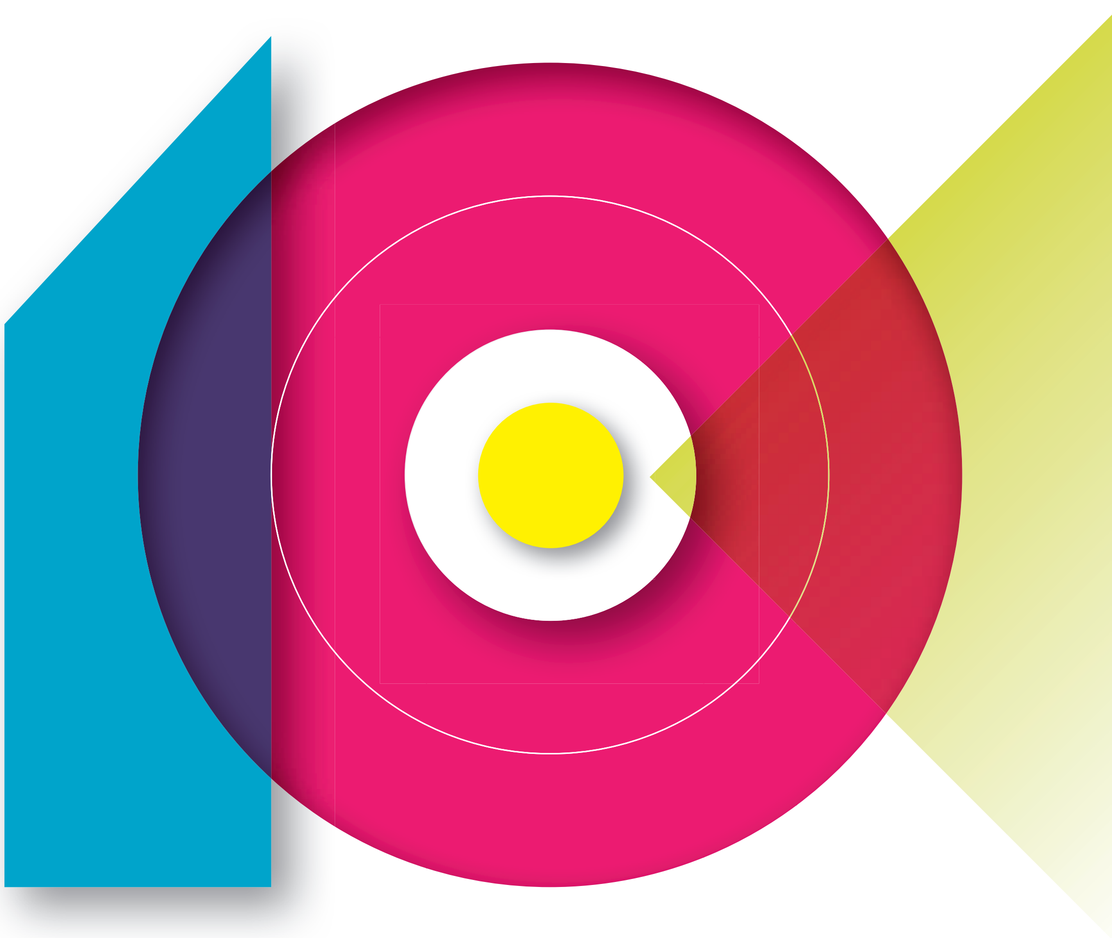

SPECIAL REPORT

# TOP 10 EMERGING TECHNOLOGIES *of 2017*

DISRUPTIVE SOLUTIONS THAT ARE POISED TO CHANGE THE WORLD

*Illustrations by Eric Petersen*

# What if

drinking water could be drawn from desert air easily, without requiring enormous amounts of electricity from a grid? What if a doctor could do a biopsy for a suspected cancer without a blade of any sort? What if we didn't have to wait too long for the result? Technologies that make these visions a reality are expected to become increasingly commonplace in the next few years. This special report, compiled and produced in a collaboration between *Scientific American* and the World Economic Forum's Expert Network, highlights 10 such emerging technologies.

To choose the entrants in this year's emerging technologies report, we convened a steering group of world-renowned technology experts. The committee made recommendations and elicited suggestions from members of the Forum's Expert Network and Global Future Councils, *Scientific American*'s board of advisers and others who are tuned in to burgeoning research and development in academia, business and government. Then the group whittled down the choices by focusing on technologies that were not yet widespread but were attracting increased funding or showing other signs of being ready to move to the next level. The technologies also had to offer significant benefits to societies and economies and to have the power to alter established ways of doing things.

