

Global Agenda

Top 10 Emerging Technologies 2018

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Introduction



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How will technology change your life in the near future? Artificial intelligence (AI) will greatly hasten the design of innovative drugs and materials. Advanced diagnostic tools will enable increasingly personalized medicine. Augmented reality will be everywhere, overlaying information and animation on real-world images to help you with everyday tasks – and to help industry operate more efficiently. If you get sick, doctors will be able to implant living cells in your body that will act like drug factories, treating what ails you. And you will eat beef, chicken and fish grown from stem cells, greatly reducing the environmental impact of animal farming and sparing countless creatures from inhumane treatment. These world-changing ideas, along with others that make up this year's list of Top 10 Emerging Technologies, were selected by leading experts in fields such as biology, inorganic chemistry, robotics and AI. The list is the result of an intensive selection process.

First, we cast a wide net, soliciting recommendations from innovators in the World Economic Forum's Global Future Councils and Expert Network communities, members of Scientific American's advisory board and editorial staff, and others. Then, in a series of virtual meetings, a Steering Group evaluated how well the candidates met several criteria. The technologies had to have the ability to provide significant benefits to societies and economies, and to do so in the next three to five years. They had to be potentially disruptive, able to alter industries or established ways of doing things. And they had to be in relatively early stages of development – not yet in widespread use but being studied by many groups, generating excitement among experts, attracting increasing investment and, ideally, being developed by more than one company. The Steering Group trimmed the initial list of more than 50 submissions in its first meeting and then compiled additional information to assess the roughly 20 candidates that remained. It made its final decisions after gathering more information in two further discussions.

Of course, the benefits of transformative technologies often come with social challenges. The articles that follow delve into these issues as well. We hope you enjoy the report and we welcome your responses.

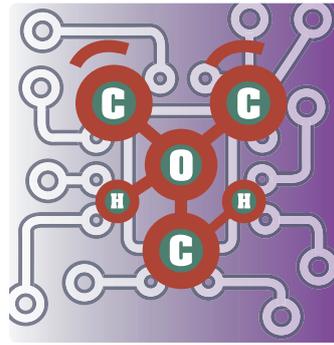
The top 10 emerging technologies for 2018



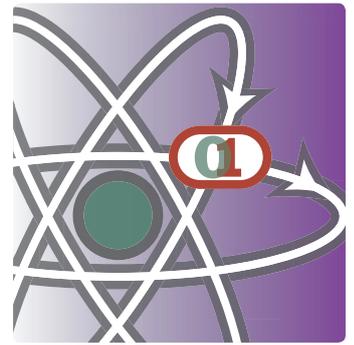
1. Augmented Reality Everywhere



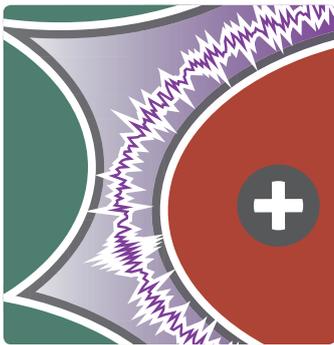
2. Advanced Diagnostics for Personalized Medicine



