Grand Challenges for engineering

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With input from people around the world an international group of leading technological thinkers were asked to identify the Grand Challenges for Engineering in the 21st Century.

From urban centers to remote corners of Earth, the depths of the oceans to space, humanity has always sought to transcend barriers, overcome challenges, and create opportunities that improve life in our part of the universe.

In the last century alone, many great engineering achievements became so commonplace that we now take them mostly for granted. Technology allows an abundant supply of food and safe drinking water for much of the world. We rely on electricity for many of our daily activities. We can travel the globe with relative ease, and bring goods and services wherever they are needed. Growing computer and communications technologies are opening up vast stores of knowledge and entertainment. As remarkable as these engineering achievements are, certainly just as many more great challenges and opportunities remain to be realized. While some seem clear, many others are indistinct and many more surely lie beyond most of our imaginations.

Today, we begin engineering a path to the future.

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1. Make Solar Energy Economical

As a source of energy, nothing matches the sun. It out-powers anything that human technology could ever produce. Only a small fraction of the sun’s power output strikes the Earth, but even that provides 10,000 times as much as all the commercial energy that humans use on the planet.

1.1 Why is solar energy important?

Already, the sun’s contribution to human energy needs is substantial — worldwide, solar electricity generation is a growing, multibillion dollar industry. But solar’s share of the total energy market remains rather small, well below 1 percent of total energy consumption, compared with roughly 85 percent from oil, natural gas, and coal.

Those fossil fuels cannot remain the dominant sources of energy forever. Whatever the precise timetable for their depletion, oil and gas supplies will not keep up with growing energy demands. Coal is available in abundance, but its use exacerbates air and water pollution problems, and coal contributes even more substantially than the other fossil fuels to the buildup of carbon dioxide in the atmosphere.

For a long-term, sustainable energy source, solar power offers an attractive alternative. Its availability far exceeds any conceivable future energy demands. It is environmentally clean, and its energy is transmitted from the sun to the Earth free of charge. But exploiting the sun’s power is not without challenges. Overcoming the barriers to widespread solar power generation will require engineering innovations in several arenas — for capturing the sun’s energy, converting it to useful forms, and storing it for use when the sun itself is obscured.

Many of the technologies to address these issues are already in hand. Dishes can concentrate the sun’s rays to heat fluids that drive engines and produce power, a possible approach to solar electricity generation. Another popular avenue is direct production of electric current from captured sunlight, which has long been possible with solar photovoltaic cells.

1.2 How efficient is solar energy technology?

But today’s commercial solar cells, most often made from silicon, typically convert sunlight into electricity with an efficiency of only 10 percent to 20 percent, although some test cells do a little better. Given their manufacturing costs, modules of today’s cells incorporated in the power grid would produce electricity at a cost roughly 3 to 6 times higher than current prices, or 18-30 cents per kilowatt hour [Solar Energy Technologies Program]. To make solar economically competitive, engineers must find ways to improve the efficiency of the cells and to lower their manufacturing costs.

Prospects for improving solar efficiency are promising. Current standard cells have a theoretical maximum efficiency of 31 percent because of the electronic properties of the silicon material. But new materials, arranged in novel ways, can evade that limit, with some multilayer cells reaching 34 percent efficiency.

Experimental cells have exceeded 40 percent efficiency.

Another idea for enhancing efficiency involves developments in nanotechnology, the engineering of structures on sizes comparable to those of atoms and molecules, measured in nanometers (one nanometer is a billionth of a meter).

Recent experiments have reported intriguing advances in the use of nanocrystals made from the elements lead and selenium. [Schaller et al.] In standard cells, the impact of a particle of light (a photon) releases an electron to carry electric charge, but it also produces some useless excess heat. Lead-selenium nanocrystals enhance the chance of releasing a second electron rather than the heat, boosting the electric current output. Other experiments suggest this phenomenon can occur in silicon as well. [Beard et al.]

Theoretically the nanocrystal approach could reach efficiencies of 60 percent or higher, though it may be smaller in practice. Engineering advances will be required to find ways of integrating such nanocrystal cells into a system that can transmit the energy into a circuit.

1.3 How do you make solar energy more economical?

Other new materials for solar cells may help reduce fabrication costs. “This area is where breakthroughs in the science and technology of solar cell materials can give the greatest impact on the cost and widespread implementation of solar electricity,” Caltech chemist Nathan Lewis writes in *Science*. [Lewis 799]

A key issue is material purity. Current solar cell designs require high-purity, and therefore expensive, materials, because impurities block the flow of electric charge. That problem would be diminished if charges had to travel only a short distance, through a thin layer of material. But thin layers would not absorb as much sunlight to begin with.

One way around that dilemma would be to use materials thick in one dimension, for absorbing sunlight, and thin in another direction, through which charges could travel. One such strategy envisions cells made with tiny cylinders, or nanorods. Light could be absorbed down the length of the rods, while charges could travel across the rods' narrow width. Another approach involves a combination of dye molecules to absorb sunlight with titanium dioxide molecules to collect electric charges. But large improvements in efficiency will be needed to make such systems competitive.

How do you store solar energy?

However advanced solar cells become at generating electricity cheaply and efficiently, a major barrier to widespread use of the sun's energy remains: the need for storage. Cloudy weather and nighttime darkness interrupt solar energy's availability. At times and locations where sunlight is plentiful, its energy must be captured and stored for use at other times and places.

Many technologies offer mass-storage opportunities. Pumping water (for recovery as hydroelectric power) or large banks of batteries are proven methods of energy storage, but they face serious problems when scaled up to power-grid proportions. New materials could greatly enhance the effectiveness of capacitors, superconducting magnets, or flyweels, all of which could provide convenient power storage in many applications. [Ranjan et al., 2007]

Another possible solution to the storage problem would mimic the biological capture of sunshine by photosynthesis in plants, which stores the sun’s energy in the chemical bonds of molecules that can be used as food. The plant’s way of using sunlight to produce food could be duplicated by people to produce fuel.

For example, sunlight could power the electrolysis of water, generating hydrogen as a fuel. Hydrogen could then power fuel cells, electricity-generating devices that produce virtually no polluting byproducts, as the hydrogen combines with oxygen to produce water again. But splitting water efficiently will require advances in chemical reaction efficiencies, perhaps through engineering new catalysts. Nature’s catalysts, enzymes, can produce hydrogen from water with a much higher efficiency than current industrial catalysts. Developing catalysts that can match those found in living cells would dramatically enhance the attractiveness of a solar production-fuel cell storage system for a solar energy economy.

Fuel cells have other advantages. They could be distributed widely, avoiding the vulnerabilities of centralized power generation.

If the engineering challenges can be met for improving solar cells, reducing their costs, and providing efficient ways to use their electricity to create storable fuel, solar power will assert its superiority to fossil fuels as a sustainable motive force for civilization’s continued prosperity.

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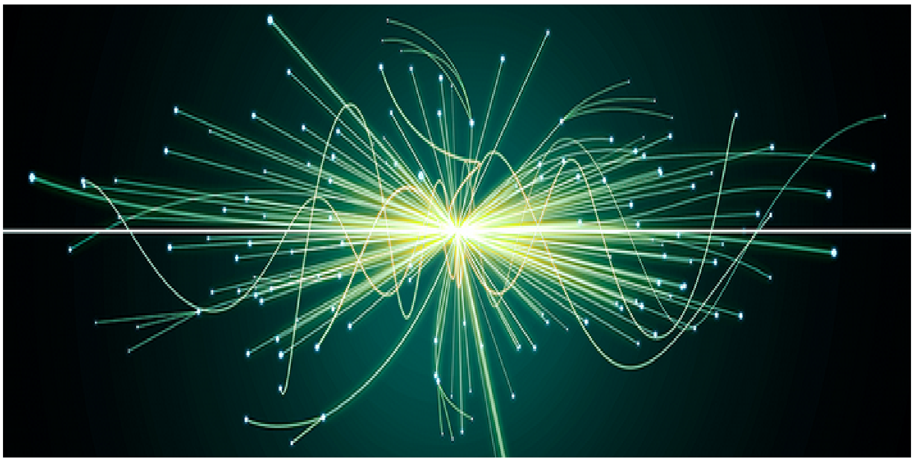
2. Provide Energy from Fusion



If you have a laptop computer, its battery probably contains the metallic element lithium. In theory, the lithium in that battery could supply your household electricity needs for 15 years. Not in the form of a battery, of course. Rather, lithium could someday be the critical element for producing power from nuclear fusion, the energy source for the sun and hydrogen bombs. Power plants based on lithium and using forms of hydrogen as fuel could in principle provide a major sustainable source of clean energy in the future.

2.1 What is fusion?

Fusion is the energy source for the sun. To be sure, producing power from fusion here on Earth is much more challenging than in the sun. There, enormous heat and gravitational pressure compress the nuclei of certain atoms into heavier nuclei, releasing energy. The single proton nuclei of two hydrogen isotopes, for example, are fused together to create the heavier nucleus of helium and a neutron. In that conversion, a tiny amount of mass is lost, transformed into energy as quantified by Einstein's famous equation, $E=mc^2$.

Earthbound reactors cannot achieve the high pressures of the sun's interior (such pressures have been achieved on Earth only in thermonuclear weapons, which use the radiation from a fission explosion to compress the fuel). But temperatures much higher than the sun's can be created to compensate for the lesser pressure, especially if heavier forms of hydrogen, known as deuterium (with one proton and one neutron) and tritium (one proton plus two neutrons) are fused.

Deuterium is a relatively uncommon form of hydrogen, but water -- each molecule comprising two atoms of hydrogen and one atom of oxygen -- is abundant enough to make deuterium supplies essentially unlimited. Oceans could meet the world's current energy needs for literally billions of years.

Tritium, on the other hand, is radioactive and is extremely scarce in nature. That’s where lithium comes in. Simple nuclear reactions can convert lithium into the tritium needed to fuse with deuterium. Lithium is more abundant than lead or tin in the Earth’s crust, and even more lithium is available from seawater. A 1,000 megawatt fusion-powered generating station would require only a few metric tons of lithium per year. As the oceans contain trillions of metric tons of lithium, supply would not be a problem for millions of years.

2.2 Can you control a fusion reaction?

Human-engineered fusion has already been demonstrated on a small scale. The challenges facing the engineering community are to find ways to scale up the fusion process to commercial proportions, in an efficient, economical, and environmentally benign way.

A major demonstration of fusion’s potential will soon be built in southern France. Called ITER (International Thermonuclear Experimental Reactor), the test facility is a joint research project of the United States, the European Union, Japan, Russia, China, South Korea, and India. Designed to reach a power level of 500 megawatts, ITER will be the first fusion experiment to produce long pulse of energy release on a significant scale.

