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THE FUTURE POSTPONED

Why Declining Investment in Basic Research Threatens a U.S. Innovation Deficit

A Report by the MIT Committee to Evaluate the Innovation Deficit

THE MIT COMMITTEE TO EVALUATE THE INNOVATION DEFICIT

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Illustrative Case Studies

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The world's fastest supercomputer resides at the Chinese National Defense University at Guangzhou, a potent symbol of China's growing science and technology power and the expanding U.S. innovation deficit.

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All authors are MIT faculty unless otherwise noted.

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INTRODUCTION

2014 was a year of notable scientific highlights, including:

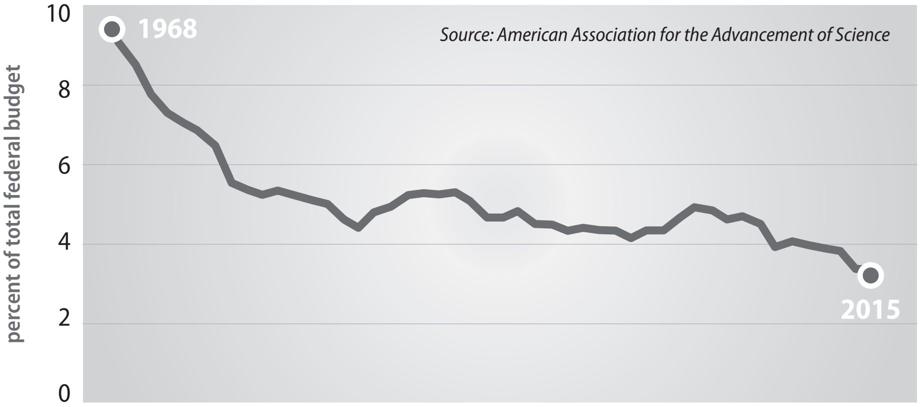
- the first landing on a comet, which has already shed important light on the formation of the Earth;
- the discovery of a new fundamental particle, which provides critical information on the origin of the universe;
- development of the world's fastest supercomputer;
- a surge in research on plant biology that is uncovering new and better ways to meet global food requirements.

None of these, however, were U.S.-led achievements. The first two reflected 10-year, European-led efforts; the second two are Chinese accomplishments, reflecting that nation's emergence as a science and technology power. Hence the wide-spread concern over a growing U.S. innovation deficit, attributable in part to declining public investment in research (see ***figure***).

This report provides a number of tangible examples of under-exploited areas of science and likely consequences in the form of an innovation deficit, including:

- opportunities with high potential for big payoffs in health, energy, and high-tech industries;

Federal R&D | *Outlays as share of total federal budget, 1968–2015*



Source: American Association for the Advancement of Science

- fields where we risk falling behind in critical strategic capabilities such as supercomputing, secure information systems, and national defense technologies;
- areas where national prestige is at stake, such as space exploration, or where a lack of specialized U.S research facilities is driving key scientific talent to work overseas.

This introduction also cites examples of the benefits from basic research that have helped to shape and maintain U.S. economic power, as well as highlighting industry trends that have made university basic research even more critical to future national economic competitiveness.

Basic research is often misunderstood, because it often seems to have no immediate payoff. Yet it was just such federally-funded research into the fundamental working of cells, intensified beginning with the "War on Cancer" in 1971, that led over time to a growing arsenal of sophisticated new anti-cancer therapies—19 new drugs approved by the U.S. FDA in the past 2 years. Do we want similar progress on Alzheimer's, which already affects 5 million Americans, more than any single form of cancer? Then we should expand research in neurobiology, brain chemistry, and the science of aging (see ***Alzheimer's Disease***). The Ebola epidemic in West Africa is a reminder of how vulnerable we are to a wider pandemic of emergent viral diseases, because of a lack of research on their biology; an even greater public health threat looms from the rise of antibiotic resistant bacteria right here at home, which, because commercial incentives are lacking, only expanded university-based research into new types of antibiotics can address (see ***Infectious Disease***).

America's emergence last year as the world's largest oil producer has been justly celebrated as a milestone for energy independence. But the roots of the fracking revolution stem from federally-funded research—begun in the wake of the first OPEC oil embargo 40 years ago—that led to directional drilling technology, diamond drill bits tough enough to cut shale, and the first major hydraulic fracturing experiments. Do we also want the U.S. to be a leader in clean energy technologies a few decades hence, when these will be needed for large scale replacement of fossil energy sources, a huge global market? Then now is when more investment in advanced thin film solar cells, new battery concepts, and novel approaches to fusion energy should begin (see ***Materials Discovery and Processing, Batteries, Fusion Energy***).

Some areas of research create opportunities of obvious economic importance. Catalysis, for example, is already a $500 billion industry in the United States alone and plays a critical role in the manufacture of virtually every fuel, all types of plastics, and many pharmaceuticals. Yet today's catalysts are relatively inefficient and require high temperatures compared to those (such as enzymes) that operate in living things. So the potential payoff in both reduced environmental impact and a powerful economic edge for countries that invest in efforts to understand and replicate these biological catalysts—as Germany and China already are—could be huge (see ***Catalysis***). The U.S. also lags in two other key areas: developing advances in plant sciences that can help meet growing world needs for food while supporting U.S. agricultural exports, and the growing field of robotics that is important not only for automated factories but for a whole new era of automated services such as driverless vehicles (see ***Plant Sciences*** and ***Robotics***).

In an increasingly global and competitive world, *where* knowledge is created and first applied has huge economic consequences: some 50 years after the rise of Silicon Valley, the U.S. still leads in the commercial application of integrated circuits, advanced electronic devices, and internet businesses. But foreseeable advances in optical integrated circuits, where both Europe and Japan are investing heavily, is likely to completely reshape the $300 billion semiconductor industry that today is largely dominated by U.S. companies (see ***Photonics***). In this area and other fields of science that will underlie the innovation centers of the future, U.S. leadership or even competitiveness is at risk. Synthetic biology—the ability to redesign life in the lab—is another area that has huge potential to transform bio-manufacturing and food production and to create breakthroughs in healthcare—markets that might easily exceed the size of the technology market. But it is EU scientists that benefit from superior facilities and dedicated funding and are leading the way (see ***Synthetic Biology***). Research progress in many such fields increasingly depends on sophisticated modern laboratories and research instruments, the growing lack of which in the U.S. is contributing to a migration of top talent and research leadership overseas.

Some areas of research are so strategically important that for the U.S. to fall behind ought to be alarming. Yet Chinese leadership in supercomputing—its Tianhe-2 machine at the Chinese National University of Defense in Guangzhou has won top ranking for the third year in a row and can now do quadrillions of calculations per second—is just such a straw in the wind. Another is our apparent and growing vulnerability to cyberattacks of the type that have damaged Sony, major banks, large retailers, and other major companies. Ultimately, it will be basic research in areas such as photonics, cybersecurity, and quantum computing (where China is investing heavily) that determine leadership in secure information systems, in secure long distance communications, and in supercomputing (see ***Cybersecurity*** and ***Quantum Information Systems***). Recent budget cuts have impacted U.S. efforts in all these areas. Also, technologies are now in view that could markedly improve the way we protect our soldiers and other war fighters while improving their effectiveness in combat (see ***Defense Technology***).

It is not just areas of science with obvious applications that are important. Some observers have asked, "What good is it?" of the discovery of the Higgs boson (the particle referred to above, which fills a major gap in our understanding of the fundamental nature of matter). But it is useful to remember that similar comments might have been made when the double helix structure of DNA was first understood (many decades before the first biotech drug), when the first transistor emerged from research in solid state physics (many decades before the IT revolution), when radio waves were first discovered (long before radios or broadcast networks were even conceived of). We are a remarkably inventive species, and seem always to find ways to put new knowledge to work.

Other potential discoveries could have global impacts of a different kind. Astronomers have now identified hundreds of planets around other stars, and some of them are clearly Earth-like. Imagine what it would mean to our human perspective if we were to discover evidence of life on these planets—a signal that we are not alone in the universe—from observations of their planetary atmospheres, something that is potentially within the technical capability of space-based research within the next decade? Or if the next generation of space telescopes can discover the true nature of the mysterious "dark matter" and "dark energy" that appear to be the dominant constituents of the universe (see ***Space Exploration***).

Do we want more efficient government, more market-friendly regulatory structures? Social and economic research is increasingly able to provide policymakers with useful guidance. Witness the way government has helped to create mobile and broadband markets by auctioning the wireless spectrum—complex, carefully-designed auctions based on insights from game theory and related research that have netted the federal government more than $60 billion while catalyzing huge new industries and transformed the way we live and do business. Empowered by access to more government data and Big Data tools, such research could point the way to still more efficient government (see ***Enabling Better Policy Decisions***).