*—Mariette DiChristina and Bernard S. Meyerson*

IN BRIEF

**When it comes to preventing and treating disease,** better biopsy techniques, genomic vaccines and a massive global project to map every human cell are a boon to public health and personalized medicine.

**Sustainably providing the resource needs** of a growing population is becoming more possible thanks to advances in solar-powered water harvesting and artificial photosynthesis that produces renewable fuel. Real-time feedback is making precision farming an efficient way to feed more people.

**Green tech is becoming** more accessible to the masses. Entire blocks of homes can be transformed into zero-emissions communities. New approaches in hydrogen-fuel cells could mean cheaper gasoline-free cars.

**Improvements in visual AI** and quantum computing are leading to a future when machines interpret data and solve complex problems better than humans.

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PUBLIC HEALTH

## WATER MADE BY THE SUN

### TECHNOLOGIES THAT PULL MOISTURE FROM THE AIR ARE NOW SOLAR-POWERED

***By Donna J. Nelson and Jeffrey Carbeck***

Billions of people lack access to clean water for all or part of the year or must travel far to collect it. Extracting water directly from the air would be an immeasurable boon for them. But existing technologies generally require a high-moisture climate and a lot of electricity, which is expensive and often unavailable. This problem is now becoming more tractable, thanks to robust systems in development that rely on readily available energy from the sun. They are scalable and work even in arid regions—where a third of the world's population lives, often in poverty.

Collaborators at the Massachusetts Institute of Technology and the University of California, Berkeley, have tested an approach that requires no electricity at all. The team intends for its technology to overcome a notable problem with most materials capable of absorbing water from the atmosphere (such as the zeolites in humidifiers): aside from needing high humidity, they give up the trapped water only when heated substantially, which takes energy.

The researchers designed their system around a class of porous crystals called metal-organic frameworks (MOFs), developed years ago by chemist Omar M. Yaghi, now in the U.C. Berkeley group. By choosing specific combinations of metals and organics, scientists can select the chemical properties of each MOF and thereby customize its uses. Beyond their versatility, MOFs' great promise lies with their phenomenally large pores: the surface area inside is almost 10 times that of porous zeolites. For context, one gram of an MOF crystal the size of a sugar cube has an internal surface area approximately equal to the area of a football field.

In April, Yaghi's group, along with that of M.I.T. mechanical engineer Evelyn Wang, reported on a prototype device incorporating MOF-801, or zirconium fumarate, which has a high affinity for water. It pulls moisture from the air into its large pores and readily

feeds the water into a collector in response to low-grade heat from natural sunlight. The device can harvest 2.8 liters of water daily per every kilogram of MOF even at relative humidity levels as low as 20 percent, similar to those of deserts. (According to Yaghi, a person needs at least a soda can's worth, or 355 milliliters, of drinking water a day.) Plus, it requires no additional input of energy. The investigators see more room for improvement. Further experimentation with MOF composition should make the technology less expensive (zirconium currently costs $150 per kilogram), increase the amount of water collected per unit of material and allow researchers to tailor MOFs to different microclimates.

Taking a different tack, a start-up called Zero Mass Water in Scottsdale, Ariz., has begun selling a solar-based system that does not have to be hooked up to an electric grid or an existing water system. A solar panel provides energy that both drives air through a proprietary water-absorbing material and powers condensation of the extracted moisture into fluid. A small lithium-ion battery operates the device when the sun is not shining. A unit with one solar panel, the company says, can produce two to five liters of liquid a day, which is stored in a 30-liter reservoir that adds calcium and magnesium for health and taste.

Cody Friesen, founder of Zero Mass Water and a materials scientist at Arizona State University, developed the system with the aim of having it work sustainably and easily anywhere in the world. An installed system with one solar panel sells in the U.S. for about $3,700. That price tag includes a required 10 percent donation toward reducing costs for installations in parts of the globe lacking water infrastructure. The same unit that reduces the need for bottled water in the U.S., Friesen notes, can also provide clean water to a school that lacks it so that children "are able to get educated and not get sick."

Over the past year, he says, systems have been placed in the southwestern U.S. and several other countries—among them, Mexico, Jordan and the United Arab Emirates—and the company has recently shipped panels to Lebanon, with funding from the U.S. Agency for International Development, to provide water to Syrian refugees. When most people think about solar, Friesen adds, "they think about electricity. In the future, people will think about water abundance."