While other approaches to fusion are being studied, the most advanced involves using magnetic forces to hold the fusion ingredients together. ITER will use this magnetic confinement method in a device known as a tokamak, where the fuels are injected into and confined in a vacuum chamber and heated to temperatures exceeding 100 million degrees. Under those conditions the fusion fuels become a gas-like form of electrically charge matter known as a plasma. (Its electric charge is what allows confinement by magnetic forces.) ITER will test the ability of magnetic confinement to hold the plasma in place at high-enough temperatures and density for a long-enough time for the fusion reaction to take place.

Construction of ITER is scheduled to start by 2009, with plasma to be first produced in 2016, and generation of 500 megawatts of thermal energy by 2025. (It will not convert this heat to electricity, however.) Among ITER's prime purposes will be identifying strategies for addressing various technical and safety issues that engineers will have to overcome to make fusion viable as a large-scale energy provider.

2.3 What are the barriers to making fusion reactors work?

For one thing, materials will be needed that can withstand the assaults from products of the fusion reaction. Deuterium-fusion reactions produce helium, which can provide some of the energy to keep the plasma heated. But the main source of energy to be extracted from the reaction comes from neutrons, which are also produced in the fusion reaction. The fast-flying neutrons will pummel through the reactor chamber wall into a blanket of material surrounding the reactor, depositing their energy as heat that can then be used to produce power. (In advanced reactor designs, the neutrons would also be used to initiate reactions converting lithium to tritium.)

Not only will the neutrons deposit energy in the blanket material, but their impact will convert atoms in the wall and blanket into radioactive forms. Materials will be needed that can extract heat effectively while surviving the neutron-induced structural weakening for extended periods of time.

Methods also will be needed for confining the radioactivity induced by neutrons as well as preventing releases of the radioactive tritium fuel. In addition, interaction of the plasma with reactor materials will produce radioactive dust that needs to be removed.

Building full-scale fusion-generating facilities will require engineering advances to meet all of these challenges, including better superconducting magnets and advanced vacuum systems. The European Union and Japan are designing the International Fusion Materials Irradiation Facility, where possible materials for fusion plant purposes will be developed and tested. Robotic methods for maintenance and repair will also have to be developed.

While these engineering challenges are

considerable, fusion provides many advantages beyond the prospect of its almost limitless supply of fuel.

2.4 Will fusion energy be safe?

From a safety standpoint, it poses no risk of a runaway nuclear reaction — it is so difficult to get the fusion reaction going in the first place that it can be quickly stopped by eliminating the injection of fuel. And after engineers learn how to control the first generation of fusion plasmas, from deuterium and tritium fuels, advanced second- or third-generation fuels could reduce radioactivity by orders of magnitude.

Ultimately, of course, fusion’s success as an energy provider will depend on whether the challenges to building generating plants and operating them safely and reliably can be met in a way that makes the cost of fusion electricity economically competitive. The good news is that the first round of challenges are clearly defined, and motivations for meeting them are strong, as fusion fuels offer the irresistible combination of abundant supply with minimum environmental consequences.

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3. Develop Carbon Sequestration Methods

The growth in emissions of carbon dioxide, implicated as a prime contributor to global warming, is a problem that can no longer be swept under the rug. But perhaps it can be buried deep underground or beneath the ocean.

3.1 Why is carbon dioxide (CO_2) a problem?

In pre-industrial times, every million molecules of air contained about 280 molecules of carbon dioxide. Today that proportion exceeds 380 molecules per million, and it continues to climb. Evidence is mounting that carbon dioxide’s heat-trapping power has already started to boost average global temperatures. If carbon dioxide levels continue upward, further warming could have dire consequences, resulting from rising sea levels, agriculture disruptions, and stronger storms (e.g. hurricanes) striking more often.

But choking off the stream of carbon dioxide entering the atmosphere does not have a simple solution. Fossil fuels, which provide about 85 percent of the world’s energy, are made of hydrocarbons, and burning them releases huge quantities of carbon dioxide. Even as renewable energy sources emerge, fossil-fuel burning will remain substantial. And the fossil fuel in greatest supply — coal — is the worst carbon dioxide emitter per unit of energy produced. A grand challenge for the 21st century’s engineers will be developing systems for capturing the carbon dioxide produced by burning fossil fuels and sequestering it safely away from the atmosphere.

3.2 What is carbon sequestration?

Carbon sequestration is capturing the carbon dioxide produced by burning fossil fuels and storing it safely away from the atmosphere.

3.3 How do you capture CO_2?

Methods already exist for key parts of the sequestration process. A chemical system for capturing carbon dioxide is already used at some facilities for commercial purposes, such as beverage carbonation and dry ice manufacture. The same approach could be adapted for coal-burning electric power plants, where smokestacks could be replaced with absorption towers. One tower would contain chemicals that isolate carbon dioxide from the other gases (nitrogen and water vapor) that escape into the air and absorb it. A second tower would separate the carbon dioxide from the absorbing chemicals, allowing them to be returned to the first tower for reuse.

A variation to this approach would alter the combustion process at the outset, burning coal in pure oxygen rather than ordinary air. That would make separating the carbon dioxide from the exhaust much easier, as it would be mixed only with water vapor, and not with nitrogen. It’s relatively simple to condense the water vapor, leaving pure carbon dioxide gas that can be piped away for storage.

In this case, though, a different separation problem emerges — the initial need for pure oxygen, which is created by separating it from nitrogen and other trace gases in the air. If that process can be made economical, it would be feasible to retrofit existing power plants with a pure oxygen combustion system, simplifying and reducing the cost of carbon dioxide capture.

Advanced methods for generating power from coal might also provide opportunities for capturing carbon dioxide. In coal-gasification units, an emerging technology, coal is burned to produce a synthetic gas, typically containing hydrogen and carbon monoxide. Adding steam, along with a catalyst, to the synthetic gas converts the carbon monoxide into additional hydrogen and carbon dioxide that can be filtered out of the system. The hydrogen can be used in a gas turbine (similar to a jet engine) to produce electric power.

3.4 How do you store CO_2?

Several underground possibilities have been investigated. Logical places include old gas and oil fields. Storage in depleted oil fields, for example, offers an important economic advantage — the carbon dioxide interacts with the remaining oil to make it easier to remove. Some fields already make use of carbon dioxide to enhance the recovery of hard-to-get oil. Injecting carbon dioxide dislodges oil trapped in the pores of underground rock, and carbon dioxide's presence reduces the friction impeding the flow of oil through the rock to wells.

Depleted oil and gas fields do not, however, have the capacity to store the amounts of carbon dioxide that eventually will need to be sequestered. By some estimates, the world will need reservoirs capable of containing a trillion tons of carbon dioxide by the end of the century. That amount could possibly be accommodated by sedimentary rock formations with pores containing salty water (brine).

The best sedimentary brine formations would be those more than 800 meters deep — far below sources of drinking water, and at a depth where high pressure will maintain the carbon dioxide in a high-density state.

Sedimentary rocks that contain brine are abundantly available, but the concern remains whether they will be secure enough to store carbon dioxide for centuries or millennia. Faults or fissures in overlying rock might allow carbon dioxide to slowly escape, so it will be an engineering challenge to choose, design, and monitor such storage sites carefully.

Concerns about leaks suggest to some experts that the best strategy might be literally deep-sixing carbon dioxide, by injecting it into sediments beneath the ocean floor. High pressure from above would keep the carbon dioxide in the sediments and out of the ocean itself. It might cost more to implement than other methods, but it would be free from worries about leaks. And in the case of some coastal sites of carbon dioxide production, ocean sequestration might be a more attractive strategy than transporting it to far-off sedimentary basins.

It is also possible that engineers will be able to develop new techniques for sequestering carbon dioxide that are based upon natural processes. For example, when atmospheric concentrations of carbon dioxide increased in geologic times to a certain unknown threshold, it went into the ocean and combined with positively charged calcium ions to form calcium carbonate – limestone. Similarly, engineers might devise ways of pumping carbon dioxide into the ocean in ways that would lock it eternally into rock.

It may well be that multiple strategies and storage locations will be needed to solve this problem, but the prospect for success appears high. “Scientific and economic challenges still exist,” writes Harvard geoscientist Daniel Schrag, “but none are serious enough to suggest that carbon capture and storage will not work at the scale required to offset trillions of tons of carbon dioxide emissions over the next century.” [Schrag, p. 812]

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4. Manage the Nitrogen Cycle

It doesn’t offer as catchy a label as “global warming,” but human-induced changes in the global nitrogen cycle pose engineering challenges just as critical as coping with the environmental consequences of burning fossil fuels for energy.

4.1 Why is the nitrogen cycle important?

The nitrogen cycle reflects a more intimate side of energy needs, via its central role in the production of food. It is one of the places where the chemistry of the Earth and life come together, as plants extract nitrogen from their environment, including the air, to make food. Controlling the impact of agriculture on the global cycle of nitrogen is a growing challenge for sustainable development.

Nitrogen is an essential component of amino acids (the building blocks of proteins) and of nucleotides (the building blocks of DNA), and consequently is needed by all living things.

Fortunately, the planet's supply of nitrogen is inexhaustible — it is the main element in the air, making up nearly four-fifths of the atmosphere in the form of nitrogen molecules, each composed of two nitrogen atoms. Unfortunately, that nitrogen is not readily available for use by living organisms, as the molecules do not easily enter into chemical reactions. In nature, breaking up nitrogen requires energy on the scale of lightning strikes, or the specialized chemical abilities of certain types of microbes.

Such microbes commonly live in soil, and sometimes live symbiotically in roots of certain plants. The microbes use enzymes to convert nitrogen from the environment into the forms that plants can use as nutrients in a process called fixation. Plants turn this fixed nitrogen into organic nitrogen — the form combined with carbon in a wide variety of molecules essential both to plants and to the animals that will eat them.

The opposite of this process is denitrification, in which organisms use nitrogen nutrients as their energy source and return nitrogen molecules to the atmosphere, completing the cycle. Denitrification also produces some nitrogen byproducts that are atmospheric pollutants.

4.2 What is wrong with the nitrogen cycle now?

Until recent times, nitrogen fixation by microorganisms (with an additional small amount from lightning strikes) was the only way in which nitrogen made its way from the environment into living organisms. Human production of additional nitrogen nutrients, however, has now disrupted the natural nitrogen cycle, with fertilizer accounting for more than half of the annual amount of nitrogen fixation attributed to human activity. Another large contribution comes from planting legumes, including soybeans and alfalfa, which are attractive hosts for nitrogen-fixing microbes and therefore enrich the soil where they grow. A third contributor is nitrogen oxide formed during burning of fuels, where the air becomes so hot that the nitrogen molecule breaks apart.

Such human activity has doubled the amount of fixed nitrogen over the levels present during pre-industrial times. Among the consequences are worsening of the greenhouse effect, reducing the protective ozone layer, adding to smog, contributing to acid rain, and contaminating drinking water.