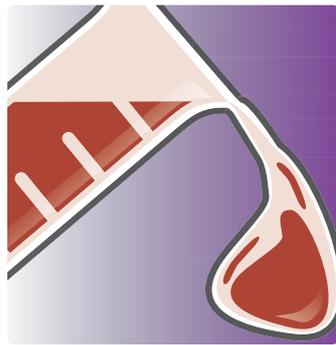
3. AI for Molecular Design



4. AI That Can Argue and Instruct



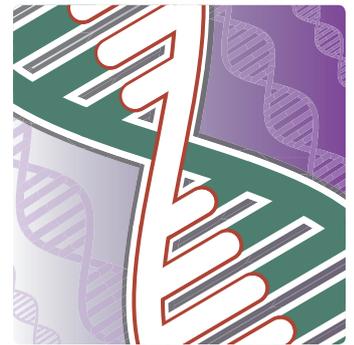
5. Implantable Drug-Making Cells



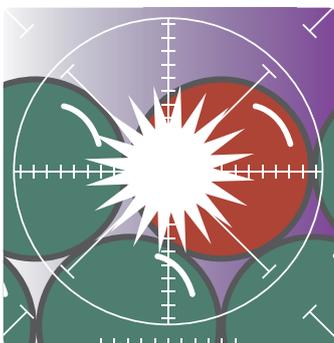
6. Lab-Grown Meat



7. Electroceuticals



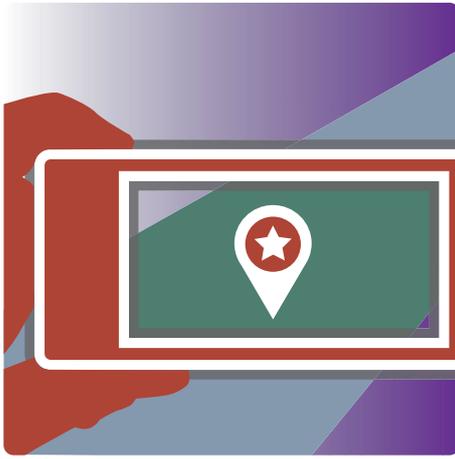
8. Gene Drive



9. Plasmonic Materials



10. Algorithms for Quantum Computers



1. Augmented Reality Everywhere

Coming soon: the world overlaid with data

Virtual reality (VR) immerses you in a fictional, isolated universe. Augmented reality (AR), in contrast, overlays computer-generated information on the real world in real time. As you look at or wear a device equipped with AR software and a camera – be it a smartphone, a tablet, a headset or smart glasses – the program analyses the incoming video stream, downloads extensive information about the scene and superposes on it relevant data, images or animations, often in 3D.

Two examples: the display that helps your car to reverse safely; and the popular game Pokémon GO. A multitude of consumer apps – including apps that translate street signs for foreign visitors, enable students to dissect virtual frogs and allow shoppers to see how a chair will look in their living room before they bring it home – also feature AR. In the future, the technology will enable museum-goers to conjure up guides resembling holograms, surgeons to visualize tissues underneath a patient's skin in 3D, architects and designers to collaborate on their creations in novel ways, drone operators to control their remote robots with enhanced imagery, and novices to speedily learn new tasks in areas ranging from medicine to factory maintenance.

Easy-to-use software for designing apps should expand consumer offerings in the coming years. At the moment, though, AR is having its greatest impact in industry, where it is an integral component of the Fourth Industrial Revolution, or Industry 4.0: the systemic transformation of manufacturing through the integration of physical and digital systems to improve quality, lower costs and increase efficiency. Many companies, for instance, are testing its use on assembly lines. AR can deliver just the right information at the very moment it is needed (such as when a worker has to select one part over another), thereby reducing errors, enhancing efficiency and improving productivity. It can also visualize stresses in equipment and create real-time images of where problems lie.

Market analysts, such as ABI Research, IDC and Digi-Capital, believe that AR is on the cusp of going mainstream. They expect the total market for AR, currently valued at about \$1.5 billion, to grow to \$100 billion by 2020. Major technology companies – including Apple, Google and Microsoft – are devoting large financial and human resources to both AR and VR products and applications. And venture capital is starting to roll in, with \$3 billion invested in AR and VR in 2017; half of that amount in the fourth quarter alone. Harvard Business Review recently highlighted AR as a transformative technology that will affect all businesses.

Obstacles persist. At the moment, limitations of hardware and communication bandwidth pose barriers to scaling up for everyday use by consumers. For example, many existing museum and travel apps that use AR to enhance an experience have to be downloaded in advance. Even then, the quality of the graphics may not meet users' expectations. However, the field is set to grow dramatically as cheaper, faster AR-ready mobile chips become available, more versatile smart glasses come to market and bandwidth increases. Then AR will join the internet and real-time video as an unexceptional part of our everyday lives.



2. Advanced Diagnostics for Personalized Medicine

A new generation of tools could help end one-size-fits-all therapeutics

For most of the 20th century, all women with breast cancer received similar treatment. Therapy has since become more individualized: breast cancers are now divided into subtypes and treated accordingly. Many women whose tumours produce oestrogen receptors, for instance, may receive drugs that specifically target those receptors, along with standard post-surgery chemotherapy. In 2018, researchers took a step closer to even more personalized treatment. They identified a significant fraction of patients whose tumours possess characteristics that indicate they can safely forgo chemo – and avoid its often serious side effects.

This march toward personalized, or precision, medicine for many disorders is being hastened by advances in diagnostic tools. These technologies can help physicians detect and quantify multiple biomarkers (molecules that signal the presence of a disorder) to divide patients into subgroups that differ in their susceptibility to a disease, prognosis or likelihood of responding to a specific treatment.

Early molecular diagnostic tools looked at single molecules – in the case of diabetes, for example, glucose. In the past decade, however, “omics” technology has progressed tremendously in the ability to quickly, reliably and cheaply sequence an individual’s entire genome or to measure levels of all the proteins (the proteome), metabolic by-products (the metabolome), or microbes (the microbiome) in a bodily fluid or tissue sample. Routine use of the technology has simultaneously begun to generate huge data sets that AI can mine to discover new biomarkers useful for the clinic. This combination of high-throughput omics technology and AI is ushering in a new era of advanced diagnostics that will transform the understanding and treatment of many diseases, allowing doctors to tailor therapies to the molecular profiles of individual patients.

