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Global Agenda

Top 10 Emerging Technologies of 2016

By the World Economic Forum's Meta-Council on Emerging Technologies

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Introduction

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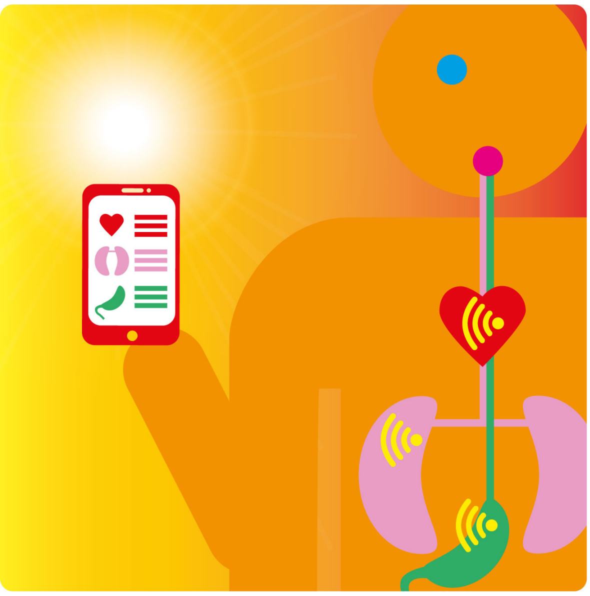
Technology is perhaps the greatest agent of change in the modern world. While never without risk, technological breakthroughs promise innovative solutions to the most pressing global challenges of our time. From batteries that can provide power to whole villages to microchips that could take the place of organs in medical research, this year's 10 emerging technologies offer a vivid glimpse of the power of innovation to improve lives, transform industries and safeguard our planet.

To compile this list, the World Economic Forum's Meta-Council on Emerging Technologies, a panel of global experts, draws on the collective expertise of the Forum's communities to identify the most important recent technological trends. By doing so, the Meta-Council aims to raise awareness of their potential and contribute to closing the gaps in investment, regulation and public understanding that so often thwart progress.



Nanosensors and the Internet of Nanothings

Tiny sensors that can connect to the web

The Internet of Things (IoT), built from inexpensive microsensors and microprocessors paired with tiny power supplies and wireless antennas, is rapidly expanding the online universe from computers and mobile gadgets to ordinary pieces of the physical world: thermostats, cars, door locks, even pet trackers. New IoT devices are announced almost daily, and analysts expected to up to 30 billion of them to be online by 2020.

The explosion of connected items, especially those monitored and controlled by artificial intelligence systems, can endow ordinary things with amazing capabilities—a house that unlocks the front door when it recognizes its owner arriving home from work, for example, or an implanted heart monitor that calls the doctor if the organ shows signs of failing. But the real Big Bang in the online universe may lie just ahead.

Scientists have started shrinking sensors from millimeters or microns in size to the nanometer scale, small enough to circulate within living bodies and to mix directly into construction materials. This is a crucial first step toward an Internet of Nano Things (IoNT) that could take medicine, energy efficiency, and many other sectors to a whole new dimension.

Some of the most advanced nanosensors to date have been crafted by using the tools of synthetic biology to modify single-celled organisms, such as bacteria. The goal here is to fashion simple biocomputers that use DNA and proteins to recognize specific chemical targets, store a few bits of information, and then report their status by changing color or emitting some other easily detectable signal. Synlogic, a start-up in Cambridge, Mass., is working to commercialize computationally enabled strains of probiotic bacteria to treat rare metabolic disorders. Beyond medicine, such cellular nanosensors could find many uses in agriculture and drug manufacturing.

Many nanosensors have also been made from non-biological materials, such as carbon nanotubes, that can both sense and signal, acting as wireless nanoantennas. Because they are so small, nanosensors can collect information from millions of different points. External devices can then integrate the data to generate incredibly detailed maps showing the slightest changes in light, vibration, electrical currents, magnetic fields, chemical concentrations and other environmental conditions.

The transition from smart nanosensors to the IoNT seems inevitable, but big challenges will have to be met. One technical hurdle is to integrate all the components needed for a self-powered nanodevice to detect a change and transmit a signal to the web. Other obstacles include thorny issues of privacy and safety. Any nanodevices introduced into the body, deliberately or inadvertently, could be toxic or provoke immune reactions. The technology could also enable unwelcome surveillance. Initial applications might be able to avoid the most vexing issues by embedding nanosensors in simpler, less risky organisms such as plants and non-infectious microorganisms used in industrial processing.