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ENERGY

# FUEL FROM AN ARTIFICIAL LEAF

## TECHNOLOGY THAT MIMICS PHOTOSYNTHESIS CONVERTS CARBON DIOXIDE TO FUELS IN A SUSTAINABLE WAY

***By Javier Garcia Martinez***

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**The notion of an artificial leaf** makes so much sense. Leaves, of course, harness energy from the sun to turn carbon dioxide into the carbohydrates that power a plant's cellular activities. For decades scientists have been working to devise a process similar to photosynthesis to generate a fuel that could be stored for later use. This could solve a major challenge of solar and wind power—providing a way to stow the energy when the sun is not shining and the air is still.

Many, many investigators have contributed over the years to the development of a form of artificial photosynthesis in which sunlight-activated catalysts split water molecules to yield oxygen and hydrogen—the latter being a valuable chemical for a wide range of sustainable technologies. A step closer to actual photosynthesis would be to employ this hydrogen in a reduction reaction that converts $CO_2$ into hydrocarbons. Like a real leaf, this system would use only $CO_2$, water and sunlight to produce fuels. The achievement could be revolutionary, enabling creation of a closed system in which carbon dioxide emitted by combustion was transformed back into fuel instead of adding to the greenhouse gases in the atmosphere.

Several researchers are pursuing this goal. Recently one group has demonstrated that it is possible to combine water splitting and $CO_2$ conversion into fuels in one system with high efficiency. In a June 2016 issue of *Science,* Daniel G. Nocera and Pamela A. Silver, both at Harvard University, and their colleagues reported on an approach to making liquid fuel (specifically fusel alcohols) that far exceeds a natural leaf's conversion of carbon dioxide to carbohydrates. A plant uses just 1 percent of the energy it receives from the sun to make glucose, whereas the artificial system achieved roughly 10 percent efficiency in converting carbon dioxide to fuel, the equivalent of pulling 180 grams of carbon dioxide from the air per kilowatt-hour of electricity generated.

The investigators paired inorganic, solar water-splitting technology (designed to use only biocompatible materials and to avoid creating toxic compounds) with microbes specially engineered to produce fuel, all in a single container. Remarkably, these metabolically engineered bacteria generated a wide variety of fuels and other chemical products even at low $CO_2$ concentrations. The approach is ready for scaling up to the extent that the catalysts already contain cheap, readily obtainable metals. But investigators still need to greatly increase fuel production. Nocera says the team is working on prototyping the technology and is in partnership discussions with several companies.

Nocera has an even bigger vision for the basic technology. Beyond producing hydrogen- and carbon-rich fuels in a sustainable way, he has demonstrated that equipping the system with a different metabolically altered bacterium can produce nitrogen-based fertilizer right in the soil, an approach that would increase crop yields in areas where conventional fertilizers are not readily available. The bacterium uses the hydrogen and $CO_2$ to form a biological plastic that serves as a fuel supply. Once the microbe contains enough plastic, it no longer needs sunshine, so it can be buried in the soil. After drawing nitrogen from the air, it exploits the energy and hydrogen in the plastic to make the fertilizer. Radishes grown in soil containing the microbes ended up weighing 150 percent more than control radishes.

**The achievement could enable creation of a closed system in which $CO_2$ emitted by combustion was transformed back into fuel instead of adding to greenhouse gases.**

Nocera admits that he initially ran the fertilizer test just to see if the idea would work. He envisions a time, however, when bacteria will "breathe in hydrogen" produced by water splitting and ultimately use the hydrogen to produce products ranging from fuels to fertilizers, plastics and drugs, depending on the specific metabolic alterations designed for the bugs.

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COMPUTING

# AI THAT SEES LIKE HUMANS

## A DEEP-LEARNING TOOL FOR VISUAL TASKS IS CHANGING MEDICINE, SECURITY AND MORE

***By Apurv Mishra***

**For most of the past 30 years** computer-vision technologies have struggled to perform well, even in tasks as mundane as accurately recognizing faces in photographs. Recently, though, breakthroughs in deep learning—an emerging field of artificial intelligence—have finally enabled computers to interpret many kinds of images as successfully as, or better than, people do. Companies are already selling products that exploit the technology, which is likely to take over or assist in a wide range of jobs that people now perform, from driving trucks to interpreting scans for diagnosing medical disorders.

Recent progress in a deep-learning approach known as a convolutional neural network (CNN) is key to the latest strides. To give a simple example of its prowess, consider images of animals. Whereas humans can easily distinguish between a cat and a dog, CNNs allow machines to categorize specific breeds more successfully than people can. It excels because it is better able to learn, and draw inferences from, subtle, telling patterns in the images.