4.3 Why should I care about the nitrogen cycle?

Ammonia factories supplement the enzymatic magic of microbial nitrogen fixation with the brute forces of temperature and pressure, extracting close to 100 million metric tons of nitrogen from the atmosphere each year. Nitrogen removed from the air by human activity adds seriously to a number of environmental problems. Fertilizer for agricultural fields is the major source of nitrous oxide, a potent greenhouse gas. One nitrous oxide molecule, in fact, traps heat about 200 times more effectively than each molecule of carbon dioxide, the most plentiful greenhouse gas. Nitrous oxide also remains in the air for a long time — on the order of a century — because it does not dissolve easily in water and resists reacting with other chemicals.

Consequently it eventually reaches the stratosphere where sunlight breaks it into nitric oxide, a key link in the chain of reactions that damages the Earth’s protective ozone layer.

At the same time, other fixed-nitrogen gases released from fertilizers contribute to producing ozone in the lower atmosphere, where it is a pollutant rather than a protector. This reactive nitrogen can also lead to production of aerosols that can induce serious respiratory illness, cancer, and cardiac disease when in the air we breathe. Yet another pollution problem, acid rain, is fueled in part by nitrogen oxides from fertilizer.

Other forms of fixed nitrogen that are applied during fertilization, particularly nitrite ions, also exacerbate water pollution problems. High nitrate concentrations in drinking water are a direct human health problem, causing “blue baby syndrome.” Additional ecological concerns arise from the role of fixed nitrogen compounds in over-enriching aquatic ecosystems, producing large amounts of phytoplankton (small water plants) that deplete oxygen supplies in the water and lead to “dead zones.”

“Globally, until nitrogen fixation is balanced by denitrification, the amount of excess fixed nitrogen in the world will grow relentlessly, with increasing consequences for ecosystems and the public health,” writes Robert Socolow of Princeton University. [Socolow, p. 6005]

4.4 What can engineering do?

Maintaining a sustainable food supply in the future without excessive environmental degradation will require clever methods for remediating the human disruption of the nitrogen cycle. Over the past four decades, food production has been able to keep pace with human population growth thanks to the development of new high-yielding crop varieties optimally grown with the help of fertilizers.

Engineering strategies to increase denitrification could help reduce the excess accumulation of fixed nitrogen, but the challenge is to create nitrogen molecules – not nitrous oxide, N_2O, the greenhouse gas. Similarly, technological approaches should be improved to help further control the release of nitrogen oxides produced in high-temperature burning of fuels.

A major need for engineering innovation will be in improving the efficiency of various human activities related to nitrogen, from making fertilizer to recycling food wastes. Currently, less than half of the fixed nitrogen generated by farming practices actually ends up in harvested crops. And less than half of the nitrogen in those crops actually ends up in the foods that humans consume. In other words, fixed nitrogen leaks out of the system at various stages in the process – from the farm field to the feedlot to the sewage treatment plant. Engineers need to identify the leakage points and devise systems to plug them.

For instance, technological methods for applying fertilizer more efficiently could ensure that a higher percentage of the fertilizer ends up in the plants as organic nitrogen. Other innovations could help reduce runoff, leaching, and erosion, which carry much of the nitrogen fertilizer away from the plants and into groundwater and surface water. Still other innovations could focus on reducing the gas emissions from soils and water systems.

Efficiency gains could also come from recycling of organic waste. Manure has always been regarded as an effective fertilizer, but the distances separating cattle feedlots and dairies from lands where crops are planted makes transporting manure expensive. Moreover, manure and food wastes have their own set of environmental challenges, including their roles as sources of potent greenhouse gases like methane and nitrous oxide. Engineering challenges include finding ways of capturing those gases for useful purposes, and converting manure into pelletized organic fertilizer. Solutions that focus on integrated ways of reducing greenhouse and other gas emissions from wastes, while at the same time improving their potential as economically transported fertilizer, are needed.

In addressing the nitrogen cycle problem, experts must remember that fertilizers and farming have played a central role in boosting worldwide food production, helping to avoid mass starvation in many areas of the world. Efforts to mitigate the agricultural disruption of the nitrogen cycle might have the effect of raising the cost of food, so such steps must be taken in concert with efforts to limit their effects on people living in poverty.

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5.Provide Access to Clean Water

When Samuel Taylor Coleridge wrote “water, water, everywhere, nor any drop to drink,” he did not have the 21st century’s global water situation in mind. But allowing for poetic license, he wasn’t far from correct. Today, the availability of water for drinking and other uses is a critical problem in many areas of the world.

5.1How serious is our water challenge?

Lack of clean water is responsible for more deaths in the world than war. About 1 out of every 6 people living today do not have adequate access to water, and more than double that number lack basic sanitation, for which water is needed. In some countries, half the population does not have access to safe drinking water, and hence is afflicted with poor health. By some estimates, each day nearly 5,000 children worldwide die from diarrhearelated diseases, a toll that would drop dramatically if sufficient water for sanitation was available.

It’s not that the world does not possess enough water. Globally, water is available in abundance. It is just not always located where it is needed. For example, Canada has plenty of water, far more than its people need, while the Middle East and northern Africa — to name just two of many — suffer from perpetual shortages. Even within specific countries, such as Brazil, some regions are awash in fresh water while other regions, afflicted by drought, go wanting. In many instances, political and economic barriers prevent access to water even in areas where it is otherwise available. And in some developing countries, water supplies are contaminated not only by the people discharging toxic contaminants, but also by arsenic and other naturally occurring poisonous pollutants found in groundwater aquifers.

Water for drinking and personal use is only a small part of society’s total water needs — household water usually accounts for less than 5 percent of total water use. In addition to sanitation, most of the water we use is for agriculture and industry. Of course, water is also needed for ecological processes not directly related to human use. For a healthy, sustainable future for the planet, developing methods of ensuring adequate water supplies pose engineering challenges of the first magnitude.

Of course, by far most of the world's water is in the oceans, and therefore salty and not usable for most purposes without desalination. About 3 percent of the planet's water is fresh, but most of that is in the form of snow or ice. Water contained in many groundwater aquifers was mostly deposited in earlier, wetter times, and the rate of use from some aquifers today exceeds the rate of their replenishment.

"Overcoming the crisis in water and sanitation is one of the greatest human development challenges of the early 21st century," a recent U.N. report warns. [United Nations Development Programme, p. 1]

5.2 Where does our water supply come from?

From digging wells to building dams, engineers have historically been prime providers of methods for meeting the water supply and quality needs of society. To meet current needs, which increasingly include environmental and ecosystem preservation and enhancement demands, the methods will have to become more sophisticated.

One large-scale approach used in the U.S., China, India, and other countries has been to divert the flow of water from regions where it is plentiful to where it is scarce. Such diversion projects provide some short-term relief for cities, but do not appear practical as widespread, long-term, ecologically sound solutions, and this method generally will not be able to meet agricultural needs. Furthermore, diverting water to some people often means less for others and can become an explosive political issue.

5.3 What is desalination?

Desalination is extracting the salt from seawater. Desalination is not a new idea and is already used in many regions, particularly in the Middle East. Saudi Arabia alone accounts for about a tenth of global desalination. Israel uses desalination technology to provide about a fourth of its domestic water needs. Modern desalination plants employ a method called reverse osmosis, which uses a membrane to separate the salt. More than 12,000 desalination plants now operate in the world.

But desalination plants are expensive to build and require lots of energy to operate, making desalination suitable mainly for seaside cities in rich countries. It therefore has limited value for impoverished countries, where water supply problems are most serious.

New technologies that would lower energy use — and therefore costs — might help desalination's contribution. One potentially useful new approach, called nano-osmosis, would filter out salt with the use of tiny tubes of carbon. Experiments have shown that such tubes, called nanotubes because their size is on the scale of nanometers, have exceptional filtering abilities.

Even with such advances, though, it seems unlikely that desalination alone will be able to solve the world's water problems. Other approaches will be needed.

5.4 What other technologies will provide clean water?

Technologies are being developed, for instance, to improve recycling of wastewater and sewage treatment so that water can be used for nonpersonal uses such as irrigation or industrial purposes. Recycled water could even resupply aquifers. But very effective purification methods and rigorous safeguards are necessary to preserve the safety of recycled water. (Various nanotechnology approaches may be helpful in this regard, such as nanofiltration membranes that can be designed to remove specific pollutants while allowing important nutrients to pass through. [Hillie et al., pp. 20-21])

A different technological approach to the water problem involves developing strategies for reducing water use. Agricultural irrigation consumes enormous quantities of water; in developing countries, irrigation often exceeds

80 percent of total water use. Improved technologies to more efficiently provide crops with water, such as “drip irrigation,” can substantially reduce agricultural water demand. Already some countries, such as Jordan, have reduced water use substantially with drip technology, but it is not a perfect solution for plant growth (e.g. it does not provide enough water to cleanse the soil). Water loss in urban supply systems is also a significant problem.

Yet another strategy for improving water availability and safety would be small decentralized distillation units, an especially attractive approach in places where infrastructure and distribution problems are severe. One of the main issues is economical distribution of water to rural and low-income areas. Some current projects are striving to produce inexpensive distillation units that can remove contaminants from any water source. A unit smaller than a dishwasher could provide daily clean water for 100 people.

Such approaches will help to address the very real problem of inequitable distribution of water resources. Even within a given country, clean, cheap water may be available to the rich while the poor have to seek out supplies, at higher costs, from intermediary providers or unsafe natural sources. Technological solutions to the world's water problems must be implemented within systems that recognize and address these inequities.

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6. Restore and Improve Urban Infrastructure

In 2005, the American Society of Civil Engineers issued a report card, grading various categories of U.S. infrastructure. The average grade was D (Updated to D+ in 2013).

6.1 What is infrastructure?

Infrastructure is the combination of fundamental systems that support a community, region, or country. It includes everything from water and sewer systems to road and rail networks to the national power and natural gas grids. Perhaps there will be a hydrogen grid in the future as well.

6.2 What is the current state of our infrastructure?

It is no secret that America’s infrastructure, along with those of many other countries, is aging and failing, and that funding has been insufficient to repair and replace it. Engineers of the 21st century face the formidable challenge of modernizing the fundamental structures that support civilization.

The problem is particularly acute in urban areas, where growing populations stress society’s support systems, and natural disasters, accidents, and terrorist attacks threaten infrastructure safety and security. And urban infrastructure is not just a U.S. issue; special challenges are posed by the problems of megacities, with populations exceeding 10 million, which are found mostly in Asia. In many parts of the world, basic infrastructure needs are still problematic, and engineers will be challenged to economically provide such services more broadly.

Furthermore, solutions to these problems must be designed for sustainability, giving proper attention to environmental and energy-use considerations (though cities take up just a small percentage of the Earth’s surface, they disproportionately exhaust resources and generate pollution), along with concern for the aesthetic elements that contribute to the quality of life.

