity flames were unsteady and lasted only a few seconds on the space station (and in an engine lasted only milliseconds). Researchers back on Earth wanted to find a way to create self-sustaining cool flames.

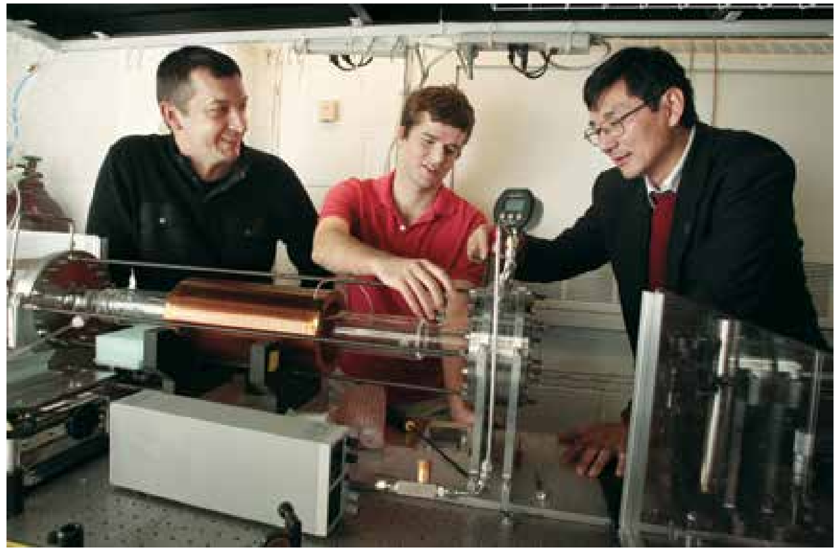
"The real challenge has been getting them steady so that you can measure them," said Christopher Reuter, a graduate student in mechanical and aerospace engineering who is a member of Ju's research team.

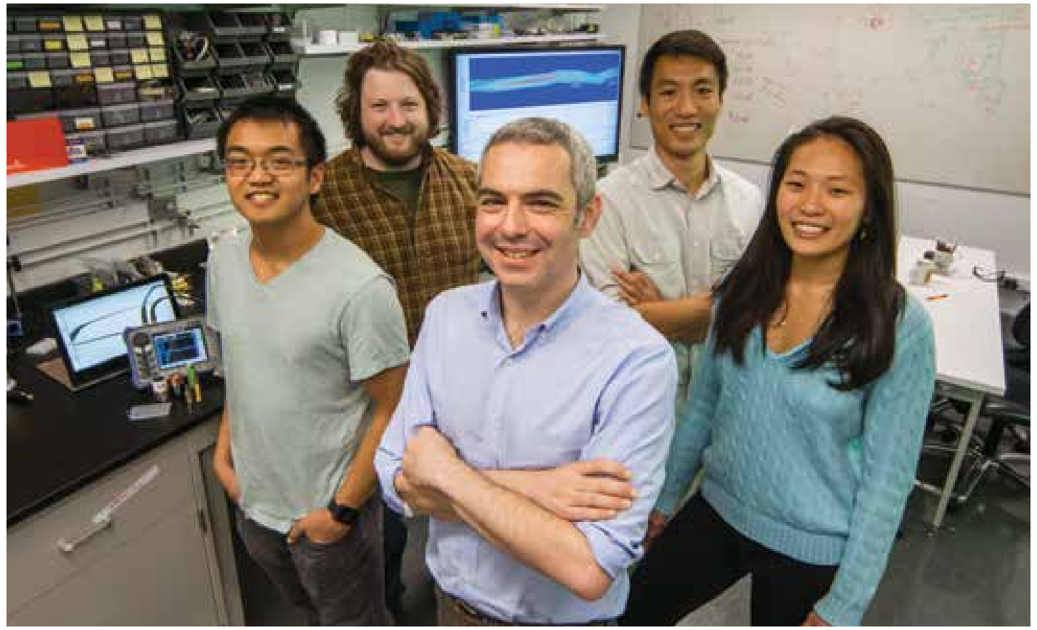
By using a burner with two nozzles and adding a small amount of ozone into the combustion chamber, the Princeton researchers have managed to create a steady, cool flame in their lab. Working through the Andlinger Center, Ju's researchers teamed up with Gerard Wysocki, an assistant professor of electrical engineering, to devise a laser diagnostic technique that quantifies chemicals playing key roles in the flames' formation. The collaborators have already demonstrated quantitative measurements of two most important components in low-temperature combustion – hydroxyl and hydroperoxyl radicals.

