THE YEAR IN REVIEW 2012-2013

STANFORD ENGINEERING

NEW DIRECTIONS

STANFORD ENGINEERS TACKLED SOME OF THE WORLD’S BIGGEST CHALLENGES DURING THE PAST ACADEMIC YEAR. LEARN HOW.
Stanford engineers have always tackled the biggest challenges, and the past academic year was no exception. Our faculty and students blazed new trails in energy, nanotechnology, bioengineering, education and many other fields. That is why we chose New Directions in Engineering as the theme for this report.

One new direction involves studies of the brain. Stanford is at the forefront of a national research initiative to reverse engineer the human CPU. As part of this effort, our faculty and students invented a process to render the brain transparent for research purposes, an advance that could transform our understanding of this important organ. Faculty and students have found ways to harness thoughts to control a computer cursor. And they have gained insights into the causes of football concussions with the ultimate goal of prevention.

In another direction, our researchers are applying the principles and practices of engineering to the molecular machinery of life. One team developed computer-like processes to control DNA in living cells. Another group engineered a skin-like polymer that can sense subtle pressure, conduct electricity and heal itself when cut. A third group studied how sunburn breaks down the lipids that hold together the outermost skin cells.

Designing instruments and tools is a core engineering skill. Our researchers have developed ways to visualize and manipulate materials at the scale of nanotechnology. These tools include an endoscope as thin as a human hair, a probe that can peer inside a cell and optical tweezers that can grasp the smallest bits of matter.

Stepping back to take a global view, Stanford engineers continue to lead the search for new sources of sustainable energy and more efficient ways to decrease energy demand. Three developments stand out: a peel-and-stick solar decal that can be applied to virtually any surface, a solar panel of record-setting thinness and a passive solar technique that cools without air conditioning.

A common thread in everything we do at Stanford Engineering is the pursuit of innovation. That extends to teaching. Our faculty is transforming the learning experience. Our design programs, which predate the “maker” trend in society, have proven enormously popular with students. At the same time, we are offering classes over the Internet, including massive open online courses, or MOOCs, to find better ways to blend classroom instruction and online learning to improve the education of Stanford Engineering students.

On a personal note, I recently announced plans to step down as Dean in the summer of 2014. By then I will have served in this post for 15 years. I plan to return to research and teaching after I take a sabbatical. It has been a privilege to serve with this great faculty, students, staff and alumni community. Let us work together with the next Dean to make Stanford Engineering an even better place to educate the students who will change the world.
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Detail by detail, science is unraveling the secrets of the brain. As the mind’s once-inscrutable mysteries are revealed, engineers are applying their pragmatism and scholarly discipline to study and treat the brain as never before. Stanford engineers are at the forefront of these efforts, and the past year was remarkable even by our lofty standards. Three developments stand out: the transparent brain, the thought-controlled computer cursor and a study of concussions in football.
In one of the year’s most notable achievements, a team under the direction of bioengineer Karl Deisseroth unveiled a process that renders a post-mortem mouse brain transparent. The brain itself remains whole—not sliced or sectioned in any way—and retains all of its three-dimensional complexity of fine neural wiring and molecular structures.

The process, called CLARITY, ushers in a new era of whole-organ imaging that stands to fundamentally change our scientific understanding of the brain and potentially other organs.

“Studying intact systems with this sort of molecular resolution and global scope—to be able to see the fine detail and the big picture at the same time—has been a major unmet goal in biology, and a goal that CLARITY begins to address,” says Deisseroth, a professor of bioengineering and of psychiatry and behavioral sciences.

“This feat of chemical engineering promises to transform the way we study the brain’s anatomy and how disease changes it,” says Thomas Insel, director of the National Institute of Mental Health.

The research in this study was performed primarily on a mouse brain, but the researchers have used CLARITY on zebrafish and on preserved human brain samples, all with similar results, establishing a path for future studies of human samples and other organisms.

CLARITY is a blend of neuroscience and chemical engineering, and the result of a years-long research effort to extract the opaque elements from an intact brain—in particular the lipids. Lipids are fatty tissues found throughout the body, but in the brain they help form cell membranes and provide structure. Lipids, however, make the brain largely impermeable both to chemicals and to light—two of the most common tools for scientific observation. Before CLARITY, removing the lipids would cause the remaining tissue to disintegrate.

CLARITY replaces the lipids with a hydrogel. The brain is immersed in a watery suspension of short molecules known as hydrogel monomers. The monomers soak into the tissue and then are “thermally triggered,” or heated slightly. As they warm, the monomers congeal into long chains known as polymers, forming a mesh throughout the brain that holds everything together. Fortuitously, the polymers bind to everything in the brain except the lipids, which can be drawn out by an electrical process. What remains is a 3-D, transparent brain with all of its important structures—neurons, axons, dendrites, synapses, proteins, nucleic acids and so forth—intact and, most important, in place.

In preserving the full continuity of neuronal structures, CLARITY not only allows tracing of individual neural connections over long distances through the brain but also provides a way to gather rich molecular information.

“We thought that if we could remove the lipids nondestructively, we might be able to get both light and macromolecules to penetrate deep into tissue, allowing not only 3-D imaging but also 3-D molecular analysis of the intact brain,” says Deisseroth, one of 15 experts on a team that is mapping out goals for a $100 million U.S. national brain research initiative.

Professor Karl Deisseroth has developed a process that renders a post-mortem mouse brain transparent (facing page) while retaining its three-dimensional complexity of fine neural wiring and molecular structures.
When a person with paralysis imagines moving a limb, cells in the part of the brain that once controlled movement of that limb still activate as though trying to make the immobile extremity work again.

In recent years, neuroscientists and neuroengineers working in the field known as neural prosthetics have begun to develop brain-implantable sensors that can measure electrical signals from these neurons and decode the signals with a mathematical algorithm that enables paralyzed people to control a computer cursor with their thoughts.

Decoding the signals is difficult business, and the algorithm is key to controlling movements that reflect what the brain is telling the cursor to do. Last year, a team of Stanford researchers devised an entirely new algorithm, known as ReFIT, that decodes brain signals in a different way than existing models. ReFIT vastly improves the speed and accuracy of these cursor-controlled movements.