6.3 What is involved in maintaining infrastructure?

Of course, maintaining infrastructure is not a new problem. For thousands of years, engineers have had to design systems for providing clean water and disposing of sewage. In recent centuries, systems for transmitting information and providing energy have expanded and complicated the infrastructure network, beginning with telegraph and telephone lines and now encompassing all sorts of telecommunications systems. Cable TV, cell phones, and Internet access all depend on elaborate infrastructure installations. Development of remote wind and solar energy resources will add more.

Much of the existing infrastructure is buried, posing several problems for maintaining and upgrading it. For one thing, in many cases, records of the locations of all the underground pipes and cables are unavailable or incomplete. One major challenge will be to devise methods for mapping and labeling buried infrastructure, both to assist in improving it and to help avoid damaging it.

A project of this sort is now underway in the United Kingdom, with the aim of developing ways to locate buried pipes using electromagnetic signals from above the ground. The idea is to find metallic structures capable of reflecting electromagnetic waves through soil, much as a reflector makes a bicycle easier to see at night.

6.4 How can you improve transportation systems?

Other major infrastructure issues involve transportation. Streets and highways will remain critical transportation conduits, so their maintenance and improvement will remain an important challenge. But the greater challenge will be engineering integrated transportation systems, making individual vehicle travel, mass transit, bicycling, and walking all as easy and efficient as possible. An increasingly important question is the need to provide better access to transportation for the elderly and disabled.

Cities around the world have begun developing integrated approaches, by establishing transportation hubs, for instance, where various transportation elements — rail, bus, taxi, walking and bicycle paths, parking lots — all conveniently meet. In Hong Kong, several transportation services are linked in a system that allows a single smart card to be used to pay for all the services, including gas and parking.

A similar integrated approach combining energy, water, and wastes (liquid and solid) into “neighborhood” systems could be considered in certain urban areas. This approach would increase sustainability while relieving pressure to meet all citizens’ needs through city-scaled infrastructures. It would be best to introduce such systems in new development areas (e.g. urban revitalization areas) and new cities, which will spring up over the next few decades in places like China and India.

While such services can help support growing urban populations, they must be accompanied by affordable and pleasant places for people to live. Engineers must be engaged in the architectural issues involved in providing environmentally friendly, energy-efficient buildings both for housing and for business.

6.5How do you build better infrastructure?

Novel construction materials may help address some of these challenges. But dramatic progress may be possible only by developing entirely new construction methods. Most of the basic methods of manual construction have been around for centuries — even millennia. Advances in computer science and robotics should make more automation possible in construction, for instance, greatly speeding up construction times and lowering costs. Electricity networks linking large central-station and decentralized power sources will also benefit from greater embedded computation.

All of these endeavors must be undertaken with clear vision for the aesthetic values that go beyond mere function and contribute to the joy of living. Major bridges, for instance, have long been regarded almost as much works of art as aids to transport. Bridges, buildings, and even freeways contribute to the aesthetical appeal of a city, and care in their design can contribute to a more enjoyable urban environment.

In previous decades, much of the rest of urban infrastructure has been erected without as much concern for its impact on a city’s appearance and cultural milieu. Recently, though, awareness of the aesthetics of engineering has begun to influence infrastructure design more generally. Integrating infrastructure needs with the desire for urban green spaces is one example.

Projects to deal with urban stormwater runoff have demonstrated opportunities to incorporate aesthetically pleasing projects. Using landscape design to help manage the flow of runoff water, sometimes referred to as “green infrastructure,” can add to a city’s appeal in addition to helping remove pollution. The vast paved area of a city needs to be rethought, perhaps by designing pavements that reduce overhead temperatures and that are permeable to allow rainwater to reach the ground table beneath. Proper engineering approaches can achieve multiple goals, such as better storm drainage and cleaner water, while also enhancing the appearance of the landscape, improving the habitat for wildlife, and offering recreational spaces for people.

Rebuilding and enhancing urban infrastructure faces problems beyond the search for engineering solutions. Various policies and political barriers must be addressed and overcome. Funding for infrastructure projects has been hopelessly inadequate in many areas, as the American Society of Civil Engineers' "report card" documented. And the practice of letting infrastructure wear out before replacing it, rather than incorporating technological improvements during its lifetime, only exacerbates the problems.

And so, a major grand challenge for infrastructure engineering will be not only to devise new approaches and methods, but to communicate their value and worthiness to society at large.

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7. Advance Health Informatics

When you dial 911 for a medical emergency, the outcome may very well depend on the 411 — the quality of the information available about your condition and ways to treat it.

7.1 What is health informatics?

No aspect of human life has escaped the impact of the Information Age, and perhaps in no area of life is information more critical than in health and medicine. As computers have become available for all aspects of human endeavors, there is now a consensus that a systematic approach to health informatics — the acquisition, management, and use of information in health — can greatly enhance the quality and efficiency of medical care and the response to widespread public health emergencies.

Health and biomedical informatics encompass issues from the personal to global, ranging from thorough medical records for individual patients to sharing data about disease outbreaks among governments and international health organizations. Maintaining a healthy population in the 21st century will require systems engineering approaches to redesign care practices and integrate local, regional, national, and global health informatics networks.

On the personal level, biomedical engineers envision a new system of distributed computing tools that will collect authorized medical data about people and store it securely within a network designed to help deliver quick and efficient care.

Basic medical informatics systems have been widely developed for maintaining patient records in doctor’s offices, clinics, and individual hospitals, and in many instances systems have been developed for sharing that information among multiple hospitals and agencies. But much remains to be done to make such information systems maximally useful, to ensure confidentiality, and to guard against the potential for misuse, for example by medical insurers or employers.

7.2 What needs to be done to improve health information systems?

For one thing, medical records today are plagued by mixtures of old technologies (paper) with new ones (computers). And computerized records are often incompatible, using different programs for different kinds of data, even within a given hospital. Sharing information over regional, national, or global networks is further complicated by differences in computer systems and data recording rules. Future systems must be engineered for seamless sharing of data, with built-in guarantees of accurate updating and ways to verify a patient’s identity.

Keeping track of individual records is just part of the challenge, though. Another major goal is developing trusted systems that offer relevant decision support to clinicians and patients as well as archive medical research information. Doctors suffering from information overload need systematic electronic systems for finding information to treat specific patients and decision support systems to offer “just in time, just for me” advice at the point of care.

“There is a need,” writes Russ Altman of Stanford University, “to develop methods for representing biological knowledge so that computers can store, manipulate, retrieve, and make inferences about this information in standard ways.” [Altman p. 120]

7.3 How can health informatics improve health care?

Apart from collecting and maintaining information, health informatics should also be put to use in improving the quality of care through new technologies. Some of those technologies will involve gathering medical data without a visit to the doctor, such as wearable devices to monitor such things as pulse and temperature. Monitoring devices might even come in the form of tiny electronic sensors embedded in clothing and within the body.

Such devices are emerging from advances in microelectronic mechanical systems for health care delivery as wireless integrated microsystems, or WIMS. Tiny sensors containing wireless transmitter-receivers could provide constant monitoring of patients in hospitals or even at home. If standardized to be interoperable with electronic health records, WIMS could alert health professionals when a patient needs attention, or even trigger automatic release of drugs into the body when necessary. In effect, every hospital room could be turned into an ICU. Seamlessly integrating the input from such devices into a health informatics system raises the networking challenge to a new level.

7.4 How can informatics improve response in public health emergencies?

On the local to global scale, a robust health informatics system would enable health professionals to detect, track, and mitigate both natural health and terrorism emergencies.

Biological and chemical warfare are not new to human history. From ancient times, warriors have tried to poison their enemies' water. Today, of course, the threat of such attacks comes not only from military engagements in ongoing wars, but from terrorists capable of striking almost anywhere at any time. Protecting against such assaults will require an elaborate and sophisticated system for prompt and effective reaction.

Meeting that challenge is complicated by the diverse nature of the problem — terrorists have a vast arsenal of biological and chemical weapons from which to choose. Perhaps the most familiar of these threats are toxic chemicals. Poison gases, such as chlorine and phosgene, essentially choke people to death. Mustards burn and blister the skin, and nerve gases, which are actually liquids, kill in the same way that pesticides kill roaches, by paralysis.

As serious as chemical attacks can be, most experts believe their risk pales in comparison with their biological counterparts. Of particular concern are potent biological toxins including anthrax, ricin, and botulism neurotoxin.

Anthrax has received special attention, partly because of the deaths it caused in the U.S. in 2001, but also because its potential to produce mass death is so large. It’s not hard to imagine scenarios where airborne release of anthrax could infect hundreds of thousands of people.

Antibiotics can be effective against anthrax bacteria if provided soon enough. But that window of opportunity is narrow; after the germs release their toxic chemicals, other defenses are needed.

7.5 How to you prepare against chemical and biological weapons?

Providing data to feed an informatics system in preparation for bio and chemical terror involves engineering challenges in three main categories. One is surveillance and detection — monitoring the air, water, soil, and food for early signs of an attack. Next is rapid diagnosis, requiring a system that can analyze and identify the agent of harm as well as track its location and spread within the population. Finally come countermeasures, powered by nimble operations that can quickly develop and mass-produce antidotes, vaccines, or other treatments to keep the effects of an attack as small as possible and track how effective the countermeasures are.

Efficient and economical monitoring of the environment to find such agents early is a major challenge, but efforts are underway to develop sensitive detectors. “Artificial noses,” for example, are computer chips that can sort out and identify signals from thousands of potentially deadly chemicals. These systems are still much less sensitive than the canine nose, however, and their perfection is an engineering challenge. Toxins or viruses might also be identified using biological detectors. Ultra-tiny biological “nanopore” devices can be engineered, for example, to send electrical signals when a dangerous molecule passes through the pore.

Yet another novel method would track not the attack molecule itself, but molecules produced by the body’s response to the invader. When exposed to bacteria, immune system cells known as neutrophils alter their internal chemistry. Profiling such changes can provide clues to the invader’s identity and suggest the best counterattack. Databases cataloging the cellular response to various threats should ultimately make it possible to identify biowarfare agents quickly with simple blood tests.

7.6 How to you prepare against a pandemic?

Nothing delivers as much potential for devastation as natural biology. From the bacterium that killed half of European civilization in the Black Death of the 14th century to the 1918 Spanish Flu pandemic that killed 20 million people, history has witnessed the power of disease to eradicate huge portions of the human population.

In the 21st century, the prospect remains real that flu — or some other viral threat, yet unknown — could tax the power of medical science to respond. Bird flu, transmitted by the virus strain known as H5N1, looms as a particularly clear and present danger.