"Quantifying hydroperoxyl radicals, which are short-lived reactive species that occur at very low concentrations in combustion, has been quite challenging before, but with this new spectroscopic sensing technology we can probe them directly in the reaction zone," Wysocki said.

Ju said cool flames present new ways of looking at internal combustion and, with more work, could lead to improvements such as "more efficient use of fuels and the development of low-emission engines."

Gerard Wysocki (left), an expert in sensor technology, and Yiguang Ju (right), an expert in combustion, worked with graduate student Christopher Reuter (center) to create and test flames that burn at a very low temperature. (Photo by Frank Wojciechowski)





SOUNDING OUT THE FUTURE OF BATTERIES

by John Sullivan

In a quest for sustainable energy systems, Princeton researchers invented a method for probing structural changes in batteries. From left: Michael Wang '16; Barry Van Tassell, postdoctoral research associate; Daniel Steingart, assistant professor of mechanical and aerospace engineering and the Andlinger Center; Andrew Hsieh Ph.D. '14, postdoctoral research associate; and Sharon Gao '15. (Photo by David Kelly Crow)

Tired of your cellphone dying during an important call or your car not starting on a cold morning? Researchers at Princeton think you should listen to your batteries.

"How sound moves through a battery indicates important things about the battery's internal structure," said Daniel Steingart, an assistant professor of mechanical and aerospace engineering and the Andlinger Center for Energy and the Environment. "It can show the level of charge and also how old the battery is and what has happened to it over its lifespan."

A team led by Steingart is using sound waves to track batteries' internal health in real time. The scientists believe their technology will offer a new way for researchers and manufacturers to peer inside batteries and monitor their structures as they discharge. The technology also could eventually be developed into a system that monitors batteries in critical situations such as medical devices or massive systems that store and release energy from wind and solar collectors.

Steingart got the idea for using sound to evaluate batteries after investigating whether fresh batteries bounced less than older ones when dropped on a table. He realized that the batteries' bounciness related to internal structural changes that occurred when batteries discharged. Steingart believed that sound could probe a battery's internal structure, similar to the way an ultrasound shows details of the body.

Working with researchers including Jason Fleischer, an associate professor of electrical engineering, and Clarence Rowley BSE '95, a professor of mechanical and aerospace engineering, Steingart's team developed a monitor that measures the internal health of a wide variety of battery types. The monitor, which uses transducers to pulse sound through the battery, provides a snapshot view of the battery's condition and tracks its health over time.

"It is in the early stage, but we are looking at a broad variety of applications," said Andrew Hsieh Ph.D. '14, a postdoctoral researcher in mechanical and aerospace engineering. "It certainly has applications as a lab tool, but we also are looking at possible uses in quality control and in battery management." **E**

ANDLINGER INTERNSHIP SPARKS DISCOVERY AND CAREER

by Anna Windemuth '17

An Andlinger Center internship helped set Christina Chang '12 on a path to a career in environmental science. In 2013, below, she gave a TEDx talk on "Powering the Planet." (Photo above by Layton Thompson, below courtesy of Christina Chang)

Cyanide might not seem like the obvious solution to cleaning up water, but as Christina Chang discovered in her junior year at Princeton, the chemical could have significant impact on both pollution cleanup and water purification.

Chang was working in the lab of chemistry professor John Groves, whose team had invented a catalyst that would help produce chlorine dioxide, a powerful disinfectant for water. When Chang added cyanide to the process, the production rate of chlorine dioxide increased 200-fold, a breakthrough. Not only that, the cyanide itself disappeared within seconds, along with the chlorine dioxide. Her question was, why?

"It was a scientific puzzle," said Chang, who graduated with a bachelor's degree in chemistry in 2012. Her quest to find the solution was part of a summer-long Lewis research internship funded by the Andlinger Center for Energy and the Environment.

Chang eventually realized that the water disinfectant was disappearing because it was simply doing its job, reacting with cyanide to make cyanate, which is much less toxic than cyanide itself.