In the past, U.S. industry took a long term view of R&D and did fundamental research, activities associated with such entities as the now-diminished Bell Labs and Xerox Park. That's still the case in some other countries such as South Korea. Samsung, for example, spent decades of effort to develop the underlying science and manufacturing behind organic light-emitting diodes (OLEDs) before commercializing these into the now familiar, dramatic displays in TVs and many other digital devices. But today, as competitive pressures have increased, basic research has essentially disappeared from U.S. companies, leaving them dependent on federally-funded, university-based basic research to fuel innovation. This shift means that federal support of basic research is even more tightly coupled to national economic competitiveness. Moreover, there will always be circumstances when private investment lags—when the innovation creates a public good, such as clean air, for which an investor can't capture the value, or when the risk is too high, such as novel approaches to new antibiotic drugs, or when the technical complexity is so high that there is fundamental uncertainty as to the outcome, such as with quantum computing or fusion energy. For these cases, government funding is the only possible source to spur innovation.

This central role of federal research support means that sudden changes in funding levels such as the recent sequester can disrupt research efforts and cause long term damage, especially to the pipeline of scientific talent on which U.S. research leadership ultimately depends. In a survey of the effects of reduced research funding conducted by the Chronicle of Higher Education last year among 11,000 recipients of NIH and NSF research grants, nearly half have abandoned an area of investigation they considered critical to their lab's mission, and more than three quarters have fired or failed to hire graduate students and research fellows. Other evidence suggests that many of those affected switch careers, leaving basic research behind forever.

Despite these challenges, the potential benefits from expanding basic research summarized in these pages—an *innovation dividend* that could boost our economy, improve human lives, and strengthen the U.S. strategically—are truly inspiring. We hope you will find the information useful.

ALZHEIMER'S DISEASE

We Are Seeing Breakthroughs in Treating Cancer—Why Not Alzheimer's?

In the past two years the FDA approved 19 new cancer drugs, and more are in the pipeline—including a powerful new class of immunotherapies that have the potential to transform many deadly cancers into managable chronic conditions. In contrast, during the past decade not a single new drug for Alzheimer's Disease has been approved. Yet over 5 million Americans currently suffer from Alzheimer's—more than for most forms of cancer—and AD prevalence is projected to double in coming decades.

The disparity is shocking, but the reason for it is quite simple: cancer is much better understood than AD. And that in turn stems from more than four decades of sustained investment in basic research into the biology of cancer, beginning in 1971 when President Nixon launched the "War on Cancer." Within a decade, the budget of the National Cancer Institute had tripled. And by the end of the century, enough was known about the mechanisms of cancer and potential targets and pathways for drug therapies that pharma and biotech companies could begin to invest large sums of private capital in drug development with a reasonable chance of success. Today's bounty of oncology drugs is the result, but it would not have happened without the foundational knowledge from which to begin.

Alzheimer's Disease has its own unique challenges. AD drugs will be more costly to develop because of the need to follow patients over longer periods, the expense of current neuroimaging techniques, and the difficulty of brain biopsies. Even more challenging is that the blood/brain barrier blocks most drugs—and all large molecule drugs—from even reaching affected cells. But even before drug development can begin, many basic questions remain unanswered: very little is known about what causes AD, how and when it begins, how it progresses, and whether it can be slowed, arrested, or reversed. The foundational knowledge is simply missing. Yet Medicare spending for Alzheimer's treatment is now $150 billion per year and growing rapidly. Private burdens are high too—last year caregivers provided 17 billion hours of unpaid care for AD family members. Total public and private costs in the U.S. are expected to reach $1.2 trillion by 2050.

There are, however, real opportunities for progress. One might be simply to slow the aging process itself, by altering what appears to be an internal "clock" that drives the process. There are strong but imperfectly understood links between nutrition and human development beginning in utero and continuing throughout life, and it is well established that sharply restricted, low-calorie diets can slow the aging

Under current funding constraints, the National Institute of Aging can fund only 6 percent of the research ideas it receives.

clock. If we understood the links better, could drugs or sophisticated nutritional interventions be found that have the same effect? In fact, drugs that activate a particular group of genes known as sirtuins are showing promise in extending lifetimes and mitigating age-related diseases in animal models, but they need further investigation and exploration of their impact on Alzheimer's.

Another opportunity might come from exploring in detail how brain cells communicate with each other—in effect mapping and understanding the brain's neural circuitry and comparing the circuit diagrams of healthy versus AD patients. For some other brain diseases—severe depression, Parkinson's disease—electrical stimulation of the brain has proved helpful. If we understood how the neural circuitry was affected by Alzheimer's, might a similar non-invasive electrical stimulation approach be of use?

Finally, it is becoming clear that there are likely many causes of Alzheimer's—many different genes that increase the risk. Yet virtually all of the clinical trials of potential AD drugs so far have focused only on a couple of genes—those that appear to trigger early onset forms of the disease. Classifying AD patients by their genetic variations, identifying the relevant genes, and understanding the mechanisms that they control or influence might lead both to a deeper understanding of the disease and to potential targets for drug development.

So it is a good thing that the "War on Alzheimer's" is beginning, with the passage of the National Alzheimer's Project Act (NAPA) in January 2011 and the creation of the Brain Initiative in 2013 which coordinates brain disease research efforts at NIH, NSF, and DARPA. Just as with cancer, it will likely take decades of sustained and rising investments in basic research to understand Alzheimer's, other dementias, and the fundamental biology of the brain well enough that drug development has a reasonable chance of success. Yet under current funding constraints, the National Institute of Aging can fund only 6 percent of the research ideas it receives. If we are serious about mitigating the human tragedy of AD and reducing the huge financial burden of caring for millions of affected seniors, then the time to start these investments is now.

CYBERSECURITY

Hack attacks are not just a nuisance; they cause costly harm and could threaten critical systems. Can they be stopped?

The recent cyberattack on Sony released embarrassing private emails, temporarily stalled the release of a film, and caused other reputational and economic harm. But while dramatic, this incident is hardly unusual. Hacking of computer systems, theft of commercial and personal data, and other cyberattacks costs the nation billions of dollars per year. The number of attacks are increasing rapidly, and so are the range of targets: major retailers (Target and Home Depot), newspapers (The New York Times), major banks (Morgan Chase), even savvy IT companies (Microsoft). The global cost of continuing to use insecure IT systems is estimated at about $400 billion per year.

Cyber insecurity also has national security implications, stemming from theft of military technology secrets. For example, China is believed to be copying designs of our most advanced aircraft and may be developing the technology to attack or disable our weapons systems through cyber means. Likewise, because computer processors linked to networks are now embedded almost everywhere in our mechanical devices and industrial infrastructure—a high end car uses almost 100 separate processors, for example—attacks that could damage or take control of cars, fuel pipelines, electric power grids, or telecommunications networks are a proven possibility. Large scale damage—as Sony found out—cannot be ruled out.

Are such vulnerabilities inevitable? It might seem so, because of the complexity of computer systems and the millions of lines of software "code" that direct them—and given that a single programming mistake could result in a major vulnerability. And if that were so, then the only strategy would seem to be changing passwords and other cybersecurity good practices, sharing risk information, and a never ending sequence of "patch and pray". But there is good reason to believe that fundamentally more secure systems—where security is built in, and doesn't depend on programmers never making mistakes or users changing their passwords—are possible.

One fundamental cause of cyber insecurity is core weaknesses in the architecture of most current computer systems that are, in effect, a historical legacy. These architectures have their roots in the late 1970's and early 1980's when computers were roughly 10,000 times slower than today's processors and had much smaller memories. At that time, nothing mattered as much as squeezing out a bit more performance and so enforcing certain key safety properties (having to do with the way in which access to computer memory is

A second fundamental cause of cyber insecurity is a weakness in our means of identifying individuals and authorizing access, which today mostly comes down to a typed-in password.

controlled and the ability of operating systems to differentiate among different types of instructions) were deemed to be of lesser importance. Moreover at that time, most computers were not networked and the threat environment was minimal. The result is that widely used programming languages such as C and C++ have features such as memory buffers that are easy to inject malicious code into and other structural flaws. Today's world is quite different and priorities need to change.