The team included Krishna Shenoy, a professor of electrical engineering, bioengineering and neurobiology, and was led by research associate Vikash Gilja and bioengineering doctoral candidate Paul Nuyujukian.

The system relies on a silicon chip that is implanted into the brain to record electrical signals. The frequency of these signals provides the computer with key information about the direction and speed of the user’s intended movement.

In side-by-side demonstrations with rhesus monkeys implanted with the chip, the ReFIT algorithm doubled the performance of existing systems and approached the accuracy and speed of a real arm moving a cursor with a mouse.

Critical to ReFIT’s time-to-target improvement was its superior ability to stop the cursor. While the old model’s cursor reached the target almost as fast as ReFIT, it often overshot the destination, requiring additional time and multiple passes to hold the target.
Assistant Professor David Camarillo’s team has developed equipment to measure the magnitude and types of forces exerted on a player’s head and neck during a game or practice.

ReFIT is a departure from earlier models in that it is able to make adjustments in real time as the monkey is guiding the cursor to a target, just as a hand and eye would work in tandem. In earlier models, scientists record brain activity while the subject moves—or imagines moving—an arm and analyze the data after the fact.

The team also decided to abandon traditional methods that try to decode the signals from individual neurons. ReFIT focuses instead on small groups of neurons. Neural implants that are fine-tuned to single neurons degrade over time as the electrodes become separated from the neurons they were intended to monitor. Gilja says the Stanford system is working well more than four years after it was implanted.

FOOTBALL CONCUSSIONS: In a drive to prevent these injuries, researchers develop technologies to analyze the hits that cause them.

Concussions have become a serious concern for America’s most popular sport, football. Arguably the game’s most notorious injuries, concussions are also its most mysterious.

With the help of the Stanford football team, a group of Stanford doctors and neuroscientists, including David Camarillo, an assistant professor of bioengineering, is working to quantify the head trauma that players receive during a game.

“We’re working as a multidisciplinary team to understand what causes a concussion,” Camarillo says.

The group is measuring the magnitude and types of forces exerted on a player’s head and neck during a game or practice using high-definition, super-slow-motion cameras that track special markings on the helmets. The researchers have also developed custom mouth guards equipped with accelerometers and gyrometers that measure linear and rotational acceleration—essentially, how violently the head gets whipped around during a game.

So far, Camarillo and his cohort are finding that the notorious helmet-to-helmet impacts are far from the only danger in football. Crushing shoulder-to-chest hits can toss the head back just as viciously, and similar forces can occur when players’ heads hit the ground.

The data the Stanford team gathers will be key in creating better protective gear for players and instituting safety protocols.

“If you really understand carefully what the mechanism of the concussion is, that is where the preventive part comes in, and then we can start zeroing in and prototyping technologies that may reduce the likelihood of sustaining an injury,” Camarillo says.
From the tensile strength of spider silk to the structural perfection of the honeycomb, engineers have always taken cues from nature to inspire their work. The past year's research included three examples of ways that Stanford engineers study biology for its secrets. Their work shows how biology itself is becoming a tool of engineering. The year saw the introduction of a biocomputer that resides within a single cell. The remarkable properties of human skin inspired two discoveries: a polymer that can conduct electricity and “heal” itself, and a deeper understanding of how ultraviolet radiation affects skin.
THE BIOCOMPUTER: Digital genetic switches use DNA, RNA and enzymes to enable computing within living cells.

Early computing machines used mechanical gears and latches to manipulate data. The first electronic computers used vacuum tubes and electricity. Today, most computers use transistors made from highly engineered semiconductors to carry out logical operations. Now, a team of Stanford bioengineers has enabled computing via DNA, RNA and enzymes — the stuff of biology — instead of gears, silicon and electrons. The biocomputer is the brainchild of Drew Endy, an assistant professor of bioengineering.

“We created what we call the ‘transcriptor,’ a simple digital genetic switch that is the key to genetic logic, inspired in part by the transistor and electronics,” says Jerome Bonnet, a former postdoctoral scholar in Endy’s lab who led development of the biocomputer.

Transcriptors can be configured to perform Boolean logic within the confines of a single cell — to compute inside living cells. As one example, such biocomputers allow researchers to program a microbe to record when it encounters certain external stimuli or environmental factors and perform specific tasks based on that information.

Though the field is in its nascence, researchers are already working to program bacteria to recognize cancer and tag it for easy identification or even produce pharmaceuticals to kill the cancer on the spot. A preprogrammed bacterium might thus become a powerful research probe — a living biochemical laboratory and drug factory in one.

“In a biological setting, the possibilities for computing are as open-ended as in electronics,” Bonnet says.

The second component of the biocomputer is the biological equivalent of ethernet — a method for transmitting arbitrary genetic information (i.e., engineered DNA molecules encoding transcriptor logic gates and any other genetic material) from cell to cell. Think of it as Wi-Fi for microbes. Using the biological Internet, it becomes possible to orchestrate the behavior of many cells.

The final component is digital memory. The team, led by Endy, perfected a system whereby a
microbe can flip a specific section of its DNA back and forth. If the section points one direction, it’s defined as a zero, Endy explains; if it points the other way, it’s a one. In other words, the researchers have created a rewritable binary digit—a “bit” in data storage parlance. They hope someday to get to a “byte”—which, as any computer scientist will tell you, is eight bits. By today’s computing standards, it’s not much. But it’s plenty for biology.

“The potential applications of such a system are limited only by the imagination of the researcher,” says co-author Monica Ortiz, a recent doctoral graduate in bioengineering who demonstrated the biological Internet portion of the research.

The biological Internet uses a benign virus, known as M13, to broadcast genetic messages between cells. To create transcriptors and digital memory, the team used carefully calibrated combinations of enzymes that control the memory state and the flow of enzymes along strands of DNA, akin to the flow of electrons through wires.

“The choice of enzymes is important,” Bonnet says. “We selected ones that function the same way in bacteria, fungi, plants and animals to guarantee that biocomputers can be engineered into many kinds of organisms.”

PLASTIC SKIN: A material that can sense pressure, conduct electricity and heal itself could lead to smarter prosthetics.