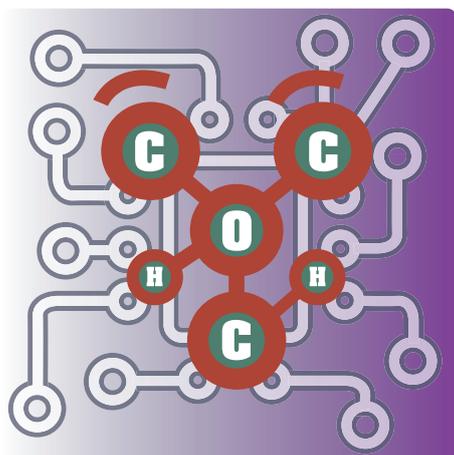
Several advanced diagnostics are already in use for cancer. One, called Oncotype DX, examines 21 genes; it is the test that revealed that many women with breast cancer can

avoid chemo. Another, called the FoundationOne CDx test, detects genetic mutations in more than 300 genes in solid tumours and indicates specific gene-targeting drugs that might be useful for a given patient.

Outside of cancer, one exciting tool applies to endometriosis, a frequently painful condition in which uterine tissue grows where it does not belong. Making the diagnosis typically involves surgery. A new, non-invasive saliva-based test from DotLabs can identify endometriosis by measuring a panel of small molecules known as microRNAs. And blood tests are being developed to help identify brain disorders – such as autism, Parkinson’s and Alzheimer’s – that are currently diagnosed via clinicians’ subjective assessments of symptoms. Investigators are even exploring whether sequencing whole genomes, analysing microbiomes and measuring levels of hundreds of proteins and metabolites in healthy people can yield personalized guidance on how those individuals might prevent disease.

A word of caution: medical facilities and researchers using such intimate diagnostic tools must rigorously enforce safeguards for protecting patient privacy. Further, clear regulatory guidelines are needed for assessing the value of a biomarker as a diagnostic tool in a consistent way. Such guidelines will speed the introduction of new biomarkers into medical practice.

Even so, advanced diagnostics are beginning to dissolve the standard approach to diagnosing and treating disease. By steering patients toward the most effective treatments, they may even reduce healthcare spending. One day many of us may possess a personal cloud of biomarker data that will accumulate over time and inform our treatment no matter where we seek care.



3. AI for Molecular Design

Machine-learning algorithms are speeding up the search for novel drugs and materials

Want to design a new material for solar energy, a drug to fight cancer or a compound that stops a virus from attacking a crop? First, you must tackle two challenges: finding the right chemical structure for the substance; and determining which chemical reactions will link up the right atoms into the desired molecules or combinations of molecules.

Traditionally, answers have come from sophisticated guesswork aided by serendipity. The process is extremely time-consuming and involves many failed attempts. A synthesis plan, for instance, can have hundreds of individual steps, many of which will produce undesired side reactions or by-products or simply not work at all. Now, though, AI is starting to increase the efficiency of both design and synthesis, making the enterprise faster, easier and cheaper while reducing chemical waste.

In AI, machine-learning algorithms analyse all known past experiments that have attempted to discover and synthesize the substances of interest – those that worked and, importantly, those that failed. Based on the patterns they discern, the algorithms predict the structures of potentially useful new molecules and possible ways of manufacturing them. No single machine-learning tool can do all this at the push of a button, but AI technologies are moving rapidly into the real-world design of drug molecules and materials.

An AI tool developed by researchers at the University of Münster in Germany, for example, repeatedly simulates the 12.4 million known single-step chemical reactions to come up with a multistep synthetic route – planning it 30 times faster than humans do.

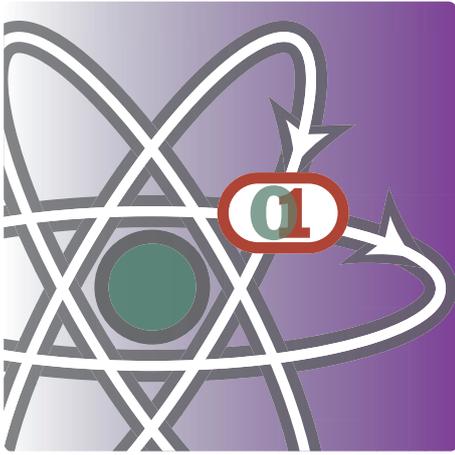
In the pharmaceutical arena, an AI-based technology called generative machine learning is also exciting. Most pharmaceutical companies store millions of compounds and screen them for the potential to serve as new drugs. But even with robotics and lab-automation tools, this screening process is slow and yields relatively few hits. Further, the “libraries” collectively include only a tiny fraction of the

more than 1030 theoretically possible molecules. Using a data set describing the chemical structures of known drugs (and drug candidates), as well as their properties, machine-learning tools can construct virtual libraries of new compounds that have similar, and potentially more useful, characteristics. This capability is starting to dramatically accelerate the identification of drug leads.