A second fundamental cause of cyber insecurity is a weakness in our means of identifying individuals and authorizing access, which today mostly comes down to a typed-in password. Cyber criminals have developed means of exploiting human laziness and credulity to steal such credentials—guessing simple passwords, bogus emails that get people to provide their passwords, and similar tricks. Even more sophisticated passwords are not really safe: a contest at a "DEFCON" conference several years ago showed that sophisticated password guessing software could guess 38,000 of 53,000 passwords within a 48 hour period. It often only takes one such theft to gain access to a machine within a corporate setting or a government agency; this machine, in turn, is accorded greater trust than an outside machine, allowing the attacker to then gain access to other machines within the organization.

Both of these fundamental weaknesses could be overcome, if we decided to do so, by redesigning computer systems to eliminate structural cybersecurity flaws, using well understood architecture principles—a conceptually simple project but difficult and costly to implement because of the need to replace legacy systems—and introducing what is called multifactor authentication systems for user access. This latter fix is far easier—a computer user would be required both to have a password and at least one other source of identity proof. This could include a smart card or other physical token; a second password generated and sent in realtime for the user to enter (such as a pin sent by text to the users mobile phone, a system already offered by Google for its email and required by many banks for certain transactions); or a biometric ID such as the fingerprint reader in Apple's new iphones. Breaking such a system requires the theft of the token or second ID, or the physical capture of the computer user, and would be almost impossible to do on a large scale.

The opportunity exists to markedly reduce our vulnerability and the cost of cyberattacks. But current investments in the priority areas identified here, especially for non-defense systems, are either non-existent or too small.

Several research activities would make such a transition to a cybersecure world much easier and more feasible. These include:

- The design of a new prototype computer system that can run the bulk of today's software and that is demonstrated through rigorous testing and/or formal methods (i.e. mathematical proofs of correctness) to be many orders of magnitude more secure than today's systems.
- Economic/behavioral research into incentives that could speed the transition to such new architectures and the adoption by consumers of multifactor authentication. At present, the cost of providing more secure computer systems would fall primarily on the major chip vendors (Intel, AMD, Apple, ARM) and the major operating system vendors (Apple, Google, Microsoft), without necessarily any corresponding increases in revenue. Consumers, too, will likely require incentives to adopt new practices. There has been little research into the design of such incentives.
- Consideration of how continued cyber insecurity or the introduction of new more secure cyber technologies would impact international relations. What national security doctrines make sense in a world where virtually all nations depend on vulnerable cyber systems and in which it is virtually impossible to attribute an attack to a specific enemy with certainty? Deterrence—as used to prevent nuclear war—is not a good model for cybersecurity, because cyber conflict is multi-lateral, lacks attribution and is scalable in its impacts.

The opportunity exists to markedly reduce our vulnerability and the cost of cyberattacks. But current investments in these priority areas especially in non-defense systems are either non-existent or too small to enable development and testing of a prototype system with demonstrably better security and with performance comparable to commercial systems. Small scale efforts have demonstrated that new, clean slate designs offer a way out of the current predicament. But a sustained effort over multiple years would be required.

SPACE EXPLORATION

Is there life on other earth-like planets? What exactly are "dark matter" and "dark energy" and how have they shaped the universe? Only research in space can answer such questions.

The U.S. role in space has been significantly reduced in recent years. What captured the public's imagination in this past year was the dramatic rendezvous with a comet—somewhere out past the orbit of Mars—by a European spacecraft. The mission was not only daring—it took a decade for the spacecraft to reach and match orbits with the comet—but also yielded important science: water on the comet is isotopically different from that on Earth, making it unlikely that comets were the source of Earth's abundant water resources. This past year, too, India has placed a spacecraft in orbit around Mars with instruments that are as sophisticated as those used by NASA, and China has successfully launched a spacecraft that orbited the moon and returned safely to Earth.

But the secrets of our solar system are not the only mystery out there in space. Are we alone in the universe? A definitive finding of life elsewhere would galvanize public attention around the world. Space telescopes including the U.S. Kepler mission have identified over 1000 confirmed planets circling other stars in our galaxy. Of these, a dozen are close enough and of a size—up to about 1.6 times the mass of Earth—that they appear to be rocky planets like Earth and with densities and apparent compositions to match. Some of them appear to be at the right distance from their stars to have liquid water, and thus could in theory support life. A new U.S. space observatory focused on such planets, the Transiting Exoplanet Survey Satellite, is to be launched in 2017, if budget cuts do not delay it.

A still more profound mystery concerns the basic "stuff" the universe is made of, how stars and galaxies evolved, and how the universe is still evolving. We know the broad outlines: our universe is almost 14 billion years old; about 5 percent of it is composed of normal matter—atoms and molecules; a much larger portion, about 27 percent, is made up of the still mysterious "dark matter" which helps to shape galaxies and the universe itself through its gravitational pull; and the rest is the even more mysterious "dark energy" that is pushing the universe to continue to expand outward, enlarging in size. The physics of both dark matter and dark energy—the dominant features of our universe—are still completely unknown, as are the details of how the push and pull of these forces controlled the evolution of the universe in the first few billion years after the Big Bang. Breakthrough discoveries here would not only transform astrophysics, but physics itself.

The centerpiece of the U.S. program of space science in the coming years is the launch of the

The James Webb telescope will again give the U.S. a leadership role in astrophysics. But its cost and recent budget cuts will likely delay or prevent other high opportunity missions. Meanwhile, other nations are pressing ahead.

James Webb space telescope, which will focus on star formation, the evolution of galaxies, and the earliest moments of the universe itself. Scientists hope that it will help shed light on both dark matter and dark energy as well as related astrophysical phenomena. The Webb telescope is far larger than the 20-year-old Hubble space telescope, for which it is the successor: the main mirror is 6.5 meters across (the Hubble main mirror was 2.5 meters). More importantly, the Webb telescope is designed to see deeper into the universe and further back in time, and for that reason will observe mostly in infrared wavelengths (faraway objects are "red-shifted), as compared to the optical and UV observing design for the Hubble. For the same reason, the new telescope will not be in Earth orbit, but instead will orbit the sun in tandem with the Earth but at a distance from us of 1.5 million kilometers, where there is less "noise" in the infrared spectrum.

This new capability will again give the U.S. a leadership role in astrophysics, but the cost of the telescope and recent budget cuts for space science will likely delay or prevent other high opportunity missions as well as related theoretical and computation research. Meanwhile, other nations are pressing ahead.

PLANT SCIENCES

Growing more food, and more nutritious food, for a hungry world is again an urgent challenge. Productivity needs to increase by at least 50 percent.

Fifty years ago, rapid population growth in developing countries was outracing global food production, creating the prospect of mass famine in many countries. What forestalled such a tragedy were the agricultural innovations known as the Green Revolution, including the creation of higher yielding varieties of wheat and rice. While world population grew from 3 billion to 5 billion, cereal production in developing countries more than doubled; crop yields grew steadily for several decades. By some estimates, as many as 1 billion people were saved from starvation.

Now the world faces similar but more complex food challenges. Population is expected to grow from 7 billion to 9 billion by 2040, but little arable land remains to be put into production. So productivity needs to increase still further, by at least 50 percent. Moreover, the Green Revolution did not specifically address the nutritional content of the food produced—and today that is critical, because of widespread malnutrition from deficiencies of iron, vitamin A, and other micronutrients. Traditional breeding approaches, and even the kind of genetic engineering that has produced more pest-resistant commercial crops, will not be enough to meet these challenges: more fundamental innovations in plant science—integrating knowledge of genetic, molecular, cellular, biochemical, and physiological factors in plant growth—will be required.

One example of the opportunities for such fundamental innovation comes from research on a non-food plant, *Arabidopsis thaliana*, which is the "lab mouse" of plant molecular biology research. Recently scientists were seeking to better understand the process by which a plant's chromosomes—normally, one set each from the male and the female parent—are distributed when a cell divides. They inserted into the plant cells a modified version of the protein that controls chromosome distribution. The resulting plants, when "crossed" or bred to unmodified plants and then treated chemically, had eliminated one set of chromosomes and had instead two copies of a single chromosome set. Such inbred plants usually don't produce well, but when two different inbred lines are crossed together, the resulting variety is usually very high yield. This phenomena, called hybrid vigor, has been created in a few crops—such as corn—via conventional breeding techniques and is responsible for huge increases in yields, stress tolerance, and other improvements in recent decades. The new "genome elimination" method could make these same improvements possible for crops such as potatoes, cassava, and bananas that have more heterogeneous chromosomes.

Creating golden rice involved adding two new genes to the plant, which increased yield and also enriched the crop in vitamin A. Such self-fortifying crops could address malnutrition far more effectively than traditional methods.