Human skin is a remarkable tissue. Not only is it sensitive to pressure, but it also heals efficiently and provides a formidable barrier against disease, germs and radiation. Engineers are trying to recreate some of these remarkable properties as they strive to emulate skin for a variety of applications, from more responsive prosthetics to go-anywhere touchscreens.

One of those researchers is Professor Zhenan Bao, a chemical engineer whose team succeeded in making the first synthetic material that can sense subtle pressure, conduct electricity and heal itself when cut.

Her team started with a plastic consisting of long chains of molecules joined by hydrogen bonds—which have relatively weak attractions.

“These dynamic bonds allow the material to self-heal,” says Chao Wang, a member of the research team. The molecules easily break apart, but when they reconnect, the bonds reorganize themselves and restore the structure of the material after it is damaged, he says.

To this resilient polymer, the researchers added tiny particles of nickel. The metal not only increases the material’s mechanical strength, but the jagged nanoscale surface of the nickel particles also improves conductivity.

To see how this material could withstand damage, the researchers cut a sample strip with a scalpel then pressed the pieces together. Before long...
Reinhold Dauskardt, a professor of materials science and engineering, has studied skin for years—real human skin. But when he asked his students to look for data on the mechanical properties of skin, they came back empty-handed.

“That motivated us to get more interested in the biomechanics of skin itself,” says Dauskardt, the school’s Ruth G. and William K. Bowes Professor.

He and his team, including doctoral student Krysta Biniek and postdoctoral researcher Kemal Levi, focused on the skin’s outermost layer: the stratum corneum. This is the body’s first line of defense against the world. It was in looking at the relationship of ultraviolet radiation and skin that Dauskardt’s team made a surprising discovery: UV rays change the way skin cells bind together.

The researchers subjected samples to UVB radiation then put them under stresses. Structurally, the stratum corneum has a “brick-and-mortar” structure. The “bricks” are flattened cells called corneocytes, which are filled with thin filaments of the protein keratin. Human skin’s elasticity—its ability to resist deformation under pressure—is caused largely by the stretching of these strands.

The researchers were surprised to find that although the keratin was structurally altered by UVB exposure, its stiffness wasn’t—it still held together. It was when they looked at the “mortar” of skin, the lipids, that they noticed a profound difference. The lipids are fatty, waxy substances that hold the skin cells together like glue. These layers take a beating from UVB. If the mortar fails, the skin cells fall apart, like bricks in a crumbling wall. Thus, sun-battered skin is weaker and prone to chapping and cracking, which invites greater damage from the sun, bacteria and other environmental factors.

Ironically, the team found that UV exposure increased the tissue’s tendency to absorb water, not to dry out, as one might expect. But the additional water loosens the bonds between the lipids, making them more likely to tear under pressure.

Dauskardt’s mechanical testing also reaffirmed one time-honored fact: the importance of sunscreen in protecting the lipids from damage. In protecting the glue that holds the skin cells together, the whole system is stronger as a result.

“It’s totally cool,” Dauskardt says. “You put a sunscreen on the lab sample, and it causes a huge change in the way the skin is affected mechanically.”

A researcher slices a piece of self-healing, skin-like polymer with a scalpel.

**SUN AND SKIN:** Exploring the mechanical properties of skin reveals how UV radiation changes the way cells bind together.

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The findings originated not only from biological curiosity but also from Dauskardt’s work studying the effects of severe terrestrial environments and prolonged UV exposure on materials—in particular, solar panels.

“Here we were looking at solar cells then suddenly thinking, ‘Hey, we should be looking at applying these techniques to understand UV damage processes in skin,’” Dauskardt explains.

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A researcher slices a piece of self-healing, skin-like polymer with a scalpel.
Engineers around the world are striving to create new sources of non-polluting energy. Nowhere are these efforts more pronounced than in the field of solar research. The promise of clean and abundant energy from the sun is fueling a global push to improve the technologies we have today. In three significant advances, Stanford engineers have developed flexible solar cells that can be attached to virtually any surface, a solar cell that set a record for thinness and a new type of solar panel that cools even in the midday sun.
PEEL-AND-STICK PANELS: Thin, flexible solar cells can be applied like a decal to virtually any surface.

For all their promise, solar cells have frustrated scientists in one crucial regard—most are rigid. They must be deployed in stiff and often heavy fixed panels, limiting their applications. So researchers have been trying to get photovoltaics to loosen up. Now Stanford engineers have succeeded in developing the world’s first peel-and-stick thin-film solar cells. The researchers have attached the thin, flexible solar cells to paper, plastic and window glass, among other materials. This flexibility could make many new surfaces potential sites for solar power generation.

“The main contribution of our work is that we have done this without modifying any existing processes, facilities or materials, making them viable commercially,” says Chi Hwan Lee, a doctoral candidate in mechanical engineering.

The new process involves a unique “sandwich.” It begins with nickel deposited on a silicon/silicon dioxide wafer. Next, the solar cells are applied, then covered with a protective polymer. A thermal release tape goes atop all of it. Then, the whole sandwich is dipped in water.

With the edge of the thermal release tape peeled back slightly, water seeps between the nickel and the wafer, freeing the solar cells from the hard substrate. The cells can then be applied to virtually any surface using double-sided tape or other adhesive. Finally, the thermal-release tape is heated and removed. Only the solar cells remain, attached to the chosen substrate.

Tests have demonstrated that the peel-and-stick process reliably leaves the thin-film solar cells intact and functional, explains Xiaolin Zheng, assistant professor of mechanical engineering and senior author of this research study.

“There’s no waste, and we didn’t lose any of the original cell efficiency,” Zheng says. “You can put them on helmets, cell phones, convex windows, portable electronic devices, curved roofs, clothing—virtually anything.”

Moreover, the peel-and-stick technology isn’t necessarily restricted to thin-film solar cells. The researchers believe the process can also be applied to thin-film electronics, including printed circuits, ultra-thin transistors and LCDs.

“Obviously, a lot of new products—from ‘smart’ clothing to new aerospace systems—might be possible by combining both thin-film electronics and thin-film solar cells,” Zheng says.
Stanford scientists have created a nanoscale photovoltaic structure thousands of times thinner than an ordinary sheet of paper.