Close to 100 start-ups are already exploring AI for drug discovery. Among them are Insilico Medicine, Kebotix and BenevolentAI; the last recently raised \$115 million to extend its AI technology to the discovery of drugs for motor neuron disease, Parkinson’s and other hard-to-treat disorders. BenevolentAI is applying AI to the entire drug development process, from the discovery of new molecules to the design and analysis of clinical trials meant to demonstrate safety and effectiveness in humans.

In the field of materials, ventures such as Citrine Informatics are using approaches similar to those of pharmaceutical makers and are partnering with large companies, including BASF and Panasonic, to speed innovation. The US government is also supporting research into AI-enabled design. Since 2011 it has invested more than \$250 million in the Materials Genome Initiative, which is establishing an infrastructure that includes AI and other computing approaches to accelerate the development of advanced materials.

Past experience teaches that new materials and chemicals can pose unforeseen risks to health and safety. Fortunately, AI approaches should be able to anticipate and reduce these undesirable outcomes. The technologies seem poised to markedly increase the speed and efficacy with which novel molecules and materials are discovered and brought to the market where they may provide such benefits as improved healthcare and agriculture, greater conservation of resources, and enhanced production and storage of renewable energy.



4. AI That Can Argue and Instruct

New algorithms will enable personal devices to learn any topic well enough to debate it

Today's digital assistants can sometimes fool you into believing they are human, but vastly more capable digital helpers are on their way. Behind the scenes, Siri, Alexa and their ilk use sophisticated speech-recognition software to figure out what you are requesting and how to provide it, and they generate natural-sounding speech to deliver scripted answers matched to your questions. Such systems must first be "trained" – exposed to many, many examples of the kinds of requests humans are likely to make – and the appropriate responses must be written by humans and organized into highly structured data formats.

That work is time-consuming and results in digital assistants that are restricted in the tasks they can perform. The systems can "learn" – their machine-learning capabilities allow them to improve their matching of incoming questions to existing answers – but only to a limited extent. Even so, they are extremely impressive.

At a higher level of sophistication, technologies are now being developed to allow the next generation of such systems to absorb and organize unstructured data (raw text, video, pictures, audio, emails and so on) from myriad sources and then autonomously compose cogent advice – or debate an opponent – on a subject they have never been trained to handle.

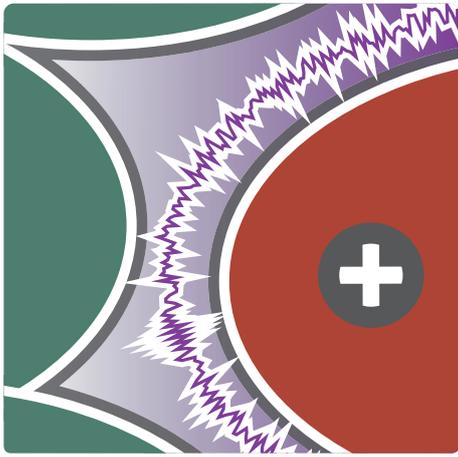
We have seen glimpses of this capability at websites offering chatbots that, out of the box, can answer natural-language questions covering a wide variety of data sets they have trained on. Such chatbots need relatively little or no training on specific questions or requests; they use a combination of preconfigured data and the emergent ability to "read" relevant background materials supplied to them. They do, however, require some training in recognizing words and intentions before they can give highly accurate responses.

In June, my employer, IBM, demonstrated a more advanced version of the technology: a system carried on a debate with a human expert in real time without having prior

training on the topic or the position to be argued. Using unstructured data (including, content from Wikipedia, some of which was edited for clarity), the system had to ascertain the relevance and veracity of the information and organize it into a reusable asset that it could call on to form coherent arguments supporting the position it had been assigned. It also had to respond to the arguments of its human opponent. The system engaged in two debates during the demonstration and was judged more persuasive in one of the two by a large group of spectators.

The enabling technology – which included software that could not only understand natural language but also handle the harder challenge of detecting positive and negative sentiment – was developed over more than five years and is still very much a work in progress. Nevertheless, the win by an unscripted AI system against an acknowledged human expert opens the door for countless related applications that could appear in the next three to five years, if not sooner. Such systems could, for instance, help physicians to quickly find research relevant to a complex case and then debate the merits of a given treatment protocol.

These intelligent systems will be useful only for assembling existing knowledge, not for creating it the way a bench scientist or an expert would. Still, as machines become increasingly intelligent, they raise the spectre of job losses. It behoves society to provide the next generation with the skills it needs to tackle problems that require human ingenuity to solve.