When it arrives, the IoNT could provide much more detailed, inexpensive, and up-to-date pictures of our cities, homes, factories—even our bodies. Today traffic lights, wearables or surveillance cameras are getting connected to the Internet. Next up: billions of nanosensors harvesting huge amounts of real-time information and beaming it up to the cloud.

Next Generation Batteries

Making large-scale power storage possible

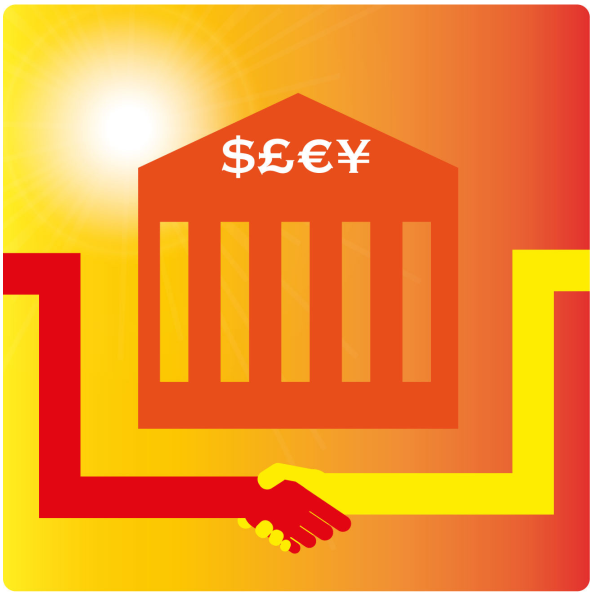
Solar and wind power capacity have been growing at double-digit rates, but the sun sets, and the wind can be capricious. Although every year wind farms get larger and solar cells get more efficient, thanks to advances in materials such as perovskites, these renewable sources of energy still satisfy less than five percent of global electricity demand. In many places, renewables are relegated to niche roles because of the lack of an affordable, reliable technology to store the excess energy that they make when conditions are ideal and to release the power onto the grid as demand picks up. Better batteries could solve this problem, enabling emissions-free renewables to grow even faster—and making it easier to bring reliable electricity to the 1.2 billion people who currently live without it.

Within the past few years, new kinds of batteries have been demonstrated that deliver high enough capacity to serve whole factories, towns, or even “mini-grids” connecting isolated rural communities. These batteries are based on sodium, aluminium or zinc. They avoid the heavy metals and caustic chemicals used in older lead-acid battery chemistries. And they are more affordable, more scalable, and safer than the lithium batteries currently used in advanced electronics and electric cars. The newer technology is much better suited to support transmissions systems that rely heavily on solar or wind power.

Last October, for example, Fluidic Energy announced an agreement with the government of Indonesia to deploy 35 megawatts of solar panel capacity to 500 remote villages, electrifying the homes of 1.7 million people. The system will use Fluidic’s zinc-air batteries to store up to 250 megawatt-hours of energy in order to provide reliable electricity regardless of the weather. In April, the company inked a similar deal with the government of Madagascar to put 100 remote villages there on a solar-powered mini-grid backed by zinc-air batteries.

For people who currently have no access to the grid—no light to work by at night, no Internet to mine for information, no power to do the washing or to irrigate the crops—the combination of renewable generation and grid-scale batteries is utterly transformative, a potent antidote for poverty. But better batteries also hold enormous promise for the rich world as it struggles to meet the formidable challenge of removing most carbon emissions from electricity generation within the next few decades—and doing so at the same time that demand for electricity is growing.

The ideal battery is not yet in hand. The new technologies have plenty of room for further improvement. But until recently, advances in grid-scale batteries had been few and far between. So it is heartening to see the pace of progress quickening.



The Blockchain

A revolutionary decentralized trust system

Blockchain–the technology behind the bitcoin digital currency–is a decentralized public ledger of transactions that no one person or company owns or controls. Instead, every user can access the entire blockchain, and every transfer of funds from one account to another is recorded in a secure and verifiable form by using mathematical techniques borrowed from cryptography. With copies of the blockchain scattered all over the planet, it is considered to be effectively tamper-proof.

The challenges that bitcoin poses to law enforcement and international currency controls have been widely discussed. But the blockchain ledger has uses far beyond simple monetary transactions. Like the Internet, the blockchain is an open, global infrastructure upon which other technologies and applications can be built. And like the Internet, it allows people to bypass traditional intermediaries in their dealings with each other, thereby lowering or even eliminating transaction costs.