“Our results show that it is possible for an extremely thin layer of material to absorb almost 100 percent of incident light of a specific wavelength,” says Stacey Bent, professor of chemical engineering and a member of the research team.

It is a significant step toward thin cells that absorb as much sunlight as possible. An ideal solar cell would absorb not just a single wavelength but also the full spectrum of visible light, as well as invisible ultraviolet and infrared light.

For the study, the Stanford team created thin wafers dotted with trillions of tiny round particles of gold. In the experiment, postdoctoral scholar Carl Hagglund and his colleagues were able to “tune” the gold nanodots to absorb light from one location on the spectrum.

The results set records.

“The volume of each dot is equivalent to a layer of gold just 1.6 nanometers thick, making it the thinnest absorber of visible light on record—about 1,000 times thinner than commercially available thin-film solar cell absorbers,” says Hagglund, lead author of the study.

The next step is to demonstrate that the technology can be used in actual solar cells. The challenge for researchers is to reduce the thickness of the material without compromising its ability to absorb and convert sunlight into clean energy.

The ultimate goal, Bent adds, is to develop improved solar cells and solar fuel devices that can absorb the maximum amount of sunlight from the smallest possible amount of material.

The scientists are also considering nanodot arrays made of less expensive metals. “Although the cost of the gold was virtually negligible, silver is cheaper and better from an optical point of view if you want to make a good solar cell,” Hagglund says.
SUNNY AND COOL: A new form of solar panel would cool buildings, cars and other structures even when the sun is shining.

Homes and buildings chilled without air conditioners. Car interiors that don’t bake in the summer sun. Tapping the frigid expanses of outer space to cool the planet.

Science fiction, you say? Well, maybe not anymore.

A team of researchers at Stanford has designed an entirely new form of cooling structure that works by reflecting sunlight back into the chilly vacuum of space.

“People usually see space as a source of heat, but it’s really a cold, cold place,” says Shanhui Fan, professor of electrical engineering. “We’ve developed a new type of structure that reflects the vast majority of sunlight and sends heat into space to cool manmade structures.”

The trick, from an engineering standpoint, is twofold. First, the structure has to reflect as much of the sunlight as possible. Poor reflectors absorb too much light, heat up and counteract the cooling effects.

The second challenge is that the structure must efficiently radiate thermal radiation in a very specific wavelength range. Otherwise, Earth’s atmosphere simply reflects the heat back down. Most people are familiar with this phenomenon as the greenhouse effect, which has been implicated in global climate change.

The new Stanford structure solves both challenges—it reflects most of the light and emits heat in the ideal range to escape the atmosphere.

“Radiative cooling at night is well established, but no one had yet been able to surmount the challenges of cooling when the sun is shining,” says Eden Rephaeli, a doctoral candidate in Fan’s lab.

The Stanford team succeeded by using nanostructured photonic materials that were engineered to enhance or suppress light reflection to certain wavelengths.

“We’re very excited because this design makes viable both industrial-scale and off-grid applications,” says Aaswath Raman, also a doctoral candidate in Fan’s lab.

Radiative cooling is a passive technology. It requires no energy. It has no moving parts. It is easy to maintain. Put it on the roof or the sides of buildings, and it starts working immediately.

Beyond the commercial implications in developed countries, Fan and his collaborators say the technology will benefit people living in sun-drenched areas around the equator where producing electricity is an economic and environmental challenge.

“We can foresee applications in off-the-grid areas of the developing world where air conditioning is not even possible at this time,” Fan says.
Biological scientists are exploring ever-smaller targets within the body to understand and treat disease. As they delve deeper, they are increasingly turning to engineers to create better research tools and techniques. The past year was notable in this regard as Stanford engineers announced an endoscope as thin a human hair, a light-emitting probe that can fit in a single cell and optical tweezers that grasp unimaginably tiny particles.

BY ANDREW MYERS
If engineers at Stanford have their way, biological research may soon be transformed by a new class of light-emitting probes small enough to be injected into individual cells without harm to the host. Even with a probe embedded, a cell is able to function, migrate and reproduce as normal.

The team’s so-called “nanobeam” looks like a piece from an old-fashioned erector set, only much smaller, just a few microns long and a few hundred nanometers wide. Tiny holes etched through the beam create photonic cavities that concentrate and amplify light to produce tiny lasers and light-emitting diodes.

At the cellular level, a nanobeam is like a needle that penetrates cell walls without injury. Once inside the cell, the beam emits light, yielding an array of research applications, according to Gary Shambat, a recent PhD graduate in electrical engineering.

“Our device has applications from fundamental physics to nanolasers and sensors that could have profound impacts on biological research,” says Jelena Vuckovic, professor of electrical engineering.

The researchers say the probe could be coated with organic molecules or antibodies that attract important biological proteins. A protein would accumulate on the probe and cause a detectable shift in the wavelength of the light being emitted from the device. This shift would be a positive indication that the protein is present and in what quantity.

“New drugs are often designed to produce or inhibit specific proteins,” explains Sanjiv Sam Gambhir, chair of the Department of Radiology in the School of Medicine and director of Stanford’s...
Canary Center for Cancer Early Detection. “Our biosensor would tell us definitively if the new drug was working and how well based on the color of the light from the probe,” he adds.

In one finding the scientists describe as “stunning,” they placed nanobeams into cells and watched as the cells grew, migrated and reproduced. Each time a cell divided, one of the daughter cells inherited the nanobeam, and the beam and the cell continued to function as expected. This heritability frees researchers to study living cells for long periods of time. “We tracked one cell for eight days. That’s a long time for a single-cell study,” Shambat says.

**HAIR-THIN ENDSCOPE:** This minimally invasive endoscope can see objects that are out of reach of today’s best medical instruments.

Engineers at Stanford have demonstrated a high-resolution endoscope that is as thin as a human hair with a resolution four times that of the best existing devices. The so-called micro-endoscope is a significant step forward in bio-imaging inside living organisms, with potential applications ranging from the study of the brain to early cancer detection.