CNNs do not need to be programmed to recognize specific features in images—for example, the shape and size of an animal's ears. Instead they are taught to spot features such as these on their own. To train a CNN to separate an English springer spaniel from a Welsh one, for instance, you start with thousands of images of animals, including examples of both breeds. Like most deep-learning networks, CNNs are organized in layers. In the lower layers, they learn simple shapes and edges from the images. In the higher layers, they learn complex and abstract concepts—in this case, the more detailed aspects of ears, tails, tongues, fur textures, and so on. Once trained, a CNN can easily decide whether a new image of an animal shows a breed of interest.

CNNs were made possible by the tremendous progress in graphics processing units and parallel processing in the past decade. But the Internet has made a profound difference as well by feeding CNNs' insatiable appetite for digitized images.

Computer-vision systems powered by deep learning are being developed for a range of applications. The technology is making self-driving cars safer by enhancing the ability to recognize pedestrians. Insurers are starting to apply these tools to assess damage to cars. In the security camera industry, CNNs are making it possible to understanding crowd behavior, which will make public places and airports safer. In agriculture, deep-learning applications can be used to predict crop yields, monitor water levels and help detect crop diseases before they spread.

Deep learning for visual tasks is making some of its broadest inroads in medicine, where it can speed experts' interpretation of scans and pathology slides and provide critical information in places that lack professionals trained to read the images—be it for screening, diagnosis, monitoring of disease progression or response to therapy. This year, for instance, the U.S. Food and Drug Administration approved a deep-learning approach from the start-up Arterys for visualizing blood flow in the heart; the purpose is to help diagnose heart disease. Also this year Sebastian Thrun of Stanford University and his colleagues described a system in *Nature* that classified skin cancer as well as human dermatologists did. The researchers noted that such a program installed on smartphones, which are ubiquitous around the world, could provide "low-cost universal access to vital diagnostic care." Systems are also being developed to assess diabetic retinopathy (a cause of blindness), stroke, bone fractures, Alzheimer's disease and other maladies.

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ENGINEERING

# PRECISION FARMING

## SENSORS, IMAGING AND REAL-TIME DATA ANALYTICS IMPROVE FARM OUTPUTS AND REDUCE WASTE

***By Geoffrey Ling and Blake Bextine***

As the world's population grows, farmers will need to produce more and more food. Yet arable acreage cannot keep pace, and the looming food security threat could easily devolve into regional or even global instability. To adapt, large farms are increasingly exploiting precision farming to increase yields, reduce waste, and mitigate the economic and security risks that inevitably accompany agricultural uncertainty.

Traditional farming relies on managing entire fields—making decisions related to planting, harvesting, irrigating, and applying pesticides and fertilizer—based on regional conditions and historical data. Precision farming, in contrast, combines sensors, robots, GPS, mapping tools and data-analytics software to customize the care that plants receive, all without increasing labor. Stationary or robot-mounted sensors and camera-equipped drones wirelessly send images and data on individual plants—information, say, about stem size, leaf shape and the moisture of the soil around a plant—to a computer, which looks for signs of health and stress. Farmers receive the feedback in real time and then deliver water, pesticide or fertilizer in calibrated doses to only the areas that need it. The technology can also help farmers decide when to plant and harvest crops.

As a result, precision farming can improve time management, reduce water and chemical use, and produce healthier crops and higher yields—all of which benefit farmers' bottom lines and conserve resources while reducing chemical runoff.

Many start-ups are developing new software, sensors, aerial-based data and other tools for precision farming, as are large companies such as Monsanto, John Deere, Dow and DuPont. The U.S. Department of Agriculture, NASA and the National Oceanic and Atmospheric Administration all support precision farming, and many colleges now offer course work on the topic.

In a related development, seed producers are applying technology to improve plant "phenotyping." By following individual plants over time and analyzing which ones flourish in different conditions, companies can correlate the plants' response to their environ-

ments with their genomics. That information, in turn, allows the companies to produce seed varieties that will thrive in specific soil and weather conditions. Advanced phenotyping may also help generate crops with enhanced nutrition.

Growers are not universally embracing precision agriculture for various reasons. The up-front equipment costs—especially the expense of scaling the technology to large row-crop production systems—pose a barrier. Lack of broadband can be an obstacle in some places, although the USDA is trying to ameliorate that problem. Seasoned producers who are less computer-literate may be wary of the technology. And large systems will be beyond the reach of many small farming operations in developing nations. But less expensive, simpler systems could potentially be applied. Salah Sukkarieh of the University of Sydney, for instance, has demonstrated a streamlined, low-cost monitoring system in Indonesia that relies on solar power and cell phones. For others, though, cost savings down the road may offset the financial concerns. And however reticent some veteran farmers may be to adopt new technology, the next generation of tech-savvy farmers are likely to warm to the approach.