5. Implantable Drug-Making Cells

Releasing drugs directly into patients' bodies as they are needed is fast becoming feasible

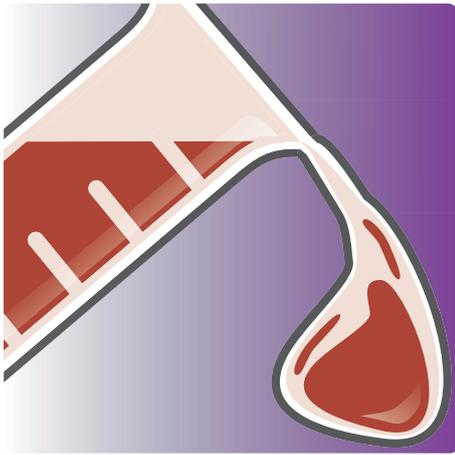
Many people with diabetes prick their fingers several times a day to measure blood sugar levels and decide on the insulin doses they need. Implants of pancreatic cells that normally make insulin in the body – so-called islet cells – can render this cumbersome process unnecessary. Likewise, cellular implants could transform treatment of other disorders, including cancer, heart failure, haemophilia, glaucoma and Parkinson's disease. But cellular implants have a major drawback: recipients must take immunosuppressants indefinitely to prevent rejection by the immune system. Such drugs can lead to serious side effects, including an increased risk of infection or malignancies.

Over several decades scientists have invented ways to enclose cells in semipermeable protective membranes that keep the immune system from attacking the implanted cells. These capsules still allow nutrients and other small molecules to flow in and needed hormones or other therapeutic proteins to flow out. Yet keeping the cells out of harm's way is not enough: if the immune system views the protective material itself as foreign, it will cause scar tissue to grow over the capsules. This "fibrosis" will prevent nutrients from reaching the cells, thereby killing them.

Now investigators are beginning to solve the fibrosis challenge. For instance, in 2016 a team at the Massachusetts Institute of Technology (MIT) published a way to make implants invisible to the immune system. After producing and screening hundreds of materials, the researchers settled on a chemically altered version of a gel called alginate, which has a long history of safe use in the body. When they implanted islet cells encapsulated in this gel into diabetic mice, the cells immediately produced insulin in response to changing blood sugar levels – keeping them under control over the course of a six-month study. No fibrosis was observed. In separate work, the team later reported that blocking a particular molecule (the colony-stimulating factor 1 receptor) on macrophages, which are immune cells important in fibrosis, can inhibit scarring. Adding such a blocker should further enhance the survival of implants.

Several companies have formed to develop encapsulated-cell therapies. One of these, Sigilon Therapeutics, is advancing the technology developed at MIT to design treatments for diabetes, haemophilia and a metabolic disorder called lysosomal storage disease. Pharmaceutical company Eli Lilly is partnering with Sigilon on the diabetes work. In other examples, Semma Therapeutics is also focusing on diabetes, using its own technology; Neurotech Pharmaceuticals has implants in clinical trials for glaucoma and various eye disorders marked by degeneration of the retina; and Living Cell Technologies is running clinical trials of implants for Parkinson's and is developing therapies for other neurodegenerative conditions.

Today the cells being incorporated into capsules are drawn from animals or human cadavers or are derived from human stem cells. One day, implantable cell therapies may include a broader array of cell types, including some engineered through synthetic biology, which reprogrammes a cell's genetics to make it perform novel functions, such as controlled, on-demand release of specified drug molecules into a tissue. These are still early days. Neither the safety nor the efficacy of encapsulated cell therapy has been proved in large clinical trials, but the signs are encouraging.



6. Lab-Grown Meat

Meat produced without killing animals is heading to your dinner table

Imagine biting into a juicy beef burger that was produced without killing animals. Meat grown in a laboratory from cultured cells is turning that vision into a reality. Several start-ups are developing lab-grown beef, pork, poultry and seafood – among them Mosa Meat, Memphis Meats, SuperMeat and Finless Foods. And the field is attracting millions in funding. In 2017, for instance, Memphis Meats took in \$17 million from sources that included Bill Gates and agricultural company Cargill.

If widely adopted, lab-grown meat, also called “clean” meat, could eliminate much of the cruel, unethical treatment of animals that are raised for food. It could also reduce the considerable environmental costs of meat production; resources would be needed only to generate and sustain cultured cells, not an entire organism from birth.

The meat is made by first taking a muscle sample from an animal. Technicians collect stem cells from the tissue, multiply them dramatically and allow them to differentiate into primitive fibres that then bulk up to form muscle tissue. Mosa Meat says that one tissue sample from a cow can yield enough muscle tissue to make 80,000 quarter-pounders.