A team led by Joseph Kahn, professor of electrical engineering, developed the endoscope. Kahn’s work began two years ago when he and fellow Stanford electrical engineer Olav Solgaard were discussing biophotonics—a field that uses light to study biological systems.

“Olav wanted to know if it would be possible to send light through a single fiber, form a bright spot inside the body and scan it to record images of living tissue,” Kahn says.

The opportunity and the challenge, Kahn and Solgaard knew, rested in multimode fibers in which light travels via many different paths. The problem is that the light becomes scrambled along the way, often beyond recognition.

Kahn found a way to undo the scrambling. He used a specialized light source that projects random light patterns down the fiber to illuminate an object inside the body. The reflected light returns through the fiber, and the image is reconstructed using algorithms developed by graduate students Reza Nasiri Mahalati and Ruo Yu Gu.

Kahn and his team have created a working prototype, which is limited only in that the fiber must remain rigid. The fiber is placed in a thin needle to hold it steady during insertion.

Kahn’s prototype can resolve objects about 2.5 microns in size, which is roughly the thickness of a strand from a spider’s web. But he says that 0.3 micron resolution is easily within reach. That’s roughly as fine as a particle of corn starch. By comparison, today’s endoscopes can only see objects down to about 10 microns—making the invention a fourfold leap in resolution at the very least. It is possible now to conceive of a fiber endoscope just thicker than a human hair that can display tiny structures in the human body on ultra-high-quality digital screens.

Looking ahead, Kahn is excited about the potential of working on new biomedical applications and by the challenge of making his endoscope flexible. “No one knows if it’s possible, but we’re going to try,” Kahn says.
Assistant Professor Jennifer Dionne (left) and doctoral candidate Amr Saleh (below) have designed optical tweezers that would theoretically grasp particles as small as 2 nanometers.

**OPTICAL TWEEZERS:** A new design harnesses plasmonics to allow manipulation of individual molecules.

Researchers can harness the power of concentrated light to grasp and manipulate bacteria and parts of living cells without ever physically touching them.

The technique, known as optical tweezing, involves sculpting a beam of light into a narrow point, which produces a strong electromagnetic field that both attracts and traps tiny objects, just like a pair of tweezers.

Unfortunately, existing optical tweezers using visible light can only trap particles about 200 nanometers wide at best. That’s about as thick as two human hairs.

That posed a problem for Jennifer Dionne, assistant professor of materials science and engineering. She needed a tool that would help her move molecular building blocks into new configurations. Unfortunately, existing devices couldn’t trap the particles she targets, such as proteins that may be just 2 nanometers wide, a hundred times smaller than is presently possible to capture.

So Dionne did what engineers do: She devised a new way of doing things.

Working with electrical engineering doctoral candidate Amr Saleh, Dionne designed an aperture that relies on plasmonics, a technology that takes advantage of both the optical and electronic properties of metals.

The new aperture looks like the coaxial cable that carries television through your house, Saleh explains. A nanoscale wire of silver is coated in a thin layer of silicon dioxide, then wrapped in another layer of silver.

When light shines through the translucent silicon dioxide, it creates ripples of energy called plasmons where the silver and silicon dioxide meet. These plasmons, in turn, travel down the device and emerge as a powerful, concentrated beam of light—but without the physical limitations inherent in the current generation of optical tweezers.

This is not the first-ever plasmonic optical trap. But Dionne and Saleh have shown that their design would, theoretically, grasp particles as small as 2 nanometers. A prototype is under development.

As nanoscale tools go, this would be quite a versatile gadget with potential applications in biology, pharmacology and genomics.

Dionne would like to use her new tweezers to study a single protein’s twisted structure or to exert a strong pulling force on stem cells, which is known to change how these important cells differentiate into the many cells of the human body.

Saleh is particularly excited about stacking tiny particles to create new, “bottom-up” materials and devices.
Stanford Engineering helps the leaders of the future learn the principles, techniques and systems they will need to solve big problems. Our engineers have transformed the worlds of communications, electronics, energy production, biomedical engineering, business and more. Innovation extends to teaching practices as well. Hands-on learning environments such as the Product Realization Laboratory and the Hasso Plattner Institute of Design are growing faster than ever. At the same time, faculty are experimenting with a virtual approach to education by using the Internet to offer massive open online courses, or MOOCs, and bring those innovations back into our classrooms.
With its saws and drill presses, furnaces and 3-D printers, the Product Realization Laboratory at Stanford Engineering allows students to think with their hands. In an age of nano-this and mega-that, such a goggles-and-apron setting might seem anachronistic. But more and more students are taking classes through the PRL. At the same time, a growing number of courses are being offered through the School of Engineering’s Hasso Plattner Institute of Design, fondly known as the d.school. Mushrooiming interest in these programs attests to the fact that Stanford students want to design and make things.

Meanwhile, some faculty members are taking the craft of teaching in an opposite, virtual direction. In 2011, a trio of Stanford Engineering professors made their courses freely available on the Internet and sparked a new interest in massive open online courses, or MOOCs. This development drew media attention, but the real story is how faculty members are experimenting with different teaching methods to improve the educational experience of students on campus.

These initiatives may seem contradictory, but School of Engineering Dean Jim Plummer sees a common thread: Both were launched by faculty members seeking to improve and extend the education of Stanford engineers.

“One of the things that is special about Stanford is that the faculty drives change,” Plummer says.

On one hand, the PRL and d.school provide academically rigorous experiences that reflect the same creative impulse expressed in the broader culture through the Maker movement.

“The huge success of our product design programs shows that people want to make things,” Plummer says.

On the other hand, Plummer notes that massive open online courses afford faculty members a chance to reach a broad audience all over the world and teach students on campus in new ways.

“At the end of the day, this place produces people and ideas,” Plummer says, adding, “Stanford Engineering has incredibly imaginative faculty who are always looking for the best ways to engage and energize our students.”

MAKERS, THEN AND NOW: The tradition and tools of prototyping now include 3-D printers and a focus on design thinking.

Dave Beach, co-director of the Product Realization Laboratory, notes that hands-on training at Stanford predates the Maker meme. “We’ve been making things here since the Student Shop was founded in 1891,” he says, adding that while other universities let their shops atrophy, Stanford preserved the tradition and the tools for prototyping. In the early 1970s, the Student Shop morphed into the Product Realization Laboratory.