*The views, opinions and findings contained in this article are those of the authors and should not be interpreted as representing the official views or policies, either expressed or implied, of the Defense Advanced Research Projects Agency or the Department of Defense.*

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MEDICINE AND BIOTECH

# MAPPING EVERY CELL

## A GLOBAL PROJECT AIMS TO UNDERSTAND HOW ALL HUMAN CELL TYPES FUNCTION

***By Sang Yup Lee***

**To truly, deeply understand** how the human body works—and how diseases arise—you would need an extraordinary amount of information. You would have to know the identity of every cell type in every tissue; exactly which genes, proteins and other molecules are active in each type; what processes control that activity; where the cells are located exactly; how the cells normally interact with one another; and what happens to the body's functioning when genetic or other aspects of a cell undergo change, among other details. Building such a rich, complex knowledge base may seem impossible. And yet a broad international consortium of research groups has taken the first steps toward creating exactly that. They call it the Human Cell Atlas.

The consortium had its inaugural planning meeting in October 2016 and continues to organize. The Chan Zuckerberg Initiative is onboard as well. In June 2017 it announced that it was providing financial and engineering support to build an open data-coordination platform to organize the findings, so they will be readily sharable by researchers in the project and beyond.

The atlas, which will combine information from existing and future research projects, has been made feasible by a host of technological achievements. Those include advances in tools for isolating individual cells, for profiling the proteins in a single cell at any given time (proteins are the major workhorses in the body), and for quickly and inexpensively sequencing DNA and RNA. It will integrate research exploring all the "omes": the genome (the full set of genes), the transcriptome (the RNA made from the genes), the proteome (the proteins), the metabolome (small molecules, such as sugars, fatty acids and amino acids, involved or generated by cellular processes), and the fluxome (metabolic reactions whose rates can vary under different conditions). Then these findings will be mapped to different subregions of cells. The integrated results should lead to a tool that will simulate all the types and states of cells in our body and provide new understandings of disease processes and ways to intervene in them.

One of the most advanced pieces underlying the cell atlas is the continually updated Human Protein Atlas. It offers a glimpse of the kind of comprehensive work that goes into building the umbrella project, as well as the value it will ultimately bring.

Participants in the Human Protein Atlas have classified a large majority of the protein-coding genes in humans using a combination of genomics, transcriptomics, proteomics and antibody-based profiling, which identifies location. Since the program's inception in 2003, approximately 100 person-years of software development have gone into keeping track of and organizing the data for systems-level analyses. More than 10 million images have been generated and annotated by pathologists. The atlas includes a high-resolution map of the locations of more than 12,000 proteins in 30 subcellular compartments, or organelles, of various cells.

All the findings are available to the research community without restriction. Users can query the database to explore the proteins in any major organ or tissue, or they can focus on proteins with specific properties, such as those that participate in basic cell maintenance or that occur only in specific tissues. The data can also help model the plethora of dynamic, interacting components that enable life and can be used to explore ideas for new therapies.

Completing the Human Cell Atlas will not be easy, but it will be an immeasurably valuable tool for improving and personalizing health care.

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MEDICINE AND BIOTECH

# LIQUID BIOPSIES

## ULTRASENSITIVE BLOOD TESTS PROMISE TO IMPROVE CANCER DIAGNOSIS AND CARE

*By Apurv Mishra*

**A patient suspected of having cancer** usually undergoes imaging and a biopsy. Samples of the tumor are excised, examined under a microscope and, often, analyzed to pinpoint the genetic mutations responsible for the malignancy. Together this information helps to determine the type of cancer, how advanced it is and how best to treat it. Yet sometimes biopsies cannot be done, such as when a tumor is hard to reach. Obtaining and analyzing the tissue can also be expensive and slow. And because biopsies are invasive, they may cause infections or other complications.

A tool known as a liquid biopsy—which finds signs of cancer in a simple blood sample—promises to solve those problems and more. A few dozen companies are developing their own technologies. Observers predict that the market for the tests could be worth billions.

The technique typically homes in on circulating-tumor DNA (ctDNA), genetic material that routinely finds its way from cancer cells into the bloodstream. Only recently have advanced technologies made it possible to find, amplify and sequence the DNA rapidly and inexpensively.