A major goal of pandemic preparedness is a good early warning system, relying on worldwide surveillance to detect the onset of a spreading infectious disease. Some such systems are now in place, monitoring data on hospital visits and orders for drugs or lab tests. Sudden increases in these events can signal the initial stages of an outbreak.

But certain events can mask trends in these statistics, requiring more sophisticated monitoring strategies. These can include tracking the volume of public Web site hits to explain acute symptoms and link them to geocodes, such as zip codes. Having an integrated national information technology infrastructure would help greatly. Closures of schools or businesses and quarantines may actually reduce hospital use in some cases, and people may even deliberately stay away from hospitals for fear of getting infected. On the other hand, rumors of disease may send many healthy people to hospitals for preventive treatments. In either case the numbers being analyzed for pandemic trends could be skewed.

New approaches to analyzing the math can help — especially when the math describes the network of relationships among measures of health care use. In other words, monitoring not just individual streams of data, but relationships such as the ratio of one measurement to another, can provide a more sensitive measure of what’s going on. Those kinds of analyses can help make sure that a surge in health care use in a given city because of a temporary population influx (say, for the Olympics) is not mistaken for the beginning of an epidemic.

Similarly, mathematical methods can also help in devising the most effective medical response plans when a potential pandemic does begin. Strategies for combating pandemics range from restricting travel and closing schools to widespread quarantines, along with vaccinations or treatment with antiviral drugs.

The usefulness of these approaches depends on numerous variables — how infectious and how deadly the virus is, the availability of antiviral drugs and vaccines, and the degree of public compliance with quarantines or travel restrictions. Again, understanding the mathematics of networks will come into play, as response systems must take into account how people interact. Such models may have to consider the “small world” phenomenon, in which interpersonal connections are distributed in a way that assists rapid transmission of the virus through a population, just as people in distant parts of the world are linked by just a few intermediate friends.

Studies of these methods, now at an early stage, suggest that rapid deployment of vaccines and drugs is critical to containing a pandemic's impact. Consequently new strategies for producing vaccines in large quantities must be devised, perhaps using faster cell culture methods rather than the traditional growing of viruses in fertilized eggs. A system will be required to acquire samples of the virus rapidly, to sequence it, and then quickly design medications and vaccines. The system needs to have technologies to enable rapid testing, accompanied by a system for accelerating the regulatory process. If there is an emergency viral outbreak that threatens widespread disease and death in days or weeks, regulatory approval that takes years would be self-defeating.

"It will be imperative to collect the most detailed data on the . . . characteristics of a new virus . . . and to analyze those data in real time to allow interventions to be tuned to match the virus the world faces," write Neil Ferguson of Imperial College London and his collaborators. [Ferguson et al. p. 451]

The value of information systems to help protect public safety and advance the health care of individuals is unquestioned. But, with all these new databases and technologies comes an additional challenge: protecting against the danger of compromise or misuse of the information. In developing these technologies, steps also must be taken to make sure that the information itself is not at risk of sabotage, and that personal information is not inappropriately revealed.

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8. Engineer Better Medicines

Doctors have long known that people differ in susceptibility to disease and response to medicines. But, with little guidance for understanding and adjusting to individual differences, treatments developed have generally been standardized for the many, rather than the few.

8.1 How will genetic science change how medicines are made?

Human DNA contains more than 20,000 genes, all of which are stored in our cells' nuclei. A gene is a strand of chemical code, a sort of blueprint for proteins and other substances necessary for life. Cells make those molecules according to the genetic blueprints.

Each person’s overall blueprint is basically the same, made up of about 3 billion “letters” of code, each letter corresponding to a chemical subunit of the DNA molecule. But subtle variants in about 1 percent of our DNA — often the result of just a single chemical letter being different — give humans their individual identities.

Beyond physical appearance, genes give rise to distinct chemistries in various realms of the body and brain. Such differences sometimes predispose people to particular diseases, and some dramatically affect the way a person will respond to medical treatments.

Ideally, doctors would be able to diagnose and treat people based on those individual differences, a concept commonly referred to as “personalized medicine.” At its core, personalized medicine is about combining genetic information with clinical data to optimally tailor drugs and doses to meet the unique needs of an individual
patient. Eventually, personalized medicine will be further informed by detailed understanding of the body’s distinct repertoire of proteins (proteomics) and complete catalog of biochemical reactions (metabolomics).

“Personalized medicine,” writes Lawrence Lesko of the U.S. Food and Drug Administration, “can be viewed . . . as a comprehensive, prospective approach to preventing, diagnosing, treating, and monitoring disease in ways that achieve optimal individual health-care decisions.” [Lesko p. 809]

Already, some aspects of the personalized medicine approach are in place for some diseases. Variants of a gene linked to breast cancer, for instance, can foretell a woman’s likely susceptibility to developing or surviving the disease, a helpful guide for taking preventive measures. In certain cases of breast cancer, the production of a particular protein signals a more aggressive form of the disease that might be more effectively controlled with the drug Herceptin.

Still, multiple challenges remain in the quest for a widespread effective system of personalized medicine. They will be addressed by the collaborative efforts of researchers from many disciplines, from geneticists to clinical specialists to engineers.

8.2 What prevents you from creating personalized medicines now?

One engineering challenge is developing better systems to rapidly assess a patient's genetic profile; another is collecting and managing massive amounts of data on individual patients; and yet another is the need to create inexpensive and rapid diagnostic devices such as gene chips and sensors able to detect minute amounts of chemicals in the blood.

In addition, improved systems are necessary to find effective and safe drugs that can exploit the new knowledge of differences in individuals. The current "gold standard" for testing a drug's worth and safety is the randomized controlled clinical trial -- a study that randomly assigns people to a new drug or to nothing at all, a placebo, to assess how the drug performs. But that approach essentially decides a drug's usefulness based on average results for the group of patients as a whole, not for the individual.

New methods are also needed for delivering personalized drugs quickly and efficiently to the site in the body where the disease is localized. For instance, researchers are exploring ways to engineer nanoparticles that are capable of delivering a drug to its target in the body while evading the body’s natural immune response. Such nanoparticles could be designed to be sensitive to the body’s internal conditions, and therefore could, for example, release insulin only when the blood’s glucose concentration is high.

In a new field called “synthetic biology,” novel biomaterials are being engineered to replace or aid in the repair of damaged body tissues. Some are scaffolds that contain biological signals that attract stem cells and guide their growth into specific tissue types. Mastery of synthetic tissue engineering could make it possible to regenerate tissues and organs.

8.3 What are the benefits of personalized medicine?

Ultimately, the personalization of medicine should have enormous benefits. It ought to make disease (and even the risk of disease) evident much earlier, when it can be treated more successfully or prevented altogether. It could reduce medical costs by identifying cases where expensive treatments are unnecessary or futile. It will reduce trial-and-error treatments and ensure that optimum doses of medicine are applied sooner. Most optimistically, personalized medicine could provide the path for curing cancer, by showing why some people contract cancer and others do not, or how some cancer patients survive when others do not.

Of course, a transition to personalized medicine is not without its social and ethical problems. Even if the technical challenges can be met, there are issues of privacy when unveiling a person's unique biological profile, and there will likely still be masses of people throughout the world unable to access its benefits deep into the century.

8.4 How do you fight drug-resistant infections?

The war against infectious agents has produced a powerful arsenal of therapeutics, but treatment with drugs can sometimes exacerbate the problem. By killing all but the drug-resistant strains, infectious agents that are least susceptible to drugs survive to infect again. They become the dominant variety in the microbe population, a present-day example of natural selection in action. This leads to an ever-present concern that drugs can be rendered useless when the microbial world employs the survival-of-the-fittest strategy of evolution. And frequently used drugs contribute to their own demise by strengthening the resistance of many enemies.

“Drug-resistant pathogens — whether parasites, bacteria, or viruses — can no longer be effectively treated with common anti-infective drugs,” writes David L. Heymann of the World Health Organization.

A healthy future for the world’s population will depend on engineering new strategies to overcome multiple drug resistances.

One major challenge in this endeavor will be to understand more fully how drug resistance comes about, how it evolves, and how it spreads. Furthermore, the system for finding and developing new drugs must itself evolve and entirely novel approaches to fighting pathogens may be needed also.

Drug resistance is nothing new. The traditional approach to this problem, still potentially useful, is expanding the search for new antibiotics. Historically, many drugs to fight disease-producing microbes have been found as naturally occurring chemicals in soil bacteria. That source may yet provide promising candidates. Even more drug candidates, though, may be available from microbes in more specialized ecological niches or from plants or from bacteria living in remote or harsh environments (e.g. deep lakes and oceans).

Bacteria that live symbiotically with insects, for instance, may offer novel chemical diversity for anti-infective drug searches. Plants provide many interesting compounds with anti-bacterial properties, and genetic manipulation can be used to devise variants of those compounds for testing. And chemical engineers may still be able to create entirely new classes of drug candidate molecules from scratch in the laboratory.

Further strategies involve directing specific counterattacks at the infectious agents' resistance weapons. Treatments can be devised that combine an antibiotic with a second drug that has little antibiotic effect but possesses the power to disarm a bacterial defense molecule. Other hybrid treatments could be devised using compounds that impair the invading pathogen's ability to pump the antibiotic component out of the bacterial cell.

The drug-resistance problem is not limited to bacteria and antibiotics — anti-viral drugs for fighting diseases such as AIDS and influenza face similar problems from emerging strains of resistant viruses. In fact, understanding the development of resistance in viruses is especially critical for designing strategies to prevent pandemics. The use of any anti-microbial drug must be weighed against its contribution to speeding up the appearance of resistant strains.

8.5 What is engineering's role in creating personalized medicine?

The engineering challenges for enabling drug discovery mirror those needed to enable personalized medicine: development of more effective tools and techniques for rapid analysis and diagnosis so that a variety of drugs can be quickly screened and proper treatments can be promptly applied. Current drugs are often prescribed incorrectly or unnecessarily, promoting the development of resistance without real medical benefit.

Quicker, more precise diagnoses may lead to more targeted and effective therapies. Antibiotics that attack a wide range of bacteria have typically been sought, because doctors could not always be sure of the precise bacterium causing an infection. Instruments that can determine the real culprit right away could lead to the use of more narrowly targeted drugs, reducing the risk of promoting resistance. Developing organism-specific antibiotics could become one of the century's most important biomedical engineering challenges.

This could be especially challenging in the case of biological agents specifically designed to be weapons. A system must be in place to rapidly analyze their methods of attacking the body and quickly produce an appropriate medicine. In the case of a virus, small molecules might be engineered to turn off the microbe's reproductive machinery. Instructions for making proteins are stored by genes in DNA. Another biochemical molecule, called "messenger RNA," copies those instructions and carries them to the cell's protein factories. Sometimes other small RNA molecules can attach to the messenger RNA and deactivate it, thereby preventing protein production by blocking the messenger, a process known as RNA interference. Viruses can be blocked by small RNAs in the same manner, if the proper small RNAs can be produced to attach to and deactivate the molecules that reproduce the virus. The key is to decipher rapidly the sequence of chemicals comprising the virus so that effective small RNA molecules can be designed and deployed.