Another research frontier is new methods to protect crops from devastating disease, such as the papaya ringspot virus that almost completely wiped out the Hawaiian papaya crop in the 1990s. What researchers did was develop a crop variety that includes a small portion of genetic material from the virus—in effect, inoculating the crop to make it immune from the disease, much like a flu vaccination protects people. Virtually all Hawaiian and Chinese farmers now grow this resistant papaya. The technique, known as RNA silencing, was initially discovered and understood through basic research into the molecular biology of tobacco and tomato plants, but seems likely to be useful against viral diseases in many crops.

Similarly, Chinese researchers doing basic research on wheat—a grain that provides 20 percent of the calories consumed by humans—developed a strain that is resistant to a widespread fungal disease, powdery mildew. The researchers identified wheat genes that encoded proteins that in turn made the plant more vulnerable to the mildew, then used advanced gene editing tools to delete those genes, creating a more resistant strain of wheat. The task was complicated by the fact that wheat has three similar copies of most of its genes—and so the deletion had to be done in each copy. The result is also an example of using genetic engineering to remove, rather than to add, genes. Since mildew is normally controlled with heavy doses of fungicides, the innovation may eventually both reduce use of such toxic agents and increase yields.

Modifications in a single gene, however, are not enough to increase the efficiency of photosynthesis, improve food nutritional content, or modify plants for biofuel production—these more complex challenges require putting together multiple traits, often from different sources, in a single plant. This will require more basic understanding of plant biology, as well as developing and utilizing new technologies like synthetic chromosomes and advanced genome editing tools that are still in their infancy, and thus will require sustained research. One example of the potential here is golden rice—the creation of which involved adding two new genes to the plant—which is not only high yielding but also produces a crop rich in Vitamin A. Such "self-fortifying" crops, because they incorporate micronutrients in a "bioavailable" form that is accessible to our bodies, could address malnutrition far more effectively than traditional methods of fortifying food or typical over-the-counter supplements. Another possibility may come from efforts to convert C3 plants such as rice into C4 plants that are more efficient at capturing and utilizing the sun's energy

Investment in basic plant-related R&D is already far below that of many other fields of science. Yet the agriculture sector is responsible for more than two million U.S. jobs and is a major source of export earnings.

in photosynthesis and perform better under drought and high temperatures—a modification which may require, among other things, changing the architecture of the leaf.

Capturing these opportunities and training necessary scientific talent cannot be done with existing resources, as has been amply documented. Not only is federal investment in plant-related R&D declining, it is already far below the level of investment (as a percentage of U.S. agricultural GNP) of many other fields of science. Yet the agriculture sector is responsible for more than two million U.S. jobs and is a major source of export earnings. Moreover, the USDA research effort effectively ignores fundamental research; the research breakthrough on genome elimination described above could not have been supported by USDA funds, which are narrowly restricted to research on food crops.

In contrast other countries, particularly in Asia, are increasing investments in plant research. The impact of these investment are exemplified by the surge in publication in fundamental plant molecular biology research: 70% of the research published in the leading journal in this field now comes from outside the Unites States, and the entire field has seen a sharp increase in publications from Chinese labs. The U.S. is at clear risk of no longer being a global leader in plant sciences.

QUANTUM INFORMATION TECHNOLOGIES

The technological challenge is immense. But the unique properties of quantum systems offer tantalizing power.

What if we could harness the bizarre and counter-intuitive physics of the quantum world to create a real-world technology revolution? What if it offered computing power that could dwarf today's supercomputers; unhackable long-distance communications systems, ways to measure time, electrical and magnetic properties, and other phenomena with unprecedented accuracy?

All of these now seem plausible, if still extremely challenging. That's because the core of quantum information devices—known as a "qubit" in analogy to the "bit" of a conventional computer memory—has to be completely shielded from outside electrical or magnetic forces. Yet at the same time, to be useful, they have to be able to communicate with each other and share information with the outside world.

A qubit can take many forms. One example is a tiny ring in which a superconducting current flows one direction or another, forming a kind of artificial atom, which when cooled to the temperatures of liquid helium exhibits quantum phenomena. These superconducting artificial atoms have already proven useful for research into quantum physics, and their potential ease of manufacture and ability to operate at nanosecond time scales make them a promising candidate for technology applications. Another form of qubit is a charged atom trapped in a vacuum by rapidly oscillating electromagnetic fields. Still a third example of a qubit is a single photon of light trapped in a wave guide.

The technological challenge is in combining multiple qubits with methods of exchanging information between them, measurement and control techniques, and architectures for practical systems—in most cases, with the whole system kept at the temperature of liquid helium. But if that can be done—which seems increasingly likely—the unique properties of quantum systems offer tantalizing power.

Take encryption, for example. With one existing widely-used public key encryption system that depends on the difficulty of finding the prime numbers that compose a code, it would take years for today's supercomputers to crack a code with 1000 binary digits; a quantum computer could do it in seconds. That's because a quantum computer with, say, 10 qubits, operates a bit like a parallel computer doing 1024 simultaneous computations; with 30 qubits, the number rises to a billion simultaneous computations; with 40 qubits, a trillion. So it doesn't take a very large quantum computer to simply overpower some kinds of computational problems or to sort through even the most massive

There are large efforts underway in several countries to install and scale up quantum technologies that will allow a huge jump ahead in computing power and absolute security in long distance communications. U.S. leadership in these strategically important areas is not assured, especially given recent budget constraints.

datasets. Scientists expect that more advanced quantum computers capable of broader applications might be possible within a decade.

Or take long-distance communications security. If two people want to send secret information over a public channel and they encrypt the message with a unique code, it's usually impossible to break the code. But the weakness in any such communication system comes when the two parties try to share and agree on a code—which can be intercepted. With a quantum communications system that operated by exchanging qubits, however, any attempt to intercept the code alters the transmission—so the parties will know it's been breached and won't use it. With automated systems capable of generating and sending thousands of potential codes a second, and then selecting and using those that have not been tampered with, secure communications becomes possible. And the security depends not on the cleverness of a code, but on the peculiar physics of quantum systems that make it impossible to measure a quantum particle without also perturbing it. Both military and commercial secrets could stay secret.

Quantum information processing devices are also useful for precision measurement—the 2012 Nobel Prize in physics was awarded to scientists who had used techniques of quantum information processing to construct devices that attained unprecedented precision in the measurement of time. Similar approaches are possible to measure electric charge, magnetic flux, heat flow, and other quantities. And just as with computational power, as the number of qubits in a device increase, so too will the ultimate limits of precision.

The field of quantum information science began in the United States, but there are now large efforts underway in several countries to install and scale up these technologies—in effect, to install a new kind of quantum internet/quantum cloud that allows communication and data storage with absolute security and very powerful solutions for certain types of computing problems. The Swiss are investing heavily in quantum communications. A Canadian company is producing the first commercial quantum information processing computer. Publications from Chinese scientists in this field are rising rapidly. So U.S. leadership is not assured, especially given recent budget constraints, while the potential outcomes seem quite important both strategically and commercially.

ENABLING BETTER POLICY DECISIONS

Insights from social and economic research can empower policymakers and aid their decisions, saving governments money and improving opportunities for economic growth.

Research in the social and economic sciences tends toward smaller projects, and smaller research teams, than the mega-projects that are often found in the physical and natural sciences. Cumulatively, the insights gained from these investigations can have significant impact on regulatory policy, on healthcare policy, and on strategies to stimulate economic growth, enabling the design of policies that more effectively accomplish their intended goals.

Designing New Markets. Over the past two decades, the federal government has auctioned off parts of the broadcast radio/TV spectrum to enable new applications such as mobile telephony and wireless broadband. These auctions have not only catalyzed huge new industries and transformed the way we live and do business, they have also netted the federal government more than $60 billion. The auctions were extremely complex, involving multiple rounds of contingent bidding, because of the unique character of spectrum leases: the value of some spectrum in one city or region depends on who owns the spectrum in neighboring regions. The design of these auctions—in effect, the design of new public markets for spectrum—has been guided by research into game theory, a branch of economics that began with the mathematician John von Neumann and has been pushed forward by university researchers in recent decades. "Design" in this context means specifying the rules of trade and the way prices are determined.