A number of the start-ups say they expect to have products for sale within the next few years. However, clean meat will have to overcome a number of barriers if it is to be commercially viable, such as cost and taste. In 2013, when a burger made from lab-grown meat was presented to journalists, the patty cost more than \$300,000 to produce and was overly dry (from too little fat). Expenses have since fallen; Memphis Meats reported this year that a quarter-pound of its ground beef costs about \$600. Given this trend, clean meat could become competitive with traditional meat within several years. Careful attention to texture and judicious supplementing with other ingredients could address taste concerns.

To receive market approval, clean meat will have to be proved safe to eat. Although there is no reason to think that lab-produced meat would pose a health hazard, the US Food and Drug Administration (FDA) is only now beginning to consider how it should be regulated. Meanwhile, traditional meat producers are pushing back, arguing that the lab-generated products are not meat at all and should not be labelled as such. And surveys show that the public has only tepid interest in eating meat from labs. Despite these challenges, the clean meat companies are forging ahead. If they can succeed in creating authentic-tasting products that are also affordable, clean meat could make our daily eating habits more ethical and environmentally sustainable.



7. Electroceuticals

Nerve-stimulating therapies could soon replace drugs for many chronic conditions

Electroceuticals – devices that treat ailments with electrical impulses – have a long history in medicine. Think of pacemakers for the heart, cochlear implants for the ears and deep-brain stimulation for Parkinson’s disease. One of these approaches is poised to become more versatile, dramatically improving care for a host of conditions. It involves delivering signals to the vagus nerve, which sends impulses from the brain stem to most organs and back again.

New uses of vagal nerve stimulation (VNS) have become possible in part because of research by Kevin Tracey of the Feinstein Institute for Medical Research and others showing that the vagus nerve emits chemicals that help to regulate the immune system. The release of a specific neurotransmitter in the spleen, for instance, quiets immune cells involved in inflammation throughout the body. These findings indicated that VNS might be beneficial for disorders beyond those marked by disturbed electrical signalling, such as autoimmune and inflammatory conditions. It could be a boon for patients with those conditions because existing drugs often fail or cause serious side effects. VNS may be easier to tolerate because it acts on a specific nerve, whereas drugs generally travel throughout the body, potentially disrupting tissues beyond those targeted for treatment.

So far, studies of inflammation-related applications are encouraging. VNS devices developed by SetPoint Medical (co-founded by Tracey) have proved safe in early human trials for rheumatoid arthritis, which causes painful, disfiguring inflammation of joints, and for Crohn’s disease, which involves inflammation of the intestines. Additional trials for both are currently under way. The electroceutical approach is also being considered for other maladies that have an inflammatory component, such as cardiovascular disease, metabolic dysregulation and dementia, as well as for autoimmune disorders such as lupus, in which the vagal nerve itself becomes underactive. Preventing immune rejection of transplanted tissues is yet another potential application.

Most vagal nerve stimulators, including SetPoint’s devices and those already in use for treating epilepsy and depression, are implants. Physicians usually place the device under the skin below the clavicle. Wires from the implant wrap around one branch of the vagus nerve and deliver electrical impulses to it at pre-set intervals; the frequency and other properties are programmed via an external magnetic wand. Today’s implants measure about an inch and a half in diameter but are expected to become smaller and more finely programmable over time.

Non-invasive, handheld vagal nerve stimulators meant to ease cluster headaches and migraine have recently also gained FDA approval, although exactly how vagal nerve stimulation helps those conditions is unclear. The handheld devices deliver mild electrical stimulation to the nerve through skin on the neck or through the ear.

The vagus nerve is not the only one to be targeted by new electroceutical approaches. In late 2017, the FDA approved a non-implanted device that eases opioid withdrawal by sending signals to branches of the cranial and occipital nerves through skin behind the ear. The device gained the FDA’s nod after 73 patients suffering from opioid withdrawal saw a 31% or higher reduction in symptom severity.

The cost of implants and surgery could hamper widespread adoption of VNS therapy, although that problem should ease as the technology becomes less invasive. But cost is not the only challenge. Researchers still need to know more about how VNS produces its effects in each condition and how best to determine the optimal patterns of stimulation for individual patients. It is also possible that impulses targeted at the vagus nerve may affect surrounding nerves in undesirable ways.

Nevertheless, as more studies and trials examine the mechanisms and effects, VNS and other electroceuticals may ultimately be able to better manage a wide range of chronic conditions, potentially reducing the need to take medicine for millions of patients.