Traditional vaccines have demonstrated the ability to prevent diseases, and even eradicate some such as smallpox. It may be possible to design vaccines to treat diseases as well. Personalized vaccines might be envisioned for either use. But, more effective and reliable manufacturing methods are needed for vaccines, especially when responding to a need for mass immunization in the face of a pandemic.

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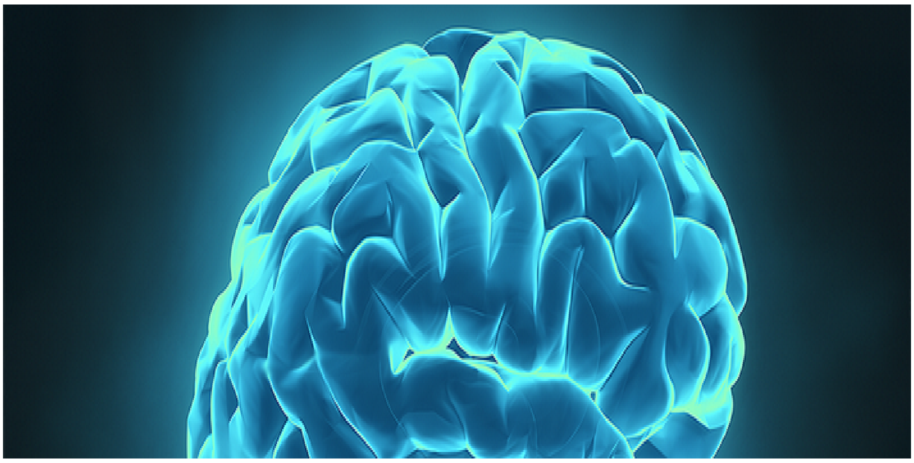
9. Reverse-Engineer the Brain

For decades, some of engineering's best minds have focused their thinking skills on how to create thinking machines — computers capable of emulating human intelligence.



9.1 Why should you reverse-engineer the brain?

While some of thinking machines have mastered specific narrow skills — playing chess, for instance — general-purpose artificial intelligence (AI) has remained elusive.

Part of the problem, some experts now believe, is that artificial brains have been designed without much attention to real ones. Pioneers of artificial intelligence approached thinking the way that aeronautical engineers approached flying without much learning from birds. It has turned out, though, that the secrets about how living brains work may offer the best guide to engineering the artificial variety. Discovering those secrets by reverse-engineering the brain promises enormous opportunities for reproducing intelligence the way assembly lines spit out cars or computers.

Figuring out how the brain works will offer rewards beyond building smarter computers. Advances gained from studying the brain may in return pay dividends for the brain itself. Understanding its methods will enable engineers to simulate its activities, leading to deeper insights about how and why the brain works and fails. Such simulations will offer more precise methods for testing potential biotechnology solutions to brain disorders, such as drugs or neural implants. Neurological disorders may someday be circumvented by technological innovations that allow wiring of new materials into our bodies to do the jobs of lost or damaged nerve cells. Implanted electronic devices could help victims of dementia to remember, blind people to see, and crippled people to walk.

Sophisticated computer simulations could also be used in many other applications. Simulating the interactions of proteins in cells would be a novel way of designing and testing drugs, for instance. And simulation capacity will be helpful beyond biology, perhaps in forecasting the impact of earthquakes in ways that would help guide evacuation and recovery plans.

Much of this power to simulate reality effectively will come from increased computing capability rooted in the reverse-engineering of the brain. Learning from how the brain itself learns, researchers will likely improve knowledge of how to design computing devices that process multiple streams of information in parallel, rather than the one-step-at-a-time approach of the basic PC. Another feature of real brains is the vast connectivity of nerve cells, the biological equivalent of computer signaling switches. While nerve cells typically form tens of thousands of connections with their neighbors, traditional computer switches typically possess only two or three. AI systems attempting to replicate human abilities, such as vision, are now being developed with more, and more complex, connections.

9.2 What are the applications for this information?

Already, some applications using artificial intelligence have benefited from simulations based on brain reverse-engineering. Examples include AI algorithms used in speech recognition and in machine vision systems in automated factories. More advanced AI software should in the future be able to guide devices that can enter the body to perform medical diagnoses and treatments.

Of potentially even greater impact on human health and well-being is the use of new AI insights for repairing broken brains. Damage from injury or disease to the hippocampus, a brain structure important for learning and memory, can disrupt the proper electrical signaling between nerve cells that is needed for forming and recalling memories. With knowledge of the proper signaling patterns in healthy brains, engineers have begun to design computer chips that mimic the brain's own communication skills. Such chips could be useful in cases where healthy brain tissue is starved for information because of the barrier imposed by damaged tissue. In principle, signals from the healthy tissue could be recorded by an implantable chip, which would then generate new signals to bypass the damage. Such an electronic alternate signaling route could help restore normal memory skills to an impaired brain that otherwise could not form them.

“Neural prostheses” have already been put to use in the form of cochlear implants to treat hearing loss and stimulating electrodes to treat Parkinson’s disease. Progress has also been made in developing “artificial retinas,” light-sensitive chips that could help restore vision.

Even more ambitious programs are underway for systems to control artificial limbs. Engineers envision computerized implants capable of receiving the signals from thousands of the brain’s nerve cells and then wirelessly transmitting that information to an interface device that would decode the brain’s intentions. The interface could then send signals to an artificial limb, or even directly to nerves and muscles, giving directions for implementing the desired movements.

Other research has explored, with some success, implants that could literally read the thoughts of immobilized patients and signal an external computer, giving people unable to speak or even move a way to communicate with the outside world.

9.3 What is needed to reverse-engineer the brain?

The progress so far is impressive. But to fully realize the brain's potential to teach us how to make machines learn and think, further advances are needed in the technology for understanding the brain in the first place. Modern noninvasive methods for simultaneously measuring the activity of many brain cells have provided a major boost in that direction, but details of the brain's secret communication code remain to be deciphered. Nerve cells communicate by firing electrical pulses that release small molecules called neurotransmitters, chemical messengers that hop from one nerve cell to a neighbor, inducing the neighbor to fire a signal of its own (or, in some cases, inhibiting the neighbor from sending signals). Because each nerve cell receives messages from tens of thousands of others, and circuits of nerve cells link up in complex networks, it is extremely difficult to completely trace the signaling pathways.

Furthermore, the code itself is complex — nerve cells fire at different rates, depending on the sum of incoming messages. Sometimes the signaling is generated in rapid-fire bursts; sometimes it is more leisurely. And much of mental function seems based on the firing of multiple nerve cells around the brain in synchrony. Teasing out and analyzing all the complexities of nerve cell signals, their dynamics, pathways, and feedback loops, presents a major challenge.

Today's computers have electronic logic gates that are either on or off, but if engineers could replicate neurons' ability to assume various levels of excitation, they could create much more powerful computing machines. Success toward fully understanding brain activity will, in any case, open new avenues for deeper understanding of the basis for intelligence and even consciousness, no doubt providing engineers with insight into even grander accomplishments for enhancing the joy of living.

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10. Prevent Nuclear Terror

Long before 2001, defenders of national security worried about the possible immediate death of 300,000 people and the loss of thousands of square miles of land to productive use through an act of terror.

From the beginnings of the nuclear age, the materials suitable for making a weapon have been accumulating around the world. Even some actual bombs may not be adequately secure against theft or sale in certain countries. Nuclear reactors for research or power are scattered about the globe, capable of producing the raw material for nuclear devices. And the instructions for building explosive devices from such materials have been widely published, suggesting that access to the ingredients would make a bomb a realistic possibility.

“It should not be assumed,” write physicists

Richard Garwin and Georges Charpak, “that terrorists or other groups wishing to make nuclear weapons cannot read.”

Consequently, the main obstacle to a terrorist planning a nuclear nightmare would be acquiring fissile material — plutonium or highly enriched uranium capable of rapid nuclear fission. Nearly 2 million kilograms of each have already been produced and exist in the world today. It takes less than ten kilograms of plutonium, or a few tens of kilograms of highly enriched uranium, to build a bomb.

Fission, or the splitting of an atom's nucleus, was discovered originally in uranium. For a bomb, you need a highly enriched mass of uranium typically consisting of 90 percent uranium-235, a form found at levels of less than 1 percent in uranium ore. Fuel for nuclear power reactors is only enriched 3 percent to 5 percent with respect to this trace form of uranium, and so is no good for explosions. Highly enriched bomb-grade uranium is, however, produced for some reactors (such as those used to power nuclear submarines and for some research reactors) and might be diverted to terrorists.

Besides uranium, another serious concern is the synthetic radioactive element plutonium. Produced by the nuclear “burning” of uranium in reactors, plutonium is a radioactive hazard in itself and also an ideal fuel for nuclear explosives. Worldwide, more than 1,000 reactors operate nowadays, some producing electric power, others mostly used for research. Plutonium produced in either reactor type could be extracted for use in weapons.

Nuclear security therefore represents one of the most urgent policy issues of the 21st century. In addition to its political and institutional aspects, it poses acute technical issues as well. In short, engineering shares the formidable challenges of finding all the dangerous nuclear material in the world, keeping track of it, securing it, and detecting its diversion or transport for terrorist use.

10.1 What are the challenges to preventing nuclear terror attacks?

Challenges include: (1) how to secure the materials; (2) how to detect, especially at a distance; (3) how to render a potential device harmless; (4) emergency response, cleanup, and public communication after a nuclear explosion; and (5) determining who did it. All of these have engineering components; some are purely technical and others are systems challenges.

Some of the technical issues are informational — it is essential to have a sound system for keeping track of weapons and nuclear materials known to exist, in order to protect against their theft or purchase on the black market by terrorists.

Another possible danger is that sophisticated terrorists could buy the innards of a dismantled bomb, or fuel from a nuclear power plant, and build a homemade explosive device. It is conceivable that such a device would produce considerable damage, with explosive power perhaps a tenth of the bomb that destroyed Hiroshima.

With help from renegade professional designers, terrorists might even build a more powerful device, equaling or exceeding the force of the Hiroshima bomb. Detonated in a large city, such a bomb could kill 100,000 people or more.

Building a full-scale bomb would not be easy, so terrorists might attempt instead to cause other forms of nuclear chaos, possibly using conventional explosives to blast and scatter radioactive material around a city. Such “dirty bombs” might cause relatively few immediate deaths, but they could contaminate large areas of land, cause potential economic havoc to the operation of a city, and increase long-term cancer incidence. There are millions of potential sources of radioactive material, which is widely used in hospitals, research facilities, and industry -- so preventing access is extremely difficult. Responding to a “dirty bomb” attack would also involve engineering challenges ranging from monitoring to cleanup, of both people and places.