Spectrum is only one example. Economic research has played a central part in creating auction markets for off-shore oil leases, for the matching of K-12 students in large city school districts like New York and Boston to the array of available schools, and even for the trading of kidneys between donors and potential recipients. The rise of electronic commerce has created new opportunities for more sophisticated pricing by sellers and bidding by potential buyers—for products and for services such as advertising. Many of the design principles that have allowed U.S. tech firms like Google, Amazon, and eBay to grow into global dominance have deep roots in recent economic research. Understanding the efficiency properties of different market structures in these new settings requires both theoretical research on the design of these markets and data-based analysis of their performance.

Economic and Behavioral Contributions to Health. The rising incidence of chronic disease—diabetes, stroke, cardiovascular disease—and of predisposing conditions such

More complex auction strategies guided by research into game theory have netted the U.S. government more than $60 billion and helped catalyze huge new industries in electronic commerce.

as obesity threatens to become a financial tidal wave that could overwhelm our healthcare system. It is well-known that patients' choices of diet and exercise, their compliance with treatment regimes, and their willingness to seek care play a critical role in health outcomes for these conditions. So a critical area of research is to understand the factors that influence such choices and to design more successful ways to influence behavior. Mobile phone reminders to refill drug prescriptions and incentives of various kinds have been shown to improve treatment compliance in some circumstances; generating support from peer groups can have the same effect. Access to insurance coverage has been shown to increase use of preventative measures. Behavioral interventions that arise from social science research are particularly attractive because they are often much less expensive than medical treatments, especially hospitalization. But much remains to be done, even as funding levels are being reduced. At a time when health costs are a significant national concern, designing and testing new behavioral interventions is an area with high potential benefits.

Insights from Big Data. Because economists and other social scientists can't usually run laboratory experiments, empirical research has been mostly based on survey data collected by government agencies such as the Bureau of Labor Statistics and the Bureau of the Census. These surveys, which provide data that has been collected in consistent fashion for many years, remain critical to understand labor market activity and a wide variety of individual economic choices important for policy making, and yet are now threatened with budget cuts. At the same time, there is a huge new opportunity in applying Big Data analytic tools to administrative records. Data collected in connection with programs such as unemployment insurance and Medicare, and potentially even data from tax returns—with careful safeguards for individual privacy—could shed light on economic patterns over long periods of time. Such patterns are difficult to study with survey data. Building the data infrastructure that would facilitate research access to these databases and designing secure access protocols would open a wide range of issues for economic research. This is an area where European countries, especially in Scandinavia, are moving well ahead of the U.S. in providing data access, enabling the linking of multiple datasets, and gaining useful insights for improved policy design.

Understanding the Causes of Long-Run Economic Growth. Economic growth is what fuels higher incomes, improved living standards, and the capacity to address national challenges.

Can the U.S. and other developed nations continue to grow, or do they face slow-growth stagnation while developing countries such as China continue to grow rapidly?

But can the U.S. and other developed nations continue to grow, or do they face slow-growth stagnation while developing countries such as China continue to grow rapidly? At present, economic theory describes growth as dependent on inputs of human capital, investments in plant and infrastructure, and scientific and technology innovation, but there is no agreement on their relative importance or the optimal design of public policy to stimulate growth. Research on the linkages between public and private R&D spending, patenting and publication, and ultimate commercialization of ideas could provide new insights, as could greater understanding of the role of education in improving economic growth. And such research would be facilitated by greater access to federal data bases with information on grants and on patents; by measuring the impact of educational inputs through comparison of cross-state differences in K-12 education systems; and by tracking the international migration of science and technology talent. Disparities in public policies toward entrepreneurship across states and countries or in different structures for R&D tax credits or corporate taxes, also provide a valuable opportunity to assess the links between policies and outcomes. Research on such issues has the potential to be controversial, but it is also a critical step toward building consensus for policies that could reduce disparities and improve opportunities at local, state, and national scale. If improved policy design could raise the annual rate of national income growth by even a very small amount, it would have a dramatic long-term effect on living standards.

CATALYSIS

Today's industrial catalysts are relatively crude and imprecise. Nature's catalysts are far better, but how they work is not well understood. Solving that puzzle would have profound impact on energy and environmental challenges.

The production of catalysts is a $500 billion industry in the United States alone. But the economic shadow of catalysis is far larger, since catalysts play a critical role in the manufacture of virtually every fuel, all types of plastics, and many pharmaceuticals by speeding up chemical reactions or even enabling them to occur at all. Many of the industrial catalysts in use today involve precious metals, such as the platinum in your car's catalytic converter that changes pollutants such as carbon monoxide or oxides of nitrogen to more innocuous molecules.

But catalysis is also an area of scientific inquiry that is critical to energy and environmental challenges that loom large in coming decades. In fact, many of today's industrial catalysts require very high temperatures and are relatively crude and imprecise compared to nature's catalysts, such as the enzymes in our body that enable and guide virtually all the biochemical reactions that sustain life. Enzymes work at room temperature, they are very selective (they enable only one reaction), and they don't involve scarce, expensive metals. Just how they do that is not really understood. So the challenge for basic research is first to figure out the mechanisms of catalytic reactions by studying them literally step by step and atom by atom, and then to develop methods of synthesizing new catalysts that are well-defined (like enzymes) on sub-nanometer scales. And to do that will require development of more powerful research tools than now exist—such as synchrotron-powered spectrometers, electron microscopes so advanced that they could see the dance of the molecules in a reaction of interest, and research facilities capable of viewing the dance under the temperatures and pressures of existing commercial catalytic processes. It will also require the development of new catalytic materials—we don't want our transport systems to be dependent on platinum, which comes largely from Russia and South Africa—and advanced computational chemistry resources.

Why should we care about this area of science? Consider just three examples where the right catalyst could have a profound impact:

- Artificial photosynthesis. Plants use carbon dioxide from the air and sunlight to synthesize carbohydrates; if we could duplicate that reaction, then feeding the world would be a lot easier.
- Converting water and sunlight into hydrogen. An efficient way to catalyze this reaction could fuel a hydrogen economy.

Economically and environmentally important advances in catalysis require investments in new fundamental science and a many-years-long effort. But the potential payoff is such that governments which finance this research—Germany and China already are—will gain a critical economic edge.

- Converting carbon dioxide into fuels. This would not only mean an inexhaustible source of conventional carbon-based fuels, but by recycling carbon dioxide would ensure that we don't worsen global warming.

These and a large number of less dramatic but economically and environmentally important advances in catalysis won't happen anytime soon. They require not only investments in new fundamental science and the research toolset described above, as well as a many-years-long effort beyond the ability of commercial entities to sustain. But the potential payoff—not just for energy and environmental concerns, but for all of chemistry—is such that governments will finance this research. Indeed, some—especially Germany and China—already are. And those that do will gain a critical economic edge.

FUSION ENERGY

Is there a faster, cheaper route to fusion energy?

For more than 50 years, scientists have pursued fusion energy as a means of generating electric power, because it is a potentially ideal energy source for human civilization—inherently safe, with an inexhaustible fuel supply of hydrogen isotopes mined from the sea, and no greenhouse gas emissions.

The goal is still far off. The international community is investing $10s of billions of dollars to build the ITER facility in France in order to study fusion reactions which are self-sustaining. But those experiments won't be ready for more than a decade, and will leave many critical issues in extracting useful electric power from a fusion reactor unsolved. What if there were a faster, cheaper route to fusion energy, based on recent superconducting magnet technology and advances in materials science?

Fusion—the process by which hydrogen atoms combine to create helium and in the process release huge amounts of energy—is what powers the sun. Containing the ionized gases that fuel the process at temperatures even hotter than the core of the sun in an earth-bound reactor requires powerful magnetic fields. ITER will use an early generation of superconducting magnets, capable of producing only a moderate strength magnetic field. Those magnets must be kept cooled to -452 degrees F while close to the hot gases, adding to the engineering complexity.

Recent progress on superconducting wires or tapes has been quite rapid, such that new high temperature superconductors are now commercially available. This progress has been largely achieved by U.S. industries. Magnets made from these materials can already operate at temperatures far above early generation designs, and can generate and tolerate much stronger magnetic fields. Future superconducting materials may eventually permit room temperature superconducting magnets. And for fusion, magnets are critical: doubling the strength of the magnetic field—about what the new magnets would permit over those in the ITER design—increases the fusion power per volume sixteen-fold. That in turn would permit a smaller, less expensive fusion reactor which operates at higher power density, with more stable plasma characteristics, while also reducing the scale of challenging engineering and materials problems. Preliminary calculations suggest that such designs, once perfected, might be capable of producing 100's of megawatts of electric power.