The PRL was inspired in part by John Arnold, a former mechanical engineering and business professor who was a pioneer of human-centered design, now a central tenet of teaching at Stanford Engineering. Early mentors of the PRL included two emeritus professors of engineering, Robert

Professor David Kelley founded the Hasso Plattner Institute of Design, where engineering students work with collaborators from other academic disciplines on project-focused teams.
H. McKim, who helped expand the teaching of a hands-on, human-centered approach to design, and Jim Adams, who integrated a fresh focus on creativity, innovation and design into the curriculum. In 1973, PRL enrollment was 150. The program has grown steadily over the years. In 2010, PRL enrollment stood at 700. By the 2013 academic year, 1,700 students were taking these hands-on classes.

Another inflection point in this Maker trend on campus came in 2005 when David Kelley, the Donald W. Whittier Professor in Mechanical Engineering, founded the Hasso Plattner Institute of Design. The d.school, as it is commonly called, brings together instructors from engineering, business, education and social sciences. Classes at the d.school put engineering students together with collaborators from other academic disciplines to work on project-focused teams. Students learn design thinking and come up with breakthrough ideas. They develop confidence in their creative abilities, a central goal of the program.

New technologies help fuel interest in making things, notably low-cost 3-D printers that build prototypes one layer at a time. Such printers are controlled by computer programs that can be shared online, a fact that allows Makers to mix and match modules as they design their 3-D creations.

From his vantage as the Bosch Chair of the Mechanical Engineering department, where the PRL and d.school converge, Ken Goodson looks beyond the confines of the school and the university. Some mass markets are giving way to niche markets. Product cycles are shortening. Goodson believes the time may be ripe for small batches of custom-ized goods produced by smart, nimble teams of tech-savvy Makers. “We may be seeing the seeds of a revival of U.S. manufacturing, with Stanford at the heart of it,” he says.

MOOCs sound exotic, but they are only the latest tech-based way to teach outside the traditional classroom. Stanford has been a leader in distance education for more than four decades, since the inception of the Stanford Instructional Television Network and continuing to the present through the Stanford Center for Professional Development.

The novelty that MOOCs bring to distance education is “the power of the deadline,” says Bernd Girod, the Robert L. and Audrey S. Hancock Professor of Electrical Engineering and Senior Associate Dean for Online Learning and Professional Development.

“MOOCs move students through weekly assignments just like a conventional classroom-taught course,” he says, breaking with the conventional wisdom that once saw self-pacing as the key strength of online learning. “One of the things we’re seeing is the power of the deadline to focus attention,” Girod says.

Girod works closely with John Mitchell, the Mary and Gordon Crary Family Professor in the
School of Engineering and Stanford Vice Provost for Online Learning.

“There are many ways to use technology creatively. While our main goal is to improve teaching and learning on campus, MOOCs are a good way to experiment and reach a broader community, including our alumni,” Mitchell says. “By advancing faculty-driven online teaching initiatives, we can transform how time is spent in the classroom and transform education for students—both at Stanford and beyond.”

Jennifer Widom, the Fletcher Jones Professor and chair of Computer Science, was one of three Stanford Engineering faculty members who launched the new MOOC movement by putting their courses online in the fall of 2011. Her experience demonstrates the link between MOOCs and the ongoing focus on classroom education.

Widom says one reason she became involved with MOOCs was that she had already been preparing to put much of her class materials online in an innovation called the flipped classroom, which is aimed at her Stanford students. In a flipped classroom, professors put lectures and assignments online, and use class meetings for such things as problem-solving exercises, guest lectures or brainstorming discussions. Widom found it relatively easy to make a pared-down version of her flipped Stanford course widely available online.

“There’s a lot of satisfaction in bringing this material to the world,” Widom says. She recalls one Stanford alumna, a stay-at-home mom looking for intellectual enrichment, who was in the middle of taking the course when she visited Widom in her office during reunion weekend to say, in effect, “Your MOOC saved my psyche.”

Widom, who was preparing to offer her MOOC for the third time when she spoke for this article, said that although the Stanford course is considerably enriched from the MOOC version, the online experience positively impacts Stanford students. “One of the benefits of having tens of thousands of eyeballs on your lectures is that everything gets thoroughly debugged,” she says. Her teaching evaluations from Stanford students taking the new flipped version of the course are statistically better than scores before the class was flipped; in other words, students seem to like it.

“Encouraging experimentation is one of the reasons we’re doing this,” Girod says. He considers MOOCs an evolution rather than a revolution in education at Stanford, blending the best of online and classroom learning.

“If you ask me how Stanford is going to look in 2020,” Girod says, “we’re still going to have the most beautiful campus with the foothills in the background and blue skies and the best residential student experience in the world.”
Faculty awards & honors

Arthur Bienenstock (MSE, Emeritus)
• Member, American Academy of Arts and Sciences

Sarah Billington (CEE)
• Milligan Family University Fellow in Undergraduate Education

Tom Bowman (ME)
• Member, National Academy of Engineering

Richard Christensen (AA, Emeritus)
• American Society of Mechanical Engineers Timoshenko Medal

William Chueh (MSE)
• International Society of Solid-State Ionics Young Scientist Award

Sigrid Close (AA)
• U.S. Department of Energy Early Career Research Award

Markus Covert (BioE)
• Paul Allen Distinguished Investigator Award

Gregory Deierlein (CEE)
• Member, National Academy of Engineering

David Dill (CS)
• Member, American Academy of Arts and Sciences
• Member, National Academy of Engineering

John Eaton (ME)
• Martin Family University Fellow in Undergraduate Education

Chuck Eesley (MS&E)
• Fellow, Stanford Center at Peking University

Abbas El Gamal (EE)
• Member, National Academy of Engineering

Drew Endy (BioE)
• Open Science Champion of Change

Charbel Farhat (AA, ME)
• Member, National Academy of Engineering

Edward Feigenbaum (CS, Emeritus)
• IEEE Computer Pioneer Award

Curtis Frank (CE)
• Member, National Academy of Engineering

Kenneth Goodson (ME)
• Fellow, IEEE
• IEEE THERMI Award

Sachin Katti (EE, CS)
• Sloan Research Fellow

Oussama Khatib (CS)
• IEEE Robotics & Automation Society Distinguished Service Award