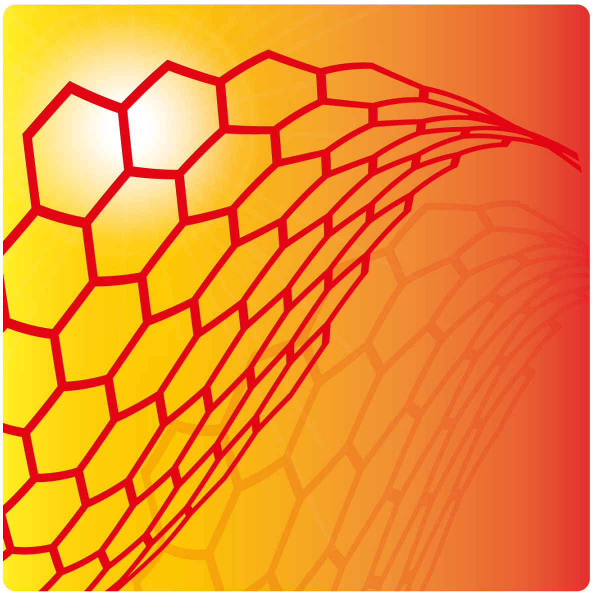
By using the blockchain, individuals can exchange money or purchase insurance securely without a bank account, even across national borders—a feature that could be transformative for the two billion people in the world currently underserved by financial institutions. Blockchain technology lets strangers record simple, enforceable contracts without a lawyer. It makes it possible to sell real estate, event tickets, stocks, and almost any other kind of property or right without a broker.

The long-term consequences for professional intermediaries, such as banks, attorneys and brokers, could be profound—and not necessarily in negative ways, because these industries themselves pay huge amounts of transaction fees as a cost of doing business. Analysts at Santander InnoVentures, for example, have estimated that by 2022, blockchain technology could save banks more $20 billion annually in costs.

Some 50 big-name banks have announced blockchain initiatives. Investors have poured more than $1 billion in the past year into start-ups formed to exploit the blockchain for a wide range of businesses. Tech giants such as Microsoft, IBM and Google all have blockchain projects underway. Many of these companies are attracted by the potential to use the blockchain to address the privacy and security problems that continue to plague Internet commerce.

Because blockchain transactions are recorded using public and private keys—long strings of characters that are unreadable by humans—people can choose to remain anonymous while enabling third parties to verify that they shook, digitally, on an agreement. And not just people: an institution can use the blockchain to store public records and binding promises. Researchers at the University of Cambridge in the U.K., for example, have shown how drug companies could be required to add detailed descriptions of their upcoming clinical drug trials to the blockchain. This would prevent the companies from later moving the goalposts if the trial did not pan out as anticipated, an all-too-common tactic. In London, mayoral candidate George Galloway has proposed putting the city's annual budget on the blockchain ledger to foster collective auditing by citizens.

Perhaps the most encouraging benefit of blockchain technology is the incentive it creates for participants to work honestly where rules apply equally to all. Bitcoin did lead to some famous abuses in trading of contraband, and some nefarious applications of blockchain technology are probably inevitable. The technology doesn't make theft impossible, just harder. But as an infrastructure that improves society's public records repository and reinforces representative and participatory legal and governance systems, blockchain technology has the potential to enhance privacy, security and freedom of conveyance of data—which surely ranks up there with life, liberty and the pursuit of happiness.



Two-Dimensional Materials
“Wonder materials” are becoming increasingly affordable

New materials can change the world. There is a reason we talk about the Bronze Age and the Iron Age. Concrete, stainless steel, and silicon made the modern era possible. Now a new class of materials, each consisting of a single layer of atoms, are emerging, with far-reaching potential. Known as two-dimensional materials, this class has grown within the past few years to include lattice-like layers of carbon (graphene), boron (borophene) and hexagonal boron nitride (aka white graphene), germanium (germanene), silicon (silicene), phosphorous (phosphorene) and tin (stanene). More 2-D materials have been shown theoretically possible but not yet synthesized, such as graphyne from carbon. Each has exciting properties, and the various 2-D substances can be combined like Lego bricks to build still more new materials.