8. Gene Drive

A genetic tool that can alter – and potentially eliminate – entire species has taken a dramatic leap forward

Research into a genetic engineering technology that can permanently change the traits of a population or even an entire species is progressing rapidly. The approach uses gene drives, genetic elements that pass from parents to unusually high numbers of their offspring, thereby spreading through populations rather quickly. Gene drives occur naturally but can also be engineered and doing so could be a boon to humanity in many ways. The technology has the potential to stop insects from transmitting malaria and other terrible infections, enhance crop yields by altering pests that attack plants, render corals resistant to environmental stress, and keep invasive plants and animals from destroying ecosystems. Yet investigators are deeply aware that altering or even eliminating a species could have profound consequences. In response, they are developing rules to govern the transfer of gene drives from the laboratory into future field tests and wider use.

Investigators have been considering ways to exploit gene drive to fight diseases and other problems for decades. The effort got a boost in recent years from the introduction of CRISPR gene editing, which makes it easy to insert genetic material into specific spots on chromosomes. In 2015, several papers reported the successful spread of CRISPR-based gene drives in yeast, fruit flies and mosquitoes. One demonstration drove genes for resistance to the malaria parasite through a mosquito population, which, in theory, should limit the parasite's transmission. Another study interfered with female fertility in a different mosquito species.

In 2018, a CRISPR gene-drive system was tested in mice by attempting to manipulate coat colour. The procedure worked only in females. Even so, the results support the possibility that the technology could help eliminate or alter invasive mice or other mammalian populations that threaten crops or wildlife or transmit disease.

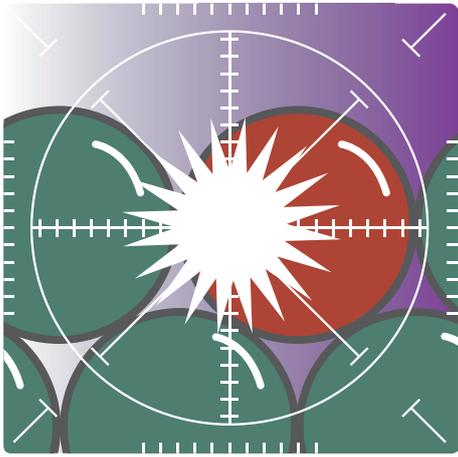
The Defense Advanced Research Projects Agency (DARPA) is among the investors who are enthusiastic about the technology. It has poured \$100 million into gene-drive research aimed at fighting mosquito-borne disease and

invasive rodents. The Bill & Melinda Gates Foundation has invested \$75 million in a research consortium working on gene drive to combat malaria.

Despite all the promise, gene drives raise many concerns. Might they inadvertently jump to, and disrupt, other species in the wild? What are the risks of eliminating selected species from an ecosystem? Could malevolent parties use gene drives as a weapon to, say, interfere with agriculture?

In an effort to avoid such dire prospects, one team has invented a switch that must be turned on by delivery of a particular substance before the gene drive will work. In parallel, multiple groups of scientists are working on protocols to guide progression through each stage of gene-drive testing. In 2016, for instance, the US National Academies of Sciences, Engineering, and Medicine reviewed the research and made recommendations for responsible practices. And in 2018, a large, international working group laid out a road map for handling research from lab studies through releases in the field. The group (some of whose meetings were attended by observers from DARPA, the Gates Foundation or other agencies) modelled its recommendations on gene drive's use to control malaria in Africa, where, it says, the public health benefit would probably be greatest.

Beyond limiting the risks of the technology itself, many investigators also want to avoid incidents and missteps that could lead to public or policy backlash. In a 2017 essay about the potential use of gene drive for eliminating pest mammals, Kevin M. Esvelt of the MIT and Neil J. Gemmill of the University of Otago in New Zealand fretted that an international incident could set back research by a decade or more. "For malaria alone," they predicted, "the cost of that delay could be measured in millions of otherwise preventable deaths."



9. Plasmonic Materials

Light-controlled nanomaterials are revolutionizing sensor technology

Writing in *Scientific American* in 2007, Harry A. Atwater of the California Institute of Technology predicted that a technology he called “plasmonics” could eventually lead to an array of applications, from highly sensitive biological detectors to invisibility cloaks. A decade later various plasmonic technologies are already a commercial reality and others are transitioning from the laboratory to the market.

These technologies all rely on controlling the interaction between an electromagnetic field and the free electrons in a metal (typically gold or silver) that account for the metal’s conductivity and optical properties. Free electrons on a metal’s surface oscillate collectively when hit by light, forming what is known as surface plasmon. When a piece of metal is large, the free electrons reflect the light that hits them, giving the material its shine. But when a metal measures just a few nanometres, its free electrons are confined in a very small space, limiting the frequency at which they can vibrate. The specific frequency of the oscillation depends on the size of the metal nanoparticle. In a phenomenon called resonance, the plasmon absorbs only the fraction of incoming light that oscillates at the same frequency as the plasmon itself (reflecting the rest of the light). This surface plasmon resonance can be exploited to create nanoantennas, efficient solar cells and other useful devices.