With this discovery, Chang and the rest of Groves' team reasoned that their chemical combination could be added to water coming out of mines, which are contaminated with cyanide. The method could quickly clean up the cyanide. Groves added Chang's innovation to a pending patent for the catalytic generation of chlorine dioxide.

"I am so grateful for the Andlinger Center's support of fundamental research that's applied to societal problems," Chang said. She added that she was inspired to pursue an environmentally relevant project and the Lewis Fund internship after hearing a lecture from the Andlinger Center's founding director, Professor Emily Carter.

"She showed me that a female scientist, a chemist, could be motivated by an important societal problem in addition to a scientific problem," Chang said.

After extending and elaborating on her summer research for her senior thesis, Chang went on to secure the Marshall Scholarship and earned master's degrees from Imperial College London and Cambridge University. There she became fascinated by how plants store sunlight energy in the form of chemical bonds.

"If we could beat plants at their own game, we could provide sustainable fuels for the world," said Chang, who recently published an article with colleagues at Cambridge on a technique to improve artificial photosynthesis.

Now a Ph.D. student at Harvard, Chang is investigating future materials for solar panels in Professor Roy Gordon's laboratory, a group of 20 chemists and engineers. The group works on understanding the chemistry and real-life application of these materials by tackling issues such as moisture sensitivity, efficiency and the photophysics of energy transfer, Chang said.

"Developing global sustainable energy is the central problem of the 21st century," Chang said of her future as a researcher. "Our generation has a great opportunity and responsibility to serve the world."

STUDENTS EMBRACE ENERGY CHALLENGES

SAMANTHA IP

CLASS OF 2018
CHEMICAL AND BIOLOGICAL ENGINEERING

Adviser: Jose Avalos, assistant professor of chemical and biological engineering and the Andlinger Center for Energy and the Environment

Involvement with the Andlinger Center: A recipient of the 2015 Andlinger Center Undergraduate Summer Internship, Ip conducted research with Avalos into the use of yeast in biofuel production. The researchers worked to engineer a strain of yeast that efficiently produces mevalonate, a highly desirable substance that can be used to form synthetic fuels, industrial chemicals, plastics and specialty chemicals.

(Photo courtesy Samantha Ip)

Extracurriculars: Ip is the head of research and development for imPACT, a Pace Center volunteer group that assists high-achieving sixth graders at a middle school in Trenton. She is a member of the Princeton Model United Nations team and travels to compete in public speaking conferences. The social committee coordinator for the Princeton Premedical Society, Ip also volunteers regularly in the critical care unit of the University Medical Center of Princeton at Plainsboro.

Honors: Shapiro Prize for Academic Excellence for 2014-15

Free time: "I really enjoy jogging and swimming. I also like baking (especially desserts) and playing the piano."

ERIC TEITELBAUM

BSE '14, GRADUATE STUDENT
CIVIL AND ENVIRONMENTAL ENGINEERING

Adviser: Forrest Meggers, assistant professor of architecture and the Andlinger Center for Energy and the Environment

Involvement with the Andlinger Center: Received support through the Beyond Shading project led by Andlinger Center faculty for his senior thesis on a novel evaporative cooling system for building surfaces and continues to work on low-energy heating and cooling systems for buildings. As part of the project, he and colleagues in Meggers' Cooling and Heating for Architecturally Optimized Systems (CHAOS) lab are redesigning a pavilion known as the "Thermoheliodome" that uses the evaporation of fluid, rather than air conditioning, to create an outdoor space that is comfortable in summer.

Other research: Teitelbaum also works on the characterization of a liquid dehumidification system and has been involved in the Campus as a Lab project, trying to find ways to cut heating and cooling costs by studying airflow in buildings. "All of our research involves leveraging physics and fundamental science in an applied, building-physics setting."

Extracurriculars: Member of the building and grounds committee for the summer camp YMCA Camp Ockanickon in Medford, New Jersey, which he attended as a child

Honors: Michele Goudie '93 Senior Thesis Award

Free time: "I'm an avid woodworker and outdoorsman. I love camping. I also really enjoyed my former position as a carpenter for Nelson Treehouse and Supply, where I got to build treehouses of varying degrees of luxury around the country. I also enjoy a good crossword puzzle."

(Photo by Frank Wojciechowski)

PRINCETON UNIVERSITY

School of Engineering and Applied Science
Princeton, NJ 08544-5263
www.princeton.edu/engineering

eqn@princeton.edu