Christian Linder (CEE)
• International Association of Applied Mathematics and Mechanics (GAMM) Richard von Mises Prize

Perry McCarty (CEE, Emeritus)
• American Association of Engineering Societies Joan Hodges Queneau Palladium Medal
Jens Nørskov (CE)
• North American Catalysis Society and European Federation of Catalysis Societies — Michel Boudart Award for the Advancement of Catalysis

John Ousterhout (CS)
• IEEE Reynold B. Johnson Information Storage Systems Award

Balaji Prabhakar (EE, CS)
• IEEE Innovation in Societal Infrastructure Award

Stephen Quake (BioE)
• Member, National Academy of Engineering

Martin Reinhard (CEE, Emeritus)
• Humboldt Research Award

Eric Roberts (CS)
• ACM Karl V. Karlstrom Outstanding Educator Award

Mendel Rosenblum (CS, EE)
• IEEE Reynold B. Johnson Information Storage Systems Award

Juan Santiago (ME)
• Fellow, American Society of Mechanical Engineers

Michael Saunders (MS&E)
• Fellow, Society for Industrial and Applied Mathematics

Keith Schwarz (CS)
• School of Engineering Tau Beta Pi Excellence in Teaching Award

Haresh Shah (CEE, Emeritus)
• Earthquake Engineering Research Institute George Housner Medal

Eric Shaqfeh (CE, ME)
• Dean’s Award for Industry Education Innovation
• Member, National Academy of Engineering

Sheri Sheppard (ME)
• Burton J. and Deedee McMurtry University Fellow in Undergraduate Education

Yoav Shoham (CS)
• ACM/AAAI Allen Newell Award
• Fellow, Association for Computing Machinery

NEW EMERITUS FACULTY

Alfred Spormann (CE, CEE)
• Fellow, American Academy of Microbiology

Bob Tatum (CEE)
• ASCE Peurifoy Construction Award

Sebastian Thrun (CS)
• Smithsonian American Ingenuity Award for Education

Gregory Valiant (CS)
• Honorable Mention, ACM Doctoral Dissertation Awards

Ryan Williams (CS)
• Sloan Research Fellow
• Microsoft Faculty Fellow

Teresa H.-Y. Meng, EE (2013)
Serge A. Plotkin, CS (2013)
2013 Stanford Engineering Heroes

The Stanford Engineering Heroes program recognizes the achievements of Stanford engineers who have profoundly advanced the course of human, social and economic progress through engineering. Because engineers often work behind the scenes, the Heroes program’s objective is to highlight the profound effect engineering has on our everyday lives and to inspire the next generation of engineers.

**John A. Blume**, considered by many in the profession to be the “father of earthquake engineering,” was a consulting professor of civil and environmental engineering at Stanford. He achieved breakthroughs in seismic and structural engineering that exerted an unprecedented influence on modern earthquake engineering. He provided engineering advice on many significant structures, notably the Stanford Linear Accelerator, restoration of the California State Capitol, and buildings and waterfront structures for Saudi Arabian oil giant Aramco. Blume was an expert in nuclear power plant design who consulted for the U.S. Nuclear Regulatory Commission as well as on about 70 nuclear plant projects. He earned his BA in civil engineering in 1933 and a second engineering degree in 1934, both from Stanford. It was not until 1967—34 years after receiving his bachelor’s degree—that Blume received his doctorate from Stanford. Blume’s many honors included membership in the National Academy of Engineering.

**James H. Clark** is an entrepreneur and computer scientist who was a founder of Silicon Graphics, Netscape, Healtheon, myCFO and Shutterfly. From 1979 to 1984, he was an associate professor of electrical engineering at Stanford, where he developed the Geometry Engine, an early hardware accelerator for rendering computer images based on geometric models. That technology was the basis for early products by Silicon Graphics, which revolutionized the design process for everything from bridges and airplanes to special effects for movies. In 1994, Clark joined Marc Andreessen (lead developer of Mosaic, one of the first web browsers) to form Netscape. Clark has a BS in physics from Louisiana State University and a PhD in computer science from the University of Utah, which also awarded him an honorary doctorate in 1995. He is a member of the National Academy of Engineering and the Horatio Alger Association of Distinguished Americans.

**David Filo**, a native of Moss Bluff, La., co-created Jerry and Dave’s Guide to the World Wide Web in April 1994 with Jerry Yang and co-founded Yahoo! Inc. in April 1995. Filo serves as a key technologist, directing the technical operations behind the company’s global network of web properties. He is credited with helping build Yahoo into the world’s most highly trafficked website and one of the Internet’s most recognized brands. Filo holds a BS in computer engineering from Tulane University and an MS in electrical engineering from Stanford University.
Martin Hellman is best known for his invention, with Whitfield Diffie and Ralph Merkle, of public key cryptography, a technology that secures trillions of dollars in financial transactions daily. He has played a key role in the computer privacy debate. His efforts to overcome ethnic tension within Stanford University were recognized by three awards from minority student organizations. His many honors include election to the National Academy of Engineering, induction into the National Inventors Hall of Fame, the Marconi Fellowship and the IEEE’s Hamming Medal. He has a deep interest in the ethics of technological development and is currently applying quantitative risk analysis to reduce the danger of a failure in nuclear deterrence. Hellman received his BE from New York University in 1966, and his MS and PhD from Stanford University in 1967 and 1969, all in electrical engineering. He was an assistant professor at MIT before joining the Stanford faculty in 1971, where he served until becoming emeritus in 1996.

John McCarthy was a professor emeritus of computer science at Stanford and a giant in the field of artificial intelligence. He is credited with coining the term “artificial intelligence” and subsequently went on to define the discipline for more than five decades from his post at Stanford. In his career, he developed the programming language LISP, played computer chess via telegraph with opponents in Russia and invented computer time-sharing—an advance that greatly improved the efficiency of distributed computing and predated the era of cloud computing by decades. The Association for Computing Machinery in 1971 honored McCarthy with the A.M. Turing Award, the highest recognition in computer science. He received the Kyoto Prize in 1988 and the National Medal of Science, the nation’s highest technical award, in 1990. He was a member of the National Academy of Sciences, the National Academy of Engineering and the American Academy of Arts and Sciences.