The recent superconductor developments represent an exciting new opportunity to pursue a faster development track to practical fusion power. But the U.S. fusion program does not

New superconducting magnets that exploit recent technology could enable powerful fusion devices with greatly decreased size, accelerating fusion energy's development. There is thus an opportunity for the U.S., if it chose, to leapfrog over existing efforts and reclaim a lead in fusion research.

have a superconducting experimental device, and there are currently no plans to build one or, indeed, any new fusion reactors. Instead, the most advanced superconducting fusion experiments in the world are currently operating in China and South Korea, with new superconducting experiments under construction in Japan, Germany and France. European and Asian countries also have aggressive plans to accelerate their own development of fusion energy. Significantly, all of the fusion devices currently operating and planned have had to employ the older generation of superconducting technology. This creates an opportunity for the U.S., if it chose to invest in a high-field, high-temperature superconductor device in parallel with its support for ITER, to leapfrog current device capabilities and help to reclaim a lead in fusion research.

The advanced superconducting magnet technology could lead to revolutionary advances in fusion reactor designs, both for "tokamaks" (like ITER and the major existing U.S. facilities) and for "stellarators", (an alternative configuration which might more easily achieve continuous operation). In fact, support for basic research in large-scale, high temperature, superconducting magnet technologies would have a large payoff for whatever new course the U.S. magnetic fusion science program might follow in the next decade, irrespective of device configuration or mission.

Such a new course would require significant resources, not just for fusion research, but also for additional research into high temperature superconducting materials and magnet designs. But it would also have significant spinoffs beyond fusion, such as high current DC power distribution cables, superconducting magnetic energy storage, and improved superconducting radiotherapy devices. Providing the materials and expertise to build and operate an advanced superconducting fusion device would also generate significant economic activity; the current U.S. fusion program employs more than 3600 businesses and contractors spread across 47 states.

The U.S. has world-leading depth in measurement, theory and computation for fusion research, but it cannot be sustained for long in the absence of new experimental facilities. No research program can guarantee a successful outcome, but the potential to accelerate the development of fusion as a source of clean, always-available electricity should not be ignored. Practical fusion power would transform energy markets forever and confer huge advantages to the country or countries with the expertise to provide this energy source to the world.

INFECTIOUS DISEASE

The ability to understand and manipulate the basic molecular constituents of living things has created an extraordinary opportunity to improve human health.

The ongoing revolution in molecular biology has shown that all forms of life contain the same basic set of molecular parts and operate by the same biochemical rules, which scientists increasingly understand and can manipulate. That has created an extraordinary opportunity to improve human health, both by preparing for and thus preventing epidemics of emerging infectious disease such as Ebola and by finding solutions to the even more deadly threat from drug resistant bacteria.

Ebola outbreaks have occurred periodically in rural Africa for many decades, and the cause of this highly transmissible and deadly disease—the Ebola virus—has been known since 1976. As the world struggles to contain the current epidemic in Western Africa, it is clear that there have been many missed opportunities to prepare the tools we now desperately need to detect, treat, and immunize against this still poorly understood disease. How did we come to be so little prepared to confront a disease that posed such an obvious risk to global health?

The answer, in part, may have been over-confidence in the established alliance between publicly funded university and hospital based research and privately funded research in pharmaceutical and biotechnology companies that has been so successful in developing drugs, tests, and procedures needed to combat the diseases of the developed world. It now seems clear that existing priorities and incentives are not sufficient to prepare for diseases that emerge by jumping from animals to humans in impoverished parts of the developing world—of which Ebola is only one of at least half a dozen equally dangerous threats.

How viruses invade and multiply within human cells is generally understood. But basic research is needed to delineate the exact molecular mechanism for each virus, because development of drugs to combat infections depend on these specifics. Likewise, the development of effective vaccines also requires extended basic research into the structure of the virus, and specifically into how it evolves by changing proteins on its surface to evade the body's immune system: then it is possible to identify surface proteins that do not change, and which become the targets for vaccines. If we are to be prepared for the next viral epidemic, we need to invest in the basic research to characterize and understand all known viruses with the potential to be highly infectious. It is not that long a list; this is a task well within the capacity of the U.S. biomedical research system; and, since these diseases threaten all countries, it would be easy to make common cause with partners in Europe and Asia.

Drug-resistant bacteria infect at least two million people in the U.S. every year, with growing fatalities. If we don't begin a major basic research effort soon, the threat to U.S. public health a decade from now may well look very challenging.

As dramatic as exotic emerging viral diseases seem, they are not the only or even the most serious infectious disease threat that the world faces. Potentially more deadly to most Americans is the spread of antibiotic resistance that undercuts our ability to treat bacterial infections we have long considered to be under control, from tuberculosis to staphylococcus and streptococcus. In fact, drug-resistant bacteria infect at least two million people in the U.S. every year, a growing number of them fatally.

The development of antibiotics – drugs that kill specifically bacterial cells by targeting differences between bacteria and the cells in our body – is one of the great achievements of modern medicine and we now take it for granted that if a child has strep throat we can cure it within days with the right antibiotic. But it is now clear that the more widely an antibiotic is used, the more rapidly that bacteria will evolve to acquire a resistance to it—and the bacteria are increasingly winning this war. Especially alarming is the spread of drug-resistance forms of staph and strep bacteria, especially in hospitals; the emergence of resistance to two "last resort" antibiotics, Methicillin and Vancomycin, used to treat infections resistant to other drugs; and the spread of a multi-drug resistant form of tuberculosis, for which no other treatment options now exist.

Development of entirely new antibiotics is at present the only way to keep ahead of the threat of incurable bacterial infectious disease. But the pharma industry has developed very few new antibiotic drugs in the past two decades—economic incentives are clearly insufficient. The alternative strategy is basic research into new bacterial processes, so that it would be possible to attack multiple targets within a bacteria, making it much harder for resistance to evolve. For that we need an infusion of fresh ideas and incentives for independent investigators—in effect, investments in a major basic research effort in the physiology and genetics of pathogenic bacteria that will attract new talent to this area. If we don't begin this effort now, the threat to U.S. public health a decade from now may well look very challenging.

DEFENSE TECHNOLOGY

We face sophisticated competitors and new terrorist threats. Yet there are opportunities to maintain U.S. leadership and, especially, to better protect our war fighters in the field.

U.S. superiority in technology pertinent to national defense has been a given for the past 70 years, but that may not be true going forward. As a nation, we face sophisticated geopolitical competitors such as China that are investing heavily in defense research, agile terrorist enemies that rapidly adapt open source civilian technology to counter U.S. hi-tech systems, and the prospect of diminishing research investments. Yet there are important opportunities to maintain U.S. leadership. These include investments in human protection and survivability that could help each war fighter safely accomplish more, opportunities for more secure battlefield communications, and badly needed improvements in cybersecurity (see ***Cybersecurity***), many of which also have commercially significant non-military applications.

Protecting our troops can take many forms, and it is the combination of these that offers really significant improvements:

- One promising opportunity is the development of advanced nano-structured coatings that change how materials absorb and reflect light, changing visibility and effectively disguising the object in visual wavelengths and in infrared and radar wavelengths, making it hard to detect war fighters as well as manned and unmanned land, sea and air vehicles. If the enemy can't see you, it's hard to shoot at you. Another promising possibility is fibers as thin as a human hair that can be woven into clothing and which are electronic devices that can be tuned to respond only to certain (easily changeable) wavelengths, such that a soldier can instantly detect whether another person is a friend or a foe. These fibers can also measure body warmth and detect sound waves, and could thus tell a wounded warfighter or a remote rescue team just where he or she was injured, perhaps the type and severity of the wound, and even the direction from which the shot came.
- Another group of opportunities are new materials for helmets and protective clothing and gear to better protect against blunt trauma injuries from blast waves, ballistic fragments, and vehicle accidents. These materials include new nanocrystalline alloys as strong as steel but much lighter and which can be formed into plates and woven structures including so-called shape memory alloys that can absorb energy from a blast or projectile and then bounce back to their original shape. Another promising material is composed of thin sheets of carbon called graphenes that can dissipate large

New materials could make it hard for an enemy to detect our soldiers; others could instantly identify friend from foe or protect against trauma injuries from bullets or blast waves. But without near-term investments, none of these will occur in time to benefit the next generation of warfighters.

amounts of mechanical energy from a bullet or blast wave. Developing these materials into protective gear would be supported by powerful mathematical simulations of how mechanical forces interact with the human body and with diverse materials to help illuminate how human injuries occur and why protective gear fails. The idea is to protect warfighers while also ensuring their mobility, but the results will also be useful for bomb disposal squads, police officers, fire fighters and other civilian workers in hazardous environments.