Right now the tests, which are available from several companies, mostly aid in treatment decisions for people already diagnosed with a particular form of cancer, such as prostate or lung. But the liquid tests can provide additional services that tissue biopsies cannot. Repeated tests could potentially detect disease progression or resistance to treatment long before it would trigger symptoms or appear on imaging. Tissue biopsies examine only selected bits of tumors and can thus miss cells that have turned more dangerous than their neighbors; in principle, the liquid biopsy can detect the full spectrum of mutations in a mass, indicating when more aggressive treatment is needed. Crucially, liquid biopsies may one day provide a fast, easy screening test for detecting a cancer and determining its type in people who seem perfectly healthy.

In a sign of the growing enthusiasm for the field, GRAIL, a company spun off from Illumina, raised $900 million in funding this past March from investors, including Amazon and several major pharmaceutical companies. GRAIL plans to use the money to further develop the technology and to run the large clinical trials (involving hundreds of thousands of subjects) needed to see if screening will be feasible. Also in March the California-based company Freenome received $65 million for clinical trials, expected to be carried out with multiple research partners, to determine whether the testing improves how cancer patients fare. And this past May Guardant Health announced it had raised $360 million from investors, on top of earlier funding, with the goal of deploying its liquid-biopsy test to one million people over the next five years.

For the tests to enter wide usage, clinical trials must prove that the approach detects cancer accurately and that by aiding in treatment decisions, it improves progression and survival rates.

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AUTOMOTIVE

# HYDROGEN CARS FOR THE MASSES

## REDUCING PRECIOUS METALS MAKES FUEL-CELL CATALYSTS AFFORDABLE

*By Donna J. Nelson*

**Battery-powered electric vehicles** that give off no carbon dioxide are about to become mainstream. Today they constitute less than 1 percent of all rolling stock on the road globally, but multiple innovations in features such as the battery's cost and lifetime have made prices so competitive that Tesla has more than 400,000 advance orders for its $35,000 Model 3, which is slated to hit the road in the middle of 2018.

Unfortunately, the other great hope for vehicles that exhaust no carbon—those powered by hydrogen-fed fuel cells—remains too pricey for broad sales. (The manufacturer's price tag for the Toyota Mirai is $57,500.) A raft of laboratories and businesses, however, are determined to cut costs by replacing one of the most expensive components in the fuel cells: the catalyst. Many commercial versions contain the precious metal platinum, which aside from being pricey, is too rare to support ubiquitous use in vehicles.

Investigators are pursuing several lines of attack to shrink the platinum content: using it more efficiently, replacing some or all of it with palladium (which performs similarly and is somewhat less expensive), replacing either of those precious metals with inexpensive metals, such as nickel or copper, and forgoing metals altogether. Commercial catalysts tend to consist of thin layers of platinum nanoparticles deposited on a carbon film; researchers are also testing alternative substrates.

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MEDICINE AND BIOTECH

# GENOMIC VACCINES

## VACCINES COMPOSED OF DNA OR RNA COULD ENABLE RAPID DEVELOPMENT OF PREVENTIVES FOR INFECTIOUS DISEASES

***By Geoffrey Ling***

Standard vaccines to prevent infectious diseases consist of killed or weakened pathogens or proteins from those microorganisms. They work by teaching the immune system to recognize certain bits of protein—called antigens—on the surface of the pathogen as a foe. The immune system is then prepared to pounce the next time it encounters those foreign antigens. (Many modern vaccines deliver only the antigens, leaving out the pathogens.) Vaccines that treat cancer also rely on proteins, which doctors may deliver to patients to enhance immune responses. These proteins can include the immune system's own guided missiles: antibodies.

In contrast, a new kind of vaccine, which is poised to make major inroads in medicine, consists of genes. Genomic vaccines promise to offer many advantages, including faster manufacture when a virus, such as Zika or Ebola, suddenly becomes more virulent or widespread. They have been decades in the making, but dozens have now entered clinical trials.

Genomic vaccines take the form of DNA or RNA that encodes desired proteins. On injection, the genes enter cells, which then churn out the selected proteins.

Compared with manufacturing proteins in cell cultures or eggs, producing the genetic material should be simpler and less expensive. Further, a single vaccine can include the coding sequences for multiple proteins, and it can be changed readily if a pathogen mutates or properties need to be added. Public health experts, for instance, revise the flu vaccine annually, but sometimes the vaccine they choose does not match the strains that circulate when flu season arrives. In the future, investigators could sequence the genomes of the circulating strains and produce a better-matched vaccine in mere weeks.