This revolution in monolayers started in 2004 when two scientists famously created 2-D graphene using Scotch tape—probably the first time that Nobel-prize-winning science has been done using a tool found in kindergarten classrooms. Graphene is stronger than steel, harder than diamond, lighter than almost anything, transparent, flexible, and an ultrafast electrical conductor. It is also impervious to most substances except water vapor, which flows freely through its molecular mesh.

Initially more costly than gold, graphene has tumbled in price thanks to improved production technologies. Hexagonal boron nitride is now also commercially available and set to follow a similar trajectory. Graphene has become cheap enough to incorporate it in water filters, which could make desalination and waste-water treatment far more affordable. As the cost continues to fall, graphene could be added to road paving mixtures or concrete to clean up urban air—on top of its other strengths, the stuff absorbs carbon monoxide and nitrogen oxides from the atmosphere.

Other 2-D materials will probably follow the trajectory that graphene has, simultaneously finding use in high-volume applications as the cost falls, and in high-value products like electronics as technologists work out ways to exploit their unique properties. Graphene, for example, has been used to make flexible sensors that can been sewn into garments—or now actually 3-D printed directly into fabrics using new additive manufacturing techniques. When added to polymers, graphene can yield stronger yet lighter airplane wings and bicycle tires.

Hexagonal boron nitride has been combined with graphene and boron nitride to improve lithium-ion batteries and supercapacitors. By packing more energy into smaller volumes, the materials can reduce charging times, extend battery life, and lower weight and waste for everything from smart phones to electric vehicles.

Whenever new materials enter the environment, toxicity is always a concern. It’s smart to be cautious and to keep an eye out for problems. Ten years of research into the toxicology of graphene has, so far, yielded nothing that raises any concerns over its effects on health or the environment. But studies continue.

The invention of 2-D materials has created a new box of powerful tools for technologists. Scientists and engineers are excitedly mixing and matching these ultrathin compounds—each with unique optical, mechanical and electrical properties—to produce tailored materials optimised for a wide range of functions. Steel and silicon, the foundations of 20th-century industrialization, look clumsy and crude by comparison.

Autonomous Vehicles

Self-driving cars coming sooner than expected

The rise of the automobile transformed modern society. It changed where we live, what we buy, how we work, and who we call friends. As cars and trucks became commonplace, they created whole classes of jobs and made other professions obsolete.

We are now on the cusp of an equally transformative technological shift in transportation: from vehicles driven by humans to vehicles that drive themselves. The long-term impact of autonomous vehicles on society is hard to predict, but also hard to overstate. The only certainty is that wherever this technology becomes ubiquitous, life will be different than it was.

Google and other companies have been testing self-driving cars for several years now, with good success. These autos process vast amounts of sensory data from on-board radars, cameras, ultrasonic range-finders, GPS, and stored maps to navigate routes through ever more complex and rapidly changing traffic situations without any human involvement.

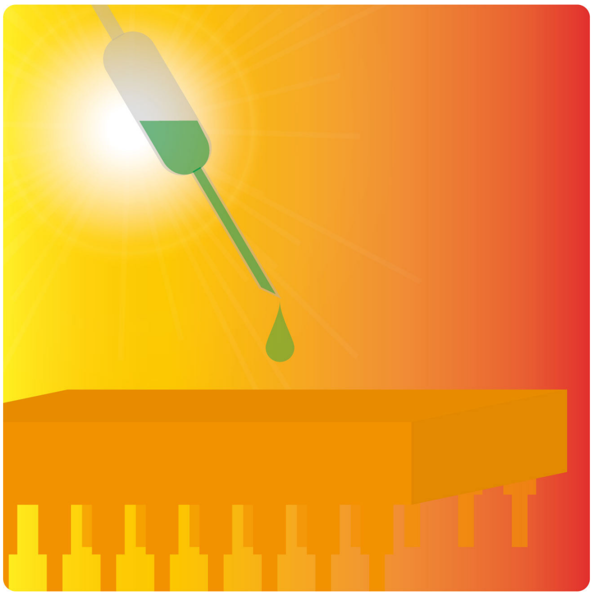
Consumer use of vehicles with autonomous capabilities, however, is just beginning. Adoption will proceed gradually, through the steady implementation of increasingly intelligent safety and convenience features in otherwise ordinary cars. Some models, for example, already offer hands-off parallel parking, automatic lane-keeping, emergency braking, or even semi-autonomous cruise control. Last October, Tesla Motors made available a software package that enables a limited form of self-driving operation for owners of its vehicles to download.