William J. Perry was secretary of defense of the United States from February 1994 to January 1997, deputy secretary of defense from 1993 to 1994 and undersecretary of defense for research and engineering from 1977 to 1981. He is known internationally to the arms control community for his many contributions to international security. At Stanford, he is the Michael and Barbara Berberian Professor, Emeritus, in the Department of Management Science and Engineering, a senior fellow at the Freeman Spogli Institute for International Studies and co-director of the Preventive Defense Project at the Center for International Security and Cooperation (CISAC). He is a former co-director of CISAC. Perry received the Presidential Medal of Freedom in 1997 and was named Knight Commander of the British Empire in 1998. His many other honors include being elected a member of the National Academy of Engineering and a fellow of the American Academy of Arts and Sciences. He has a BS and MS from Stanford and a PhD from Pennsylvania State University, all in mathematics.

Entrepreneur Jerry Yang co-founded Yahoo! Inc. in 1995 and served on the board of directors and as a key member of the executive management team until 2012. While at Yahoo, he led a number of initiatives, including two of the biggest investments in the Internet: Yahoo Japan and Alibaba Group. Yang holds BS and MS degrees in electrical engineering from Stanford University. He is widely recognized as a visionary and pioneer in the Internet technology sector and was named one of the top 100 innovators in the world under age 35 by MIT Technology Review in 1999. Yang is currently a vice-chair on Stanford University’s Board of Trustees. Yang and his wife, Akiko Yamazaki, are well-known philanthropists who focus on higher education, conservation and the arts.
Financial Information

This report covers the fiscal year that began September 1, 2012, and closed August 31, 2013. During this period the School of Engineering reported expenses of $336,650,254 (see chart below for breakdown). In addition to these expenses, the school incurred $50,400,333 in indirect costs on sponsored research and $2,155,923 in infrastructure costs, for a total of $389,206,510 in consolidated expenditures.

### Expenses by Category

**Total Direct Expenses**
- Faculty Salaries: $56,567,932
- Other Teaching: $4,212,631
- Research & Admin Staff Salaries: $69,468,007
- Student Aid: $106,507,009
- Equipment & Supplies: $99,894,675

**Total All Sources**
- General Funds: $71,037,380
- Endowment Income: $53,181,411
- Gifts: $20,501,167

### Sources of Funding

**Total All Sources**
- Federal Grants & Contracts: $113,542,731
- Non-Federal Grants & Contracts: $25,792,461

### 2012-13 Research Volume

**Total expenditures by agency in millions**

- **Total Federal**
  - Department of Defense: $57,529,182.43
  - National Institutes of Health: $33,346,144.86
  - National Science Foundation: $25,640,720.30
  - Department of Energy: $14,039,156.81
  - Other Federal: $13,764,991.67
  - National Aeronautics and Space Administration: $5,712,855.87

- **Non-Federal**

- **TOTAL**
  - $183,919,260.67

### 2012-13 Gifts and Affiliates Fees

**Total gifts/fees received in millions (rounded)**

- **Gifts**
  - Living Individuals: $49,449,000.00
  - Corporations: $11,969,000.00
  - Foundations & Associations: $6,089,000.00
  - Bequests: $233,000.00

- **Affiliate Revenues**
  - $15,601,486.00

- **TOTAL**
  - $83,341,486.00
Stanford Engineering Then and Now

These charts show alumni and current students broken down by department or degree-granting program. Some departments, such as mechanical and electrical engineering, have alumni records dating back to the 1920s. Other degrees, such as computational and mathematical engineering, are new. The data for current students, a definition that includes postdoctoral scholars, is a snapshot taken in the fall of 2013.

Alumni by Department or Degree
(As of October 2013)

- Aeronautics & Astronautics: 3,588
- Bioengineering: 192
- Chemical Engineering: 2,513
- Civil & Environmental Engineering: 9,280
- Computational & Mathematical Engineering: 186
- Computer Science: 7,814
- General Engineering: 4,007
- Mechanical Engineering: 10,851
- Materials Science & Engineering: 2,490
- Electrical Engineering: 18,854

Total Alumni: 62,935

Students by Department or Degree
(As of October 2013)

- Aeronautics & Astronautics: 207
- Bioengineering: 161
- Chemical Engineering: 253
- Civil & Environmental Engineering: 517
- Computational & Mathematical Engineering: 119
- Computer Science: 995
- General Engineering: 316
- Materials Science & Engineering: 501
- Mechanical Engineering: 236
- Electrical Engineering: 965

Total Students: 4,959
The Stanford School of Engineering has been at the forefront of innovation for nearly a century, turning big ideas into solutions that have improved people’s lives across the globe. Our mission is to seek solutions to important global problems and educate leaders who will make the world a better place by using the power of engineering principles, techniques and systems.

We believe it is essential to educate engineers who possess not only deep technical excellence but also the creativity, cultural awareness and entrepreneurial skills that come from exposure to the liberal arts, business, medicine and other disciplines that are an integral part of the Stanford experience.

Collaborating with colleagues across disciplines, Stanford engineers are finding better ways to create efficient energy sources, diagnose and treat diseases, ensure clean water, enhance global communication and unleash human creativity.

**STANFORD ENGINEERING AT A GLANCE**

- 4,959 students
- 251 faculty members
- Three No. 1 department rankings; all departments in the top six
- More than 80 labs, centers and affiliate programs involving students in research
- All nine departments in 21st-century facilities by fall 2014
- Nearly 13,000 companies founded by Stanford Engineering faculty and graduates

**THE SCHOOL’S NINE DEPARTMENTS**

- Aeronautics and Astronautics
- Bioengineering
- Chemical Engineering
- Civil and Environmental Engineering
- Computer Science
- Electrical Engineering
- Management Science and Engineering
- Materials Science and Engineering
- Mechanical Engineering