Genomics also enables a new twist on a vaccination approach known as passive immune transfer, in which antibodies are delivered instead of antigens. Scientists can now identify people who are resistant to a certain pathogen, isolate the antibodies that provide that protection and design a gene sequence that will induce a person's cells to produce those antibodies.

With such goals in mind, the U.S. government, academic laboratories and companies large and small are pursuing the technology. A range of clinical trials to test safety and immunogenicity are under way, including for avian influenza, Ebola, hepatitis C, HIV, and breast, lung, prostate, pancreatic and other cancers. And at least one trial is looking at efficacy: the National Institutes of Health has begun a multisite clinical trial to see if a DNA vaccine can protect against Zika.

Meanwhile researchers are working to improve the technology—for example, by finding more efficient ways to get the genes into cells and by improving the stability of the vaccines in heat. Oral delivery, which would be valuable where medical personnel are scarce, is not likely to be feasible anytime soon, but nasal administration is being studied as an alternative. Optimism is high that any remaining obstacles such as these can be resolved.

Stanislaus S. Wong of Stony Brook University, who works closely with Radoslav R. Adzic of Brookhaven National Laboratory, is among those leading the charge. He and his colleagues have, for instance, combined relatively small amounts of platinum or palladium with cheaper metals such as iron, nickel or copper, producing many alloyed varieties that are far more active than commercial catalysts. Wong's group has fashioned the metals into ultrathin one-dimensional nanowires (roughly two nanometers in diameter). These nanowires have a high surface-area-to-volume ratio, which enhances the number of active sites for catalytic reactions.

Naturally, platinum-free catalysts would be ideal. Work on them is newer but bustling. In late 2016 Sang Hoon Joo of Ulsan National Institute of Science and Technology (UNIST) in South Korea reported that an iron- and nitrogen-doped carbon nanotube catalyst has activity comparable to commercial catalysts. Also, Liming Dai of Case Western Reserve University and his colleagues have invented a catalyst using no metal at all; it is a nitrogen- and phosphorus-doped carbon foam that is as active as standard catalysts.

Inventing and preparing a material that has excellent catalytic activity is just part of the challenge, Wong notes. Researchers are also working to scale up existing lab production methods to ensure consistency in the activity and durability of the best candidates. In all phases of their efforts, experimentalists are getting help from theorists who apply sophisticated computer models to figure out how all kinds of variables affect performance—from the chemical compositions, sizes and shapes of metal nanoparticles to the architectures of the support structures. Such collaborations, Wong says, should one day make it possible to rationally design superior catalysts for affordable fuel-cell vehicles.

Of course, the goal of a sustainable transport system demands not only zero carbon emissions during driving but also during the production and distribution of the fuel, be it electricity or hydrogen. That larger challenge remains.

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ENERGY

# SUSTAINABLE COMMUNITIES

## INSTEAD OF "GREENING" INDIVIDUAL HOUSES, ENTIRE BLOCKS OF HOMES ARE RETROFIT INTO A SINGLE EFFICIENT UNIT

***By Daniel M. Kammen***

**In the past decade** the construction and retrofitting of individual homes to reduce energy and water use has grown explosively. Yet applying green construction to multiple buildings at once may be an even better idea. Sharing resources and infrastructure could reduce waste, and retrofitting impoverished or moderate-income neighborhoods could also bring cost savings and modern technology to people who would typically lack such opportunities. Working at the neighborhood level does add complexity to planning, but these neighborhood efforts offer rewards that even green single-family homes cannot offer.

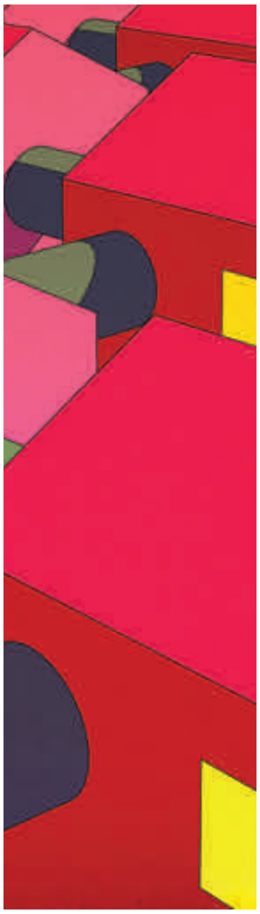
One such example is the Oakland EcoBlock project, which I lead at the University of California, Berkeley, with my colleague Harrison Fraker, a professor of architecture and urban design. It is a multidisciplinary endeavor involving urban designers, engineers, social scientists and policy experts from city, state and federal governments, academia, private industry, nonprofits and grassroots organizations.