This trend is likely to continue as such technology matures and as legal and regulatory barriers start to fall. A half-dozen states have already authorized autonomous road vehicles, and more have plans to do so. Discussions are well underway among auto insurers and legislators about how to apportion liability and costs when self-driving cars get into crashes, as they inevitably will—although it is widely expected that these cars will prove to be much safer, on average, than driver-operated cars are today.

There is plenty of room for improvement on that front. In the United States, crashes and collisions claim more than 30,000 lives and cause some 2.3 million injuries annually. Self-driving systems may have bugs—the software that runs them is complicated—but they are free from the myriad distractions and risk-taking behaviors that are the most common causes of crashes today. In the near term, semi-autonomous safety systems that engage only to prevent accidents, but that otherwise leave the driver in charge, will also likely reduce the human cost of driving significantly.

Far more profound transformations will follow once cars and trucks can be trusted to pilot themselves routinely—even with no one inside. Exclusive car ownership could then cease to be the necessity of modern living that it is today for so many people. Shared cars and driverless taxi and delivery services could become the norm. This transition might help the aged and infirm—an increasing fraction of the population—to “age in place” more gracefully. Shared programmable vehicles could reduce the need for local parking structures, reduce congestion by preventing accidents and enabling safe travel at higher speeds and closer following distances, and unlock numerous secondary benefits.

Like every technology, autonomous vehicles will involve drawbacks as well. In some distant day, commercial driving may no longer be a sustainable career. Shared vehicles raise some thorny privacy and security concerns. In some regions, increased affordability of car access may greatly exacerbate traffic and pollution problems rather than easing them. But the many benefits of self-driving cars and trucks are so compelling that their widespread adoption is a question of when, not if.



Organs-on-chips

Using chips instead of organs for medical testing purposes

Outside of Hollywood special effects shops, you won't find living human organs floating in biology labs. Set aside all the technical difficulties with sustaining an organ outside the body—full organs are too precious as transplants to use in experiments. But many important biological studies and practical drug tests can be done only by studying an organ as it operates. A new technology could fill this need by growing functional pieces of human organs in miniature, on microchips.

In 2010, Donald Ingber from the Wyss Institute developed a lung-on-a-chip, the first of its kind. The private sector quickly jumped in, with companies such as Emulate, headed by Ingber and others from the Wyss Institute, forming partnerships with researchers in industry and government, including DARPA, the U.S. Defense Advanced Research Projects Agency. So far, various groups have reported success making miniature models of the lung, liver, kidney, heart, bone marrow, and cornea. Others will certainly follow.

Each organ-on-a-chip is roughly the size of a USB memory stick. It is made from a flexible, translucent polymer. Microfluidic tubes, each less than a millimeter in diameter and lined with human cells taken from the organ of interest, run in complex patterns within the chip. When nutrients, blood, and test compounds such as experimental drugs are pumped through the tubes, the cells replicate some of the key functions of a living organ.

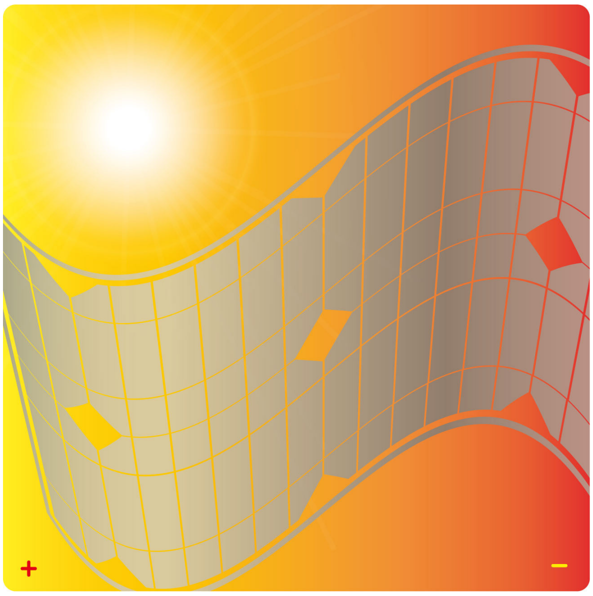
The chambers inside the chip can be arranged to simulate the particular structure of an organ tissue, such as a tiny air sac in a lung. Air running through a channel, for example, can then very accurately simulate human breathing. Meanwhile, blood laced with bacteria can be pumped through other tubes, and scientists can then observe how the cells respond to the infection, all without any risk to a person. The technology allows scientists to see biological mechanisms and physiological behaviors never before seen.