- A third group of opportunities include new ways to detect environmental hazards that a warfighter might encounter. A promising approach for detecting trace amounts of hazardous materials in air, water, soil, or food involves laser stimulation of a nanoparticle (a quantum dot) linked to a dye molecule, which each emit light of characteristic frequencies and intensities when a particular hazard is present. Means of protecting soldiers from human-made and natural toxins or infectious agents include new surface-treatment technologies that fight viruses and bacteria. Research on nano-structured coatings shows promise to improve adsorbents in gas masks and air filters, detoxify water and blood products, coat common surfaces and objects to make them microbiocidal, and prevent and treat infectious diseases. All of these might have significant public health benefits for civilian life as well.

Military communications face multiple threats, including loss of GPS access, enemy eavesdropping, false information from enemy spoofing, and network incapacitation by electronic weapons. New technologies are needed to:

- Allow troops and vehicles on the move to securely and efficiently communicate in urban, rural, and remote locations that are GPS-denied or contaminated by strong electromagnetic interference (EMI). Promising approaches are emerging from research on applications of mathematical and statistical theories to communication, detection, and estimation problems that could markedly improve capabilities in network localization and navigation, the use of time-varying communication channels, as well as the development of multiple antenna, ultra-wide bandwidth, or even optical transmission systems.
- Protect military and civilian electronics from electromagnetic interference (EMI) and electromagnetic pulse (EMP) weapons that disrupt communications and can damage or disable military and civilian infrastructure

Switching from electrical to optical circuits could protect critical communications and infrastructure from electromagnetic pulse (EMP) weapons.

for communications, transportation, water and electric power supply, and public safety. One promising approach is lightweight electrically conducting polymer coatings for EMI shielding of electrical and electronic cables in military vehicles and on individual military personnel. Another is to use all optical integrated circuits, which because they do not depend on electrical currents, are effectively immune to EMP weapons (see ***Photonics***). Using laser beams for line-of-sight communications, combined with relays for redirection and increased range is also a possibility, with the advantage that these communications are immune to radio frequency jamming and enemy detection through triangulation.

There are also opportunities to extend the operational life of defense systems and thus lower lifecycle costs by building in to such systems and platforms the ability for real-time monitoring to improve performance, to detect and correct potential failures before accidents, and to ensure adherence to required maintenance schedules. Another cost-lowering potential is to increase the ability of defense platforms—including drones and other unmanned platforms—to detect and avoid threats and, by using self-healing materials, to recover from damage. Both of these could lower the costs of defense modernization efforts.

But research takes time. Without near-term investments, none of these opportunities can be exploited in time to benefit the next generation of soldiers or of defense systems. And that would likely raise the cost—in human lives and in defense dollars—of dealing with a growing number of defense challenges.

PHOTONICS

The development of photonic integrated circuits will transform supercomputing and the semiconductor industry in ways that are important strategically and commercially.

Optical fibers have dominated long-distance telecommunications for decades, because light—photons—can transfer much more data at lower cost than electrons in copper wires. A typical optical fiber, for example, can transmit as many as 100 wavelength channels each carrying 100 Gigabits of information—and each channel more than 10 times as much as a copper wire. Moreover, the optical fibers can transmit signals with little distortion or loss over many kilometers. Now optical technology, in the form of photonics or photonic integrated circuits, is poised to move into computing in a big way—an opportunity with major strategic, commercial, and environmental advantages for the country that leads in this technology.

This transition is being driven by advances in the development of photonic chips— photonic integrated circuits (PICs) made from silicon and indium phosphide that can now be reliably and inexpensively produced—but also by the need for ever faster supercomputers and the ever-expanding Internet data centers. In fact, internal data transfer speeds are becoming the limiting factor for both supercomputers and data centers. A data center is, in effect, a massive network that interconnects millions of storage nodes and shuttles data back and forth, an activity that, with copper wiring, also consumes huge amounts of electric power. Already such centers can consume as much as 100 megawatts of power each, enough power for a small city, and all U.S. data centers together account for about 2 percent of national electric power consumption, a number that is growing rapidly. In supercomputers, the internal data communication networks will account for nearly all of the power consumption—and the cost—of these machines within another five years. So switching from copper wires to photonic circuits, which can operate at much higher bandwidth with lower power consumption and lower costs, makes a lot of sense.

But the opportunity does not stop there. Even within a given storage node, or server "blade", of a data center, the wires that connect processors to memory will face similar constraints and will need photonic solutions. Ultimately photonic circuits may be needed even at the intra-chip level, within microprocessors. Supercomputers face similar constraints to those of data centers, since they are massive networks of processing nodes that need to share data across the network rapidly and accurately. Here, too, photonic circuits are already needed to enable faster data transfer, especially for still larger computers that can solve complex problems more effectively. And in supercomputers too, data transfer capacity between processors

It is not clear that the U.S. can maintain a leadership or even a competitive role in supercomputers, despite their strategic importance, or ultimately even in the semiconductor industry.

and memory will become a growing constraint. The inevitable transition to photonic circuits is likely to completely reshape much of the $300 billion semiconductor industry, now dominated by U.S. companies.

Photonics has implications beyond supercomputing and datacenters in all kinds of measurement and sensing applications. One example is microwave photonics, where applications to radar signal processing on aircraft could be important. Radar units are typically located at numerous locations on an aircraft, and the signals from these units collected for central processing and interpretation. Transmitting these signals with photonic circuits and optical fibers instead of wires offers greater signal fidelity, lower power consumption, and greater freedom from interference or jamming. Photonic-based clocks and oscillators also have greater stability and accuracy than their microwave counterparts. Optical sensing and distance-ranging techniques imbedded in photonic circuits are finding their way into applications of autonomous and semi-autonomous vehicles and robots, enabling capabilities that will dramatically improve both safety and productivity. By 2025, nearly every new vehicle on the road could have silicon photonic-based chips providing three-dimensional information about a vehicle's surroundings.

Historically, the U.S. has led in the field of photonics. Now both Europe and Japan have much larger R&D programs in this space. The recent photonics initiative announced by President Obama proposes to increase funding by about $20M a year for photonics manufacturing, but does not adequately address the need for more fundamental work—such as intra-chip communications, quantum, and ultrafast optics—needed for continued progress. Such research has historically been carried out by universities, which also train the next generation of talent for the field, while industry has typically built on that research and focused more on manufacturing. So as things stand, it is not clear that the U.S. can maintain a leadership or even a competitive role in data centers or supercomputers, despite the strategic importance of the latter, or ultimately even in the semiconductor industry, as it shifts to incorporate photonics into electronic chips.

SYNTHETIC BIOLOGY

Redesigning life itself in the lab, and in the process potentially transforming bio-manufacturing, food production, and healthcare.

Suppose that it was possible for biological engineers to create living cells designed for specific purposes as easily as tech engineers now create new digital circuits and the software to run them? Suppose scientists could program bacteria, plants, or even human cells to make them more productive or cure disease? In fact, the beginnings of just such a revolution in the field called synthetic biology is well underway. And once developed, the techniques for designing and altering the DNA found in every living cell, such that genes can be turned on or off at will or altered in useful ways, are relatively easy to apply: this year some 2300 high school and college students from around the world participated in an international synthetic biology competition to program biological circuits in novel ways.

Just as with the IT revolution, synthetic biology started by designing simple circuits, such as on/off switches, for the DNA in bacterial cells. Then they built more complex circuits, including ways for living cells to communicate with each other and methods (analogous to software programs for biological circuits) to orchestrate the behavior of whole groups of cells in a variety of organisms—yeasts, plants, and mammalian cells. To do this requires understanding in detail exactly how DNA behaves and then ensuring that engineered circuits also do exactly what they are intended to do. But what has facilitated progress is that the mechanics of how DNA functions in a cell and the interactions between genes, proteins, and other cellular constituents is remarkably similar across species. In particular, all DNA contains sequences of the same four nucleotides. Some of these sequences are the genes that guide synthesis of proteins, and others are "promotor" sequences that turn neighboring genes on and off. And biological engineers have learned how to control the promotors, in turn, by using the fact that there are specific proteins that bind to them.

The process of designing biological circuits and thus programming biological functions first at the cellular level and then in ways that affect the entire organism is still difficult and labor intensive, in part because there has not yet been enough investment in automating the toolset. Experiments involve a few cells at a time, not billions of cells. By the same token, large-scale industrial applications of synthetic biology are still in the future—even though the potential markets in bio-manufacturing, in food production, and in healthcare might easily exceed the size of the technology market. Nonetheless, the field is making progress, developing cellular sensors and actuators and learning how to organize the logic operations of

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biological circuits within a cell—technologies that are the equivalent of USB connectors and integrated circuit chips in the tech world. What this means is that synthetic biologists can now begin to take circuit elements and easily plug them together to create the genetic behavior they desire.