The program, which has been planned in great detail but has not yet begun construction, will retrofit 30 to 40 contiguous old homes in a lower- to middle-income neighborhood near California's famous Golden Gate Bridge. It aims to apply existing technology to dramatically reduce fossil-fuel and water consumption and greenhouse gas emissions. We expect to rapidly recoup the money spent on infrastructure with savings from operating expenses while ensuring residents' long-term comfort and security.

To bring in renewable power, we will install solar panels on buildings throughout the area and send the energy to a smart microgrid. Excess solar energy will be stored via flywheels housed in a communal building. The residents will also share electric cars, which will have access to more than two dozen local charging stations. These measures should reduce annual electricity consumption by more than half and bring carbon emissions to zero—a valuable feat, considering that more than a quarter of U.S. greenhouse gas emissions emanate from residences.

The Environmental Protection Agency estimates that as much as 50 percent of California's home water consumption goes to lawns and gardens. We will treat and reuse wastewater from toilets as well as gray water sent down drains and released by washing machines. The recycled fluid will go toward gardening and irrigation. We will collect rainwater and deliver it to toilets and washers and install efficient fixtures and taps. Treated solid wastes, meanwhile, will be incorporated into compost. Our estimates suggest that the EcoBlock's system-level redesign will cut demand for potable water by up to 70 percent.

The Oakland EcoBlock project will provide local construction jobs and help revitalize a community. If it is as successful as we predict, it could serve as a model of sustainability that can be replicated elsewhere in the U.S. and beyond. To date, we have received inquiries from Europe, North Africa and Asia, confirming widespread interest in targeting and redesigning whole communities, not just individual homes.



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COMPUTING

# QUANTUM COMPUTING

## NEW ALGORITHMS AND TECHNIQUES OPEN THE DOOR TO INNOVATIVE APPLICATIONS

*By Dario Gil*

Quantum computing has captured imaginations for almost 50 years. The reason is simple: it offers a path to solving problems that could never be answered with classical machines. Examples include simulating chemistry exactly to develop new molecules and materials, as well as solving complex optimization problems, which seek the best solution from among many possible alternatives. Every industry has a need for optimization, which is one reason this technology has so much disruptive potential.

Quantum computers tackle problems by harnessing the power of quantum mechanics. Rather than considering each possible solution one at a time, as a classical machine would, they behave in ways that cannot be explained with classical analogies. They start out in a quantum superposition of all possible solutions, and then they use entanglement and quantum interference to home in on the correct answer—processes that we do not observe in our everyday lives.

Every industry has a need for optimization, which is one reason this technology has so much disruptive potential.

The promise they offer comes at the cost of them being difficult to build. A popular design requires superconducting materials that must be kept 100 times colder than outer space, exquisite control over delicate quantum states, and proper shielding so not a single stray ray of light reaches the processor. Until recently, access to nascent quantum computers was restricted to specialists in a few facilities around the world. But progress over the past several years has enabled the construction of the world's first prototype systems that can finally test out ideas, algorithms and other techniques that until now were strictly theoretical.

Existing machines are still too small to fully solve problems more complex than supercomputers can handle today. Nevertheless, tremendous progress has been made. Algorithms have been developed that will run faster on a quantum machine. Techniques now exist that prolong coherence (the lifetime of quantum information) in superconducting quantum bits by a factor of more than 100 compared with 10 years ago. We can now measure the most important kinds of quantum errors. And in 2016 IBM provided the public access to the first quantum computer in the cloud—the IBM Q experience—with a graphical interface for programming it and now an interface based on the popular programming language Python. Opening this system has fueled innovations that are vital for this technology to progress, and more than 20 academic papers have been published using this tool. The field is expanding dramatically. Academic research groups and more than 50 start-ups and large corporations worldwide are focused on making quantum computing a reality.

With these technological advancements and a machine at anyone's fingertips, now is the time for getting "quantum ready." People can begin to figure out what they would do if machines existed today that could solve complex problems. Many quantum computing guides are available online to help them get started.

There are still many obstacles. Coherence times must improve; quantum error rates must decrease, and eventually we must mitigate or correct the errors that do occur. Researchers will continue to drive innovations in both the hardware and software. Investigators disagree, however, over which criteria should determine when quantum computing has achieved technological maturity. Some have proposed a standard defined by the ability to perform a scientific measurement so obscure that it is not easily explained to a general audience. I and others disagree, arguing that quantum computing will not have truly emerged as a technology until it can solve problems that have commercial, intellectual and societal importance. The good news is, that day is finally within our sights.


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