Concern for nuclear security complicates the use of nuclear energy for peaceful purposes, such as generating electricity. Ensuring that a nation using nuclear power for energy does not extract plutonium for bomb building is not easy. Diversion of plutonium is much more difficult when a country opts for a “once through” fuel cycle that keeps the plutonium with the highly radioactive spent fuel, rather than a “closed” fuel cycle where spent fuel is reprocessed and plutonium separated out. Simple record keeping could be faked or circumvented. Regulations requiring human inspection and video monitoring are surely not foolproof.

10.2 What are the possible engineering solutions?

A possible engineering solution would be the development of a passive device, situated near a reactor, which could transmit real-time data on the reactor’s contents, betraying any removal of plutonium. (This sort of device would be especially useful if it could also detect signs that the reactor was being operated in a way to maximize plutonium production rather than power.) Such devices are already being designed and tested.

Of course, if dangerous nuclear materials are diverted from a power reactor, or probably more likely from some other source, preventing their transportation to a possible point of use remains a serious problem. Protecting U.S. borders from nuclear transgression poses a formidable challenge, because so many imports are legitimately shipped into the country within large shipping containers. Individual inspection of each container would be costly and very disruptive — each can hold 30 tons, and roughly 10 million arrive in the United States every year.

Various ways of detecting nuclear materials hidden in such containers have been proposed or tested, but most are ineffective.

One new approach has shown promise, though. Nicknamed the “nuclear car wash,” it consists of a sophisticated scanning system that containers would pass by while on a conveyor belt, much as a vehicle glides through an automated car wash. As the containers pass the device, they receive pulses of neutrons, a common subatomic particle often used to induce nuclear reactions. In this case, the neutrons would induce fission in any weapons-grade nuclear materials within the container. The fission, in turn, produces radioactive substances that would emit gamma rays, a form of radiation that could be reliably detected from outside the container. Still, it leaves residual radioactivity and could be shielded with a large amount of water. High-energy X-rays leave no radioactivity, and may even be able to detect shields against their beams, but they damage sensitive material like photographic film.

A simulation program might be engineered that would help shippers in packing, ensuring that it leaves acceptable detail for current security scanning of the contents. Incentives might include charging for more complex scans when items are shielded by their packing.

There are already real-time mutual surveillance systems in operation between Russia and the U.S.’s Sandia National Laboratory to ensure that there is no unauthorized access to storage containers of weapons-usable materials. A challenge for engineers would be to expand such schemes at a reasonable cost.

No doubt other nuclear challenges will surface and additional engineering methods will be needed to protect against the variety of possible nuclear assaults. But the ingenuity of systems and nuclear engineers, and the deep understanding of nature’s nuclear secrets provided by basic physics research, offer encouragement that those challenges can be met in the 21st century.

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11. Secure Cyberspace

Personal privacy and national security in the 21st century both depend on protecting a set of systems that didn’t even exist until late in the 20th — the electronic web of information-sharing known as cyberspace.

11.1 Why is cyberspace security important?

Electronic computing and communication pose some of the most complex challenges engineering has ever faced. They range from protecting the confidentiality and integrity of transmitted information and deterring identity theft to preventing the scenario recently dramatized in the Bruce Willis movie "*Live Free or Die Hard,*" in which hackers take down the transportation system, then communications, and finally the power grid.

As that movie depicted, networks of electronic information flow are now embedded in nearly every aspect of modern life. From controlling traffic lights to routing airplanes, computer systems govern virtually every form of transportation. Radio and TV signals, cell phones, and (obviously) e-mail all provide vivid examples of how communication depends on computers — not only in daily life, but also for military, financial, and emergency services. Utility systems providing electricity, gas, and water can be crippled by cyberspace disruptions. Attacks on any of these networks would potentially have disastrous consequences for individuals and for society.

In fact, serious breaches of cybersecurity in financial and military computer systems have already occurred. Identity theft is a burgeoning problem. Viruses and other cyber-attacks plague computers small and large and disrupt commerce and communication on the Internet.

Yet research and development for security systems has not progressed much beyond a strategy akin to plugging the hole in the dike — cobbling together software patches when vulnerabilities are discovered.

11.2 What are the engineering solutions for securing cyberspace?

Historically, the usual approach to computer protection has been what is called “perimeter defense.” It is implemented by placing routers and “firewalls” at the entry point of a sub-network to block access from outside attackers. Cybersecurity experts know well that the perimeter defense approach doesn’t work. All such defenses can eventually be penetrated or bypassed. And even without such breaches, systems can be compromised, as when flooding Web sites with bogus requests will cause servers to crash in what is referred to as a “denial of service” attack or when bad guys are already inside the perimeter.

The problems are currently more obvious than the potential solutions. It is clear that engineering needs to develop innovations for addressing a long list of cybersecurity priorities. For one, better approaches are needed to authenticate hardware, software, and data in computer systems and to verify user identities.

Biometric technologies, such as fingerprint readers, may be one step in that direction.

A critical challenge is engineering more secure software. One way to do this may be through better programming languages that have security protection built into the ways programs are written. And technology is needed that would be able to detect vulnerable features before software is installed, rather then waiting for an attack after it is put into use.

Another challenge is providing better security for data flowing over various routes on the Internet so that the information cannot be diverted, monitored, or altered. Current protocols for directing data traffic on the Internet can be exploited to make messages appear to come from someplace other than their true origin.

All engineering approaches to achieving security must be accompanied by methods of monitoring and quickly detecting any security compromises. And then once problems are detected, technologies for taking countermeasures and for repair and recovery must be in place as well. Part of that process should be new forensics for finding and catching criminals who commit cybercrime or cyberterrorism.

Finally, engineers must recognize that a cybersecurity system’s success depends on understanding the safety of the whole system, not merely protecting its individual parts. Consequently cybercrime and cyberterrorism must be fought on the personal, social, and political fronts as well as the electronic front.

Among other things, that means considering the psychology of computer users — if security systems are burdensome, people may avoid using them, preferring convenience and functionality to security. More research is needed on how people interact with their computers, with the Internet, and with the information culture in general. Cultural and social influences can affect how people use computers and electronic information in ways that increase the risk of cybersecurity breaches.

It would also be helpful to gain a better understanding of the psychology and sociology that leads to deliberate computer crime. Systems must be secure not just against outsiders, but also against insiders who might sabotage a system from within.

Furthermore, laws and regulations concerning cybersecurity need to be evaluated for their influence on how people use or misuse electronic information. And perhaps most important, political forces need to be marshaled to support and fund the many lines of research that will be needed to accomplish the complex task of protecting cyberspace from attack.

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12. Enhance Virtual Reality

To most people, virtual reality consists mainly of clever illusions for enhancing computer video games or thickening the plot of science fiction films. Depictions of virtual reality in Hollywood movies range from the crude video-viewing contraption of 1983’s "*Brainstorm*" to the entire virtual universe known as "*The Matrix.*"

But within many specialized fields, from psychiatry to education, virtual reality is becoming a powerful new tool for training practitioners and treating patients, in addition to its growing use in various forms of entertainment. Virtual reality is already being used in industrial design, for example. Engineers are creating entire cars and airplanes "virtually" in order to test design principles, ergonomics, safety schemes, access for maintenance, and more.

12.1 What is virtual reality?

Basically, virtual reality is simply an illusory environment, engineered to give users the impression of being somewhere other than where they are. As you sit safely in your home, virtual reality can transport you to a football game, a rock concert, a submarine exploring the depths of the ocean, or a space station orbiting Jupiter. It allows the user to ride a camel around the Great Pyramids, fly jets, or perform brain surgery.

True virtual reality does more than merely depict scenes of such activities — it creates an illusion of actually being there. Piloting a Boeing 777 with a laptop flight simulator, after all, does not really convey a sense of zooming across the continent 5 miles above the surface of a planet. Virtual reality, though, attempts to re-create the actual experience, combining vision, sound, touch, and feelings of motion engineered to give the brain a realistic set of sensations.

And it works. Studies show that people immersed in a virtual reality scene at the edge of a cliff, for instance, respond realistically — the heart rate rises and the brain resists commands to step over the edge. There are significant social applications as well. It has been shown that people also respond realistically in interactions with life-sized virtual characters, for example exhibiting anxiety when asked to cause pain to a virtual character, even though the user knows it's not a real person and such anxiety makes no rational sense. It is clearly possible to trick the brain into reacting as though an illusory environment were real.

What are the practical applications of virtual reality?

Virtual reality offers a large array of potential uses. Already it has been enlisted to treat people suffering from certain phobias. Exposing people who are afraid of heights to virtual cliff edges has been shown to reduce that fear, in a manner much safer than walking along real cliffs. Similar success has been achieved treating fear of spiders.

Other experiments have tested virtual reality's use in treating social anxieties, such as fear of public speaking, and show that it can be a successful treatment for some more serious disorders, such as post-traumatic stress disorder. Virtual reality also offers advantages for various sorts of research, education, and training. Some neuroscientists believe that virtual reality experiments can provide insight into the nature of awareness and consciousness itself. Surgeons can practice virtual operations before cutting into real people; soldiers can learn combat tactics in virtual worlds without shooting real bullets.

Virtual reality could also be used in business, advancing video conferencing to a level in which people located in widely dispersed parts of the world can interact in a shared environment and carry out tasks together. Meeting the engineering challenge of allowing dispersed people to seamlessly see, hear, and touch each other, as well as share real objects and equipment, would be particularly useful for the military and emergency response teams, too.

All of these scenarios involve outfitting the user with a virtual reality interface — often a display screen mounted on the head so as to cover the eyes and ears — that communicates with a computer. The computer stores all the necessary information to generate the virtual scenes and sounds. Typically, the visual and auditory information is transmitted separately to each eye and ear, giving realistic stereovision images and two- or three-dimensional impression of sounds. As users move their heads, the computer quickly generates new images to reflect what people moving about in a real world would see next. Since head movements result in corresponding changes to what is seen, as they do in real life, this acts as a very powerful mechanism for immersing the user in the virtual world.

12.2 What engineering advances are needed?

For virtual reality systems to fully simulate reality effectively, several engineering hurdles must be overcome. The resolution of the video display must be high enough, with fast enough refresh and update rates, for scenes to look like and change like they do in real life. The field of view must be wide enough and the lighting and shadows must be realistic enough to maintain the illusion of a real scene. And for serious simulations, reproducing sensations of sound, touch, and motion are especially critical.

While advances have been made on all of these fronts, virtual reality still falls short of some of its more ambitious depictions. Fine-grained details of the virtual environment are impossible to reproduce precisely. In particular, placing realistic “virtual people” in the scene to interact with the user poses a formidable challenge.