One of the best studied applications of plasmonic materials is sensors for detecting chemical and biological agents. In one approach, researchers coat a plasmonic nanomaterial with a substance that binds to a molecule of interest – say, a bacterial toxin. In the absence of the toxin, light shining on the material is re-emitted at a specific angle. But if the toxin is present, it will alter the frequency of the surface plasmon and, consequently, the angle of the reflected light. This effect can be measured with great accuracy, enabling even trace amounts of the toxin to be detected and measured. Several start-ups are developing products based on this and related approaches, among them an internal sensor for batteries that allows their activity to be monitored to assist in increasing power density and charge rate and a device that

can distinguish viral from bacterial infections. Plasmonics is also working its way into magnetic memory storage on disks. For instance, heat-assisted magnetic recording devices increase memory storage by momentarily heating tiny spots on a disk during writing.

In the medical field, light-activated nanoparticles are being tested in clinical trials for their ability to treat cancer. Nanoparticles are infused into the blood, after which they concentrate inside a tumour. Then light of the same frequency as the surface plasmon is shone into the mass, causing the particles to heat by resonance. The heat selectively kills the cancer cells in the tumour without hurting surrounding healthy tissue.

As new companies emerge to take advantage of plasmonics, they will need to ensure that their products are reasonably priced, reliable, robust and easy to fabricate at scale and integrate with other components. Despite these challenges, the prospects look bright. The advent of metamaterials – synthetic nanoscale materials in which plasmons generate unusual optical effects – has enabled plasmonics researchers to use materials other than gold and silver, such as graphene and semiconductors. An analysis from Future Market Insights predicts that the value of the North American market for plasmonic sensor applications alone will grow from nearly \$250 million in 2017 to nearly \$470 million by 2027.



10. Algorithms for Quantum Computers

Developers are perfecting programs meant to run on quantum computers

Within a few years, quantum computers could catch up to or even outperform classical computers thanks to significant work on hardware and the algorithms to run on it.

Quantum computers exploit quantum mechanics to perform calculations. Their basic unit of computation, the qubit, is analogous to the standard bit (zero or one), but it is in a quantum superposition between two computational quantum states: it can be a zero and a one at the same time. That property, along with another uniquely quantum feature known as entanglement, can enable quantum computers to resolve certain classes of problems more efficiently than any conventional computer.

This technology, while exciting, is notoriously finicky. A process called decoherence, for example, can disrupt its function. Investigators have determined that stringently controlled quantum computers that have a few thousand qubits could be made to withstand decoherence through a technique known as quantum-error correction. But the largest quantum computers that laboratories have demonstrated so far – the most notable examples are from IBM, Google, Rigetti Computing and IonQ – contain just tens of quantum bits. These versions, which John Preskill of the California Institute of Technology named noisy intermediate-scale quantum (NISQ) computers, cannot perform error correction yet. Nevertheless, a burst of research on algorithms written specifically for NISQs might enable these devices to perform certain calculations more efficiently than classic computers.

Increased access to NISQ machines for users around the world has contributed greatly to this progress, enabling a growing number of academic researchers to develop and test small-scale versions of programs for the machines. An ecosystem of start-up companies focused on different aspects of quantum software is blossoming as well.

Researchers see particular promise in two kinds of algorithms for NISQs: those for simulation and for machine learning. In 1982, the legendary theoretical physicist

Richard Feynman suggested that one of the most powerful applications of quantum computers would be simulating nature itself: atoms, molecules and materials. Many researchers, myself included, have developed algorithms to simulate molecules and materials on NISQ devices (as well as on the fully error-corrected quantum computers of the future). These algorithms could enhance the design of new materials for use in areas from energy to health science.

Developers are also assessing whether quantum computers would be superior at machine-learning tasks, in which computers learn from large data sets or experience. Tests of a rapidly growing set of algorithms for NISQ devices have shown that quantum computers can indeed facilitate such machine-learning tasks as classifying information by categories, clustering similar items or features together, and generating new statistical samples from existing ones – for instance, predicting molecular structures likely to display a desired mix of properties. At least three research groups have independently reported progress in developing quantum versions of a machine-learning approach known as generative adversarial networks (GANs), which has taken the machine-learning field by storm in the past several years.

Although a number of algorithms do seem to work well on existing NISQ machines, no one has yet produced formal proofs that they are more powerful than those that can be performed on conventional computers. These proofs are difficult and can take years to complete.

In the next few years, researchers most likely will develop larger and more controllable NISQ devices, followed by fully error-corrected machines with thousands of physical qubits. Those of us working on algorithms are optimistic that algorithms for NISQ will be effective enough to achieve an advantage over state-of-the-art conventional computers, although we might have to wait until fully error-corrected machines are available.

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