Organ microchips will also give a boost to companies developing new medicines. Their ability to emulate human organs allows for more realistic and accurate tests of drug candidates. Last year, for example, one group used a chip to mimic the way that endocrine cells secrete hormones into the blood stream and used this to perform crucial tests on a diabetes drug.

Other groups are exploring the use of organs-on-chips in personalized medicine. In principle, these microchips could be constructed using stems cells derived from the patients themselves, and then tests could be run to identify individualized therapies that are more likely to succeed.

There is reason to hope that miniature organs could greatly reduce the pharmaceutical industry's reliance on animal testing of experimental compounds. Millions of animals are sacrificed each year to such tests, and the practice provokes heated controversy. Ethical considerations aside, it has proven to be immensely wasteful—animal trials rarely provide reliable insights into how humans will react to the same drug. Tests done on miniaturized human organs might do better.

Military and biodefence researchers see the potential for organs-on-chips to save lives in a different way. The simulated lung, and other devices like it, could be the next big step in testing responses to biological, chemical or radiological weapons. It isn't possible to do this today, for obvious ethical reasons.



Perovskite Solar Cells

Making progress towards ubiquitous solar power generation

The silicon solar cells that currently dominate the world market suffer from three fundamental limitations. A promising new way of making high-efficiency solar cells, using perovskites instead of silicon, could address all three at once and supercharge the production of electricity from sunlight.

The first major limitation of silicon photovoltaic (PV) cells is that they are made from a material that is rarely found in nature in the pure, elemental form needed. While there is no shortage of silicon in the form of silicon dioxide (beach sand), it takes tremendous amounts of energy to get rid of the oxygen attached to it. Typically, manufacturers melt silicon dioxide at 1500–2000 degrees Celsius in an electrode arc furnace. The energy needed to run such furnaces sets a fundamental lower limit on the production cost of silicon PV cells and also adds to the emissions of greenhouse gases from their manufacture.

Perovskites—a wide-ranging class of materials in which organic molecules, made mostly of carbon and hydrogen, bind with a metal such as lead and a halogen such as chlorine in a three-dimensional crystal lattice—can be made much more cheaply and with fewer emissions. Manufacturers can mix up batches of liquid solutions and then deposit the perovskites as thin films on surfaces of virtually any shape, no furnace needed. The film itself weighs very little.

Those features thus eliminate the second big limitation of silicon solar cells, which is their rigidity and weight. Silicon PV cells work best when they are flat and housed in large, heavy panels. But those panels make large-scale installations very expensive, which is in part why you typically see them on rooftops and big solar "farms."

The third major limitation of conventional solar cells is their power conversion efficiency, which has been stuck at 25 percent for 15 years. When they were first described, perovskites offered much lower efficiency. In 2009, perovskite cells made of lead, iodide and methylammonium converted less than 4 percent of the sunlight that hit them into electricity. But the pace of improvement in perovskites has been phenomenal, thanks in part to the fact that thousands of different chemical compositions are possible within this class of material. By 2016, perovskite solar-cell efficiencies were above 20 percent—a five-fold improvement in just seven years and a stunning doubling in efficiency within just the past two years. They are now commercially competitive with silicon PV cells, and the efficiency limits of perovskites could be far higher still. Whereas silicon PV technology is now mature, perovskite PVs continue to improve rapidly.

Researchers still need to answer some important questions about perovskites, such as how durable they will be when exposed to years of weathering and how to industrialize their production to churn out quantities large enough to compete with silicon wafers in the global market. But even a relatively small initial supply of these new cells could be important in bringing solar power to remote locations that are not yet connected to any electrical grid. When paired with emerging battery technology, perovskite solar cells could help transform the lives of 1.2 billion people who currently lack reliable electricity (see "Next Generation Batteries page 7").

Open AI Ecosystem

From artificial to contextual intelligence

One of the advantages that CEOs and celebrities have over ordinary workers is that they don’t need to spend much time handling the uninteresting, time-consuming aspects of daily life: scheduling appointments, making travel plans, searching for the information they want. The elite have PAs, personal assistants who handle such things. But soon—maybe even this year—most of us will be able to afford this luxury for the price of few lattes a month, thanks to the emergence of an open AI ecosystem.