Moreover, the toolset is not likely to be limited to the DNA and genes that nature has created. Just last year, researchers in California engineered a bacteria by inserting two new, synthetic nucleotides in its DNA—in effect, adding two new letters to the genetic alphabet and potentially expanding the chemistry of life. That gives biological engineers yet more flexibility to construct altered genes and designer proteins and thus program cells to operate in new ways, or to create novel catalysts and materials.

What might the synthetic biology revolution make possible? One likely application might be to create a kind of super probiotic able to identify and kill harmful bacteria in the stomach by sensing specific molecules they secrete. Another possibility stems from a recent discovery of biomarkers that identify a cancer cell; with a list of such biomarkers, it should be possible to engineer a virus with the circuitry to identify cancer cells, enter them, and direct the cancer cells DNA to produce a protein that will kill them—irrespective of the type of cancer. As synthetic biology research in mammalian cells expands, it seems likely that it will be possible to largely eliminate animal testing for new drugs and even to regenerate new organs. Eventually, treatments for many health conditions that have genetic origins, customized to the individual, might be possible, since it is far easier and faster to engineer a virus to turn off a bad gene than it is to develop a new pharmaceutical drug. Engineering yeast or algae to produce foods or other biomaterials is likely to become an even larger industry than it already is, manufacturing far more complex materials. There is clear potential to create climate-friendly fuels and engineered plants or bacteria to restore degraded environments. The fundamental knowledge and the toolset needed is common to all these applications—and manipulating DNA to control living cells is potentially far easier than traditional drug development or chemical synthesis of materials.

Indeed, so powerful is this approach that synthetic biologists are already developing ways to consider in advance what could go wrong or how an innovation could be mis-used—in effect, to de-risk innovations before they happen. That can't completely guarantee against future mis-use, but since the technology is

While U.S. research agencies debate which will fund this new field, China and half a dozen other countries have already launched national initiatives.

already widespread, it's clearly important that the U.S. have the capacity to identify harmful uses and quickly develop countermeasures. Yet while US research agencies debate how—and which agency—will fund this new field, research in synthetic biology is expanding very rapidly internationally, especially in Europe, in Latin America, and in Asia; China and half a dozen other countries have already launched national initiatives. One measure of the innovation deficit is that—even though the synthetic biology revolution began in the U.S.—student teams from this country have failed to win the international synthetic biology competition in 8 of the past 9 years, in part because of a lack of laboratory facilities. That same lack impedes research progress as well. And what is at stake—leadership or at least a competitive role in a transformative new technology—is far more important than a student competition.

MATERIALS DISCOVERY AND PROCESSING

If the U.S. is to be a competitive player in the next generation of advanced materials, it will need to invest significantly more in materials research, in crystal growth and similar facilities, and in training the next generation of material scientists.

Since the times of early civilization, the advancement of the human race has been closely connected with the development of new materials and the means to process them into tools and other useful forms. We even keep track of history in terms of important materials—the Bronze Age, the Iron Age. This process has accelerated in the last half-century, in what is sometimes referred to as the Information Age, resulting in a wide variety of advances:

- integrated circuits and batteries small enough to enable tablets, laptop computers, and cell phones, as well as massive data storage facilities that comprise the internet "cloud";
- solid state lasers and optical fibers used in surgery, manufacturing, and long distance communications;
- low-cost solar cells and ultra-high efficiency, long-lived LED lightbulbs;
- sophisticated new medical diagnostic tools such as CAT and MRI scans;
- more efficient, safer, and more reliable automobiles.

In all of these cases and many more, advancements made in the development of new materials and materials processing techniques have enabled the implementation of structural materials and electronic and optical devices with remarkable performance characteristics. These developments, in turn, have resulted in significant improvements in the quality of life and the strength of our economy.

A key factor in these remarkable developments was heavy investment by industry, especially in the United States, in basic science and engineering. Particularly in the first half of this period, in what might be called the Bell Labs era, industry took a relatively long-term view of the process of new technology development. Coupled with the fundamental knowledge generated at universities, this led to the explosive growth of many materials dependent industries. In addition to most of the examples mentioned above, these included superconducting wires and magnets, silicon-based semi-conductor materials for electronics, and a variety of high performance polymers, metals and ceramics. But over the past few decades, international competitive pressures and the short term focus of the financial sector have caused U.S. industry to move away from long-term investments in R&D and to essentially eliminate corporate sponsored basic research, instead relying heavily on academic-based discovery. Thus, without adequate investment in the funding

U.S. industry has essentially eliminated corporate sponsored basic research. Without adequate investment at universities, this country will simply not generate the fundamental knowledge for the next generation of materials and processing techniques.

of basic science and engineering at universities, this country will simply not be generating the fundamental knowledge required to enable the next generation of new materials and materials processes.

One example is the facilities for growing crystals, an area in which the U.S. was the undisputed leader 25 years ago, but is no longer. Growing crystals is an important method of discovering new materials and improving existing ones. High purity silicon crystals served as the canvas for modern electronics; single crystals of inter-metallic alloys made possible modern jet engine turbines; and still other crystals gave rise to high temperature superconductors. New computational techniques may soon allow the design of even more complex materials. Yet the U.S. does not support an open access crystal growing facility nor a facility which couples dedicated supercomputer-based materials design to synthesis and characterization as done at, for example, Japan's leading materials laboratory at the University of Tokyo.

That means that the U.S. is not training a new generation of experts in crystal growth and related materials specialties. The innovation deficit can be measured in the scientific literature, where U.S. contributions now account for less than 12 percent of publications in the leading crystal growth journals, including a steadily declining proportion of the most-cited (e.g. most important) articles.

At the same time, investment in crystal growth research and facilities has expanded significantly in other countries, most notably Japan, China, South Korea, and Germany. China has become a major and at times dominant contributor to the crystal growth literature, with innovations in both synthesis of new materials and measurements of their properties. Industrial investment in materials R & D has also been stronger abroad, especially in Japan and Korea, resulting in such important developments by Samsung of commercially important organic light-emitting diodes (OLEDs)—in which a thin film of an organic compound emits light in response to an electric current—that now provide some of the dramatic displays in TVs and many other digital devices. In this later case, the materials and device technology was actually invented in the US at Eastman Kodak more than 40 years ago, but it took the intensive R&D efforts of companies like Samsung and LG to finally capitalize on this new technology. Samsung's commitment to R&D is illustrated by its practice of sending some of its best employees to work for a time in the laboratories of leading U.S. universities.

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The opportunities in advanced materials are many, including the growing area of nano-materials, in which the composition is controlled almost atom by atom. Another example is computational efforts to identify all possible types of new materials and calculate their structural properties, as proposed by the Administration's Materials Genome initiative.

The challenge is not only in the materials, but also the means to process them efficiently. Thin film solar cells, for example, is an area in which the U.S. still leads, for now, and which holds the potential for both far more efficient cells and processing techniques far less costly than the Chinese-dominated market for single-crystal silicon cells. Equally important are multi-functional materials, such as glass that is both anti-reflective, anti-static and super-hydrophobic, which would make possible dust resistant, self-cleaning windows and solar cell covers. Another important, high-growth area is nano-manufacturing, such as in 3-D printers, in which the required functionality has to be embedded in the tiny particles sprayed into position by a device equivalent to an ink-jet printer. But if the US is to be a competitive player in the next generation of advanced materials, it will need to invest significantly more in materials research, in crystal growth and similar facilities, and in training the next generation of both academic and industrial material scientists.

ROBOTICS

Robots and other intelligent, man-made machines such as drones or driverless cars have moved beyond the factory floor and are finding use in healthcare and other service industries and even in the home.

The idea of man-made machines that can perform burdensome tasks that would otherwise be carried out by humans is a powerful one. From the first practical robots developed in the U.S. in the 1950's, these useful devices have acquired an increasingly fundamental role in manufacturing, especially in the automotive industry: advanced factories such as Tesla's are able to produce cars with great precisions and efficiency. Use of robots is also growing rapidly in electronics, food/beverage, pharmaceuticals, and medical devices. Even small and medium sized business are putting robots to work.

While robots undeniably sometimes replace low-skill workers in the U.S., they also are allowing the U.S. and other developed countries to "reshore" a significant part of their economies, creating numerous opportunities for domestic employment and economic growth