“Rendering of a virtual human that can purposefully interact with a real person — for example, through speech recognition, the generation of meaningful sentences, facial expression, emotion, skin color and tone, and muscle and joint movements — is still beyond the capabilities of real-time computer graphics and artificial intelligence,” write neuroscientist Maria V. Sanchez-Vives and computer scientist Mel Slater. [Sanchez-Vives, p. 335]

Yet virtual reality users routinely respond to even crude “virtual people” as though they are real. So one of the challenges of virtual reality research is identifying just what level of detail is necessary for a user to accept the illusion, in other words to respond to virtual events and simulations in a realistic way. Already, it seems that visually precise detail may not be as important as accurate reproduction of sound and touch.

Touch poses an especially formidable challenge. For some uses, gloves containing sensors can record the movements of a user's hand and provide tactile feedback, but somewhat crudely. That's not good enough to train a surgeon who, when cutting through virtual tissue, should feel different degrees of resistance to the motion of a scalpel at different places along the tissue. Moreover, with today's technology you can't feel an accidental bump against a virtual piece of furniture.

Efforts to solve such problems are in the beginning stages. One possible approach would make use of electrorheological fluids, which alter their thickness when exposed to electric fields of different strengths. Perhaps an advanced virtual reality computer could make use of this effect to send electrical signals to adjust a glove or garment’s resistance to touch, providing touch feedback to the user.

It may not be virtual reality per se, but a related concept also seems to be growing in cyberspace, as the World Wide Web has become host to whole worlds populated by virtual people guided by their real-world owners. One such site, known as Second Life, already has millions of participants, some who just visit, some who buy virtual property, establish virtual businesses, and communicate and form relationships with other inhabitants through various communication channels.

What’s more, such worlds could be in the process of merging with the real world, as computer records of the physical environment (as available via Google Earth or Microsoft’s Virtual Earth) could be interlaced with the sites like Second Life. It would then be possible to virtually visit real locations, explore a city’s restaurants and hotels, and engage in other virtual tourist activities.

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13. Advance Personalized Learning

For years, researchers have debated whether phonics or whole-word recognition is the best way to teach children how to read. Various experts can be found who will advocate one approach or the other.

Ask an astute first-grade teacher, though, and the answer is likely to be that it depends on the kid. Some pupils respond more favorably to the whole-word approach; others learn faster with phonics. Young brains (and older brains, for that matter) are not all alike. Learning is personal.

Throughout the educational system, teaching has traditionally followed a one-size-fits-all approach to learning, with a single set of instructions provided identically to everybody in a given class, regardless of differences in aptitude or interest. Similar inflexibility has persisted in adult education programs that ignore differences in age, cultural background, occupation, and level of motivation.

In recent years, a growing appreciation of individual preferences and aptitudes has led toward more “personalized learning,” in which instruction is tailored to a student’s individual needs. Personal learning approaches range from modules that students can master at their own pace to computer programs designed to match the way it presents content with a learner’s personality.

13.1 Why is personalized learning useful?

Some learners are highly self-motivated and self-driven, learning best by exploring a realm of knowledge on their own or at least with very little guidance. Other learners prefer some coaching and a more structured approach; they are typically self-motivated when the subject matter appeals to their interests. Still another type is more often motivated by external rewards and may learn best with step-by-step instruction. Some may resist learning altogether and have little motivation or interest in achieving goals established by others.

These general categorizations provide a base for developing personalized instruction, but truly personalized learning could be even more subtly individualized. Within the basic types of learners, some prefer to learn by example, others by finding answers to questions, and others by solving problems on their own. Under different conditions, people might even switch their preferences, preferring examples in some contexts but questions in others.

Not surprisingly, many efforts to take this into account make use of computerized instruction, often in the classroom or via the Internet. Among the many projects attempting to meet the personalized education challenge are “intelligent” Web-based education systems, development of “recommender” systems that guide individual learning using Web-based resources, and creation of algorithms that adjust recommendations to the abilities of the student.

13.2 What personalized learning systems are available now?

Web-based education systems are already common. Systems have been designed for storing instructional content, delivering it to students, and facilitating the interaction between instructors and learners. Multimedia modules of information can provide text, audio, video, animation, or static graphics in any order suitable for the student.

The delivery of instructional material is an important part of personalized learning. For example, different sequences are used in intelligent tutoring systems to deliver content tailored for each individual. Aspects of this approach may include the use of pre-assessments to gauge an individual’s most effective learning habits. The information collected can then be used to modify the sequence of material presented.

Many methods for optimizing the order of presentation have been explored. One novel approach, used in other fields to solve complex problems, is the mathematical method known as the genetic algorithm (so named because of its similarity to evolutionary natural selection). It eliminates unsuccessful presentation sequences and modifies successful ones for a new round of tests, in which the least successful are again eliminated and the best are modified once more.

While some personalized learning methods apply to education in general, other systems may be designed for specific learning problems, such as a recommender system for mastering a second language.

Recommender systems are widely encountered on the Web — search engines that fail to find a particular term often recommend alternatives, for instance, and pages that sell books or music will suggest additional purchases based on what someone has already bought. But such systems have not yet been developed extensively for education.

A particular recommender system for learning English as a second language helps find the reading lessons most suited to motivating an individual learner. In this system, students' errors and learning weaknesses are tracked, and the students can rate the lessons that they are given. Data on weaknesses and interest are then used to generate a lesson tailored to the individual.

13.3 What can engineering do to improve learning?

Ongoing research in neuroscience is providing new insights into the intricacies of neural processes underlying learning, offering clues to further refine individualized instruction. Given the diversity of individual preferences, and the complexity of each human brain, developing teaching methods that optimize learning is a major challenge for the software engineers of the future.

Engineers will have roles in most aspects of these complex problems, though the solutions will require contributions of people from many disciplines. Further challenges await as advances in neuroscience and medical measurement technology probe the very foundations of learning in the brain. Mastery of these processes in advanced software could make learning more reliable. New research may even provide the path to something like immediate knowledge acquisition, as when a character named Trinity in the movie "*The Matrix*" learns to fly a helicopter through an instant download to her brain. Knowledge transfers of such complexity may not become commonplace in the 21st century, but a movie with such scenes may no longer be viewed as so far-fetched.

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14. Engineer the Tools of Scientific Discovery

In the popular mind, scientists and engineers have distinct job descriptions. Scientists explore, experiment, and discover; engineers create, design, and build.

But in truth, the distinction is blurry, and engineers participate in the scientific process of discovery in many ways. Grand experiments and missions of exploration always need engineering expertise to design the tools, instruments, and systems that make it possible to acquire new knowledge about the physical and biological worlds.

In the century ahead, engineers will continue to be partners with scientists in the great quest for understanding many unanswered questions of nature.

14.1 How will engineering impact biological research?

Biologists are always seeking, for instance, better tools for imaging the body and the brain. Many mysteries also remain in the catalog of human genes involving exactly how genes work in processes of activation and inhibition. Scientists still have much to learn about the relationship of genes and disease, as well as the possible role of large sections of our DNA that seem to be junk with no function, leftover from evolution.

To explore such realms, biologists will depend on engineering help — perhaps in the form of new kinds of microscopes, or new biochemical methods of probing the body’s cellular and molecular machinations. New mathematical and computing methods, incorporated into the emerging discipline of “systems biology,” may show the way to better treatments of disease and better understanding of healthy life. Perhaps even more intriguing, the bioengineering discipline known as “synthetic biology” may enable the design of entirely novel biological chemicals and systems that could prove useful in applications ranging from fuels to medicines to environmental cleanup and more.

Turning to the mysteries of our own minds, new methods for studying the brain should assist the study of memory, learning, emotions, and thought. In the process, mental disorders may be conquered and learning and thinking skills enhanced. Ultimately, such advances may lead to a credible answer to the deepest of human mysteries, the question of the origin and nature of consciousness itself.

14.2 How will engineering help us explore the universe?

In its profundity, only one question compares with that of consciousness — whether the universe is host to forms of life anywhere else than on Earth. Systems capable of probing the cosmos for evidence surely represent one of engineering’s grandest challenges.

Even apart from the question of extraterrestrial life, the exploration of space poses a considerable challenge. Long-distance human space flight faces numerous obstacles, from the danger of radiation to the need to supply sustainable sources of food, water, and oxygen. Engineering expertise will be critical to overcoming those obstacles, and many efforts to expand that expertise are underway. One line of research, for example, envisions a set of connected bioreactors populated by carefully chosen microbes. Metabolism by the microbes could convert human wastes (and in some cases the microbes' own wastes) into the resources needed to support long-term travel through space.

But the allure of space extends well beyond the desire to seek novel life and explore new phenomena. Space represents the mystery of existence itself. The universe's size and age exceeds most people's comprehension. Many of its less obvious features have been fathomed by the methods and tools of modern astrophysics, revealing that, amazingly, our entire universe seems to have arisen in an initial fireball from an infinitely small point. Matter and energy coalesced into such structures as galaxies, stars, and planets supporting the even more intricate atomic arrangements making up minerals, plants, and animals.

Beneath all this compelling complexity lies an embarrassing fact — scientists do not know what most of the universe is made of. We only understand a small percentage of all the matter and energy in the cosmos. The greatest part of matter is a dark form of unknown identity, and even more abundant is a mysterious energy that exerts a repulsive force on space, inducing the universe to expand at an ever-increasing rate.

Engineers have continually been at work on better, and cheaper, ways to search space for answers to these questions. New and improved telescopes, both on the ground and in space, make up part of the investigatory arsenal. Other devices measure waves of gravity rippling through space, or detect the flux of the elusive lightweight particle known as the neutrino.

Whether these and other approaches can shed sufficient light to disclose the universe’s darkest secrets remains unknown. It may be that further investigation of earthly materials will be needed as well, along with the continued assault on the problems of physics with the power of thought, an approach used so successfully by Einstein. Maybe answers will come only if scientists can succeed in discovering the ultimate laws of physics.

In that regard, the underlying question is whether there exists, as Einstein believed, one single, ultimate underlying law that encompasses all physics in a unified mathematical framework. Finding out may require new tools to unlock the secrets of matter and energy. Perhaps engineers will be able to devise smaller, cheaper, but more powerful atom smashers, enabling physicists to explore realms beyond the reach of current technology.

Another possible avenue to discovering a unified law might be by achieving a deeper understanding of how the world’s tiniest and most basic building blocks work, the foundations of quantum physics. Engineers and physicists are already collaborating to develop computers based on quantum principles. Such computers, in addition to their possible practical value, may reveal new insights into the quantum world itself.

All things considered, the frontiers of nature represent the grandest of challenges, for engineers, scientists, and society itself. Engineering’s success in finding answers to nature’s mysteries will not only advance the understanding of life and the cosmos, but also provide engineers with fantastic new prospects to apply in enterprises that enhance the joy of living and the vitality of human civilization.