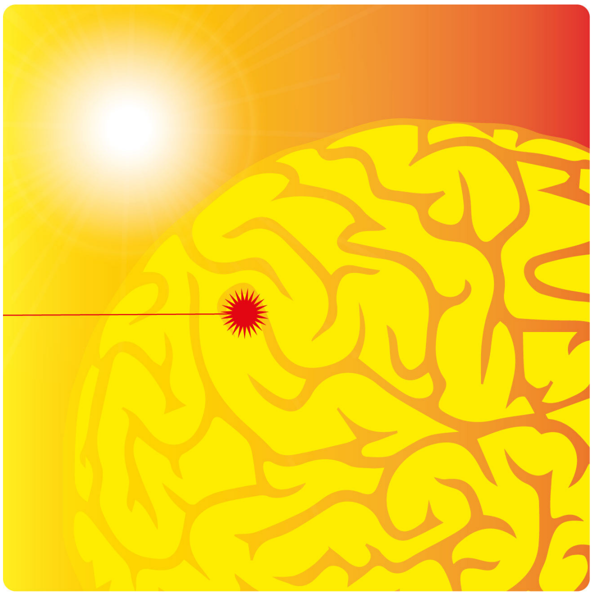
AI here refers, of course, to artificial intelligence. Apple’s Siri, Microsoft’s Cortana, Google’s OK Google, and Amazon’s Echo services are nifty in the way that they extract questions from speech using natural-language processing and then do a limited set of useful things, such as look for a restaurant, get driving directions, find an open slot for a meeting, or run a simple web search. But too often their response to a request for help is “Sorry, I don’t know about that” or “here’s what I found on the web.” You would never confuse these digital assistants for a human PA. Moreover, these systems are proprietary and hard for entrepreneurs to extend with new features.

But over the past several years, several pieces of emerging technology have linked together in ways that make it easier to build far more powerful, human-like digital assistants—that is, into an open AI ecosystem. This ecosystem connects not only to our mobile devices and computers—and through them to our messages, contacts, finances, calendars and work files—but also to the thermostat in the bedroom, the scale in the bathroom, the bracelet on the wrist, even the car in the driveway. The interconnection of the Internet with the Internet of Things and your own personal data, all instantly available almost anywhere via spoken conversations with an AI, could unlock higher productivity and better health and happiness for millions of people within the next few years.

By pooling anonymized health data and providing personalized health advice to individuals, such systems should lead to substantial improvements in health and reductions in the costs of health care. Applications of AI to financial services could reduce unintentional errors, as well as intentional (fraudulent) ones—offering new layers of protection to an aging population.
The secret ingredient in this technology that has been largely lacking to date is context. Up to now, machines have been largely oblivious to the details of our work, our bodies, our lives. A human PA knows when you are interruptible, stressed, bored, tired or hungry. The PA knows who and what is important to you, and also what you would prefer to avoid. AI systems are gaining the ability to acquire and interpret contextual cues so that they can gain these skills as well. Although initially these AI assistants will not outperform the human variety, they will be useful—and roughly a thousand times less expensive.

Various companies have already demonstrated AI systems that have some of these capabilities. Microsoft Research built one that knows when you are too busy to take a call (and which calls should ring through regardless) and that automatically schedules meetings at times you would likely choose yourself. Other companies such as Angel.ai have introduced services that search for flights that suit your preferences and constraints based on simple plain-English requests.

Just as discretion and loyalty are prized among human PAs, digital versions will succeed only to the extent that we trust them with our security and privacy. Vendors will no doubt try to use such systems to influence our purchase choices. We will have to decide when and whether we are comfortable with that.



Optogenetics

Using light to control genetically modified neurons

Brains—even relatively simple ones like those in mice—are daunting in their complexity. Neuroscientists and psychologists can observe how brains respond to various kinds of stimuli, and they have even mapped how genes are expressed throughout the brain. But with no way to control when individual neurons and other kinds of brain cells turn on and off, researchers found it very difficult to explain *how* brains do what they do, at least not in the detail needed to thoroughly understand—and eventually cure—conditions such as Parkinson's disease and major depression.

Scientists tried using electrodes to record neuronal activity, and that works to some extent. But it is a crude and imprecise method because electrodes stimulate every neuron nearby and cannot distinguish among different kinds of brain cells.

A breakthrough came in 2005, when neurogeneticists demonstrated a way to use genetic engineering to make neurons respond to particular colors of light. The technique, known as optogenetics, built on research done in the 1970s on pigment proteins, known collectively as rhodopsins and encoded by the opsin gene family. These proteins work like light-activated ion pumps. Microbes, lacking eyes, use rhodopsins to help extract energy and information from incoming light.

By inserting one or more opsin genes into particular neurons in mice, biologists are now able to use visible light to turn specific neurons on or off at will. Over the years, scientists have tailored versions of these proteins that respond to distinct colors, ranging from deep red to green to yellow to blue. By putting different genes into different cells, they use pulses of light of various colors to activate one neuron and then several of its neighbours in a precisely timed sequence.

That is a crucial advance because in living brains, timing is everything. A signal issued at one moment may have the complete opposite effect from the same signal sent out a few milliseconds later.

The invention of optogenetics greatly accelerated the pace of progress in brain science. But experimenters were limited by the difficulty of delivering light deep into brain tissue. Now ultrathin, flexible microchips, each one hardly bigger than a neuron, are being tested as injectable devices to put nerves under wireless control. They can be inserted deep into a brain with minimal damage to overlying tissue.

Optogenetics has already opened new doors to brain disorders, including tremors in Parkinson's disease, chronic pain, vision damage and depression. The neurochemistry of the brain is clearly important for some brain conditions, which is why drugs can help improve symptoms—up to a point. But where the high-speed electrical circuitry of the brain is also disturbed, optogenetic research, especially when enhanced by emerging wireless microchip technology, could offer new routes to treatment. Recent research suggests, for example, that in some cases non-invasive light therapy that shuts down specific neurons can treat chronic pain, providing a welcome alternative to opoids.

With mental disorders affecting one in four people globally and psychiatric diseases a leading source of disability, the better understanding of the brain that advanced optogenetics will provide cannot come soon enough.

Systems Metabolic Engineering
Chemicals from renewable sources' microorganisms

Trace the products we buy and use every day—from plastics and fabrics to cosmetics and fuels—back to their origins, and you'll find that the vast majority were made using stuff that came from deep underground. The factories that make the products of modern life do so, by and large, out of chemicals of various kinds. And those chemicals come from plants powered primarily by fossil fuels that transform feedstocks—also mainly petrochemicals—into myriad other compounds.

It would be much better for the climate, and possibly better for the global economy as well, to make many of the chemical inputs to industry from living organisms instead of from oil, gas, and coal. We already use agricultural products in this way, of course—we wear cotton clothes and live in wooden houses—but plants are not the only source of ingredients. Microbes arguably offer even more potential, in the long term, to make inexpensive materials in the incredible variety of properties that we now take for granted. Rather than digging the raw materials of modern life from the ground, we can instead "brew" them in giant bioreactors filled with living microorganisms.

For bio-based chemical production to really take off, it must compete with conventional chemical production on both price and performance. This goal now seems within reach, thanks to advances in systems metabolic engineering, a discipline that tweaks the biochemistry of microbes so that more of their energy and resources go into synthesizing useful chemical products. Sometimes the tweaks involve changing the genetic makeup of the organism, and sometimes it involves more complex engineering of microbial metabolism and brewing conditions as a system.

With recent advances in synthetic biology, systems biology, and evolutionary engineering, metabolic engineers are now able to create biological systems that manufacture chemicals that are hard to produce by conventional means (and thus expensive). In one recent successful demonstration, microbes were customized to make PLGA [poly(lactate-co-glycolate)], an implantable, biodegradable polymer used in surgical sutures, implants, and prosthetics, as well as in drug delivery materials for cancer and infections.

Systems metabolic engineering has also been used to create strains of yeast that make opioids for pain treatment. These drugs are widely needed in the world, and in particular in the developing world, where pain is insufficiently managed today.

The range of chemicals that can be made using metabolic engineering is widening every year. Although the technique is not likely to replicate all of the products currently made from petrochemicals, it is likely to yield novel chemicals that could never be made affordably from fossil fuels—in particular, complex organic compounds that currently are very expensive because they must be extracted from plants or animals that make them in only tiny amounts.

Unlike fossil fuels, chemicals made from microbes are indefinitely renewable and emit relatively little greenhouse gas—indeed, some could potentially even serve to reverse the flow of carbon from Earth to atmosphere by absorbing carbon dioxide or methane and incorporating it into products that are eventually buried as solid waste.

As biochemical production scales up to large industrial use, it will be important to avoid both competing with food production for land use and also accidental releases of engineered microorganisms into the environment. Although these highly engineered microbes will likely be at a great disadvantage in the wild, it's best to keep them safely in their tanks, happily working away at making useful stuff for the benefit of humanity and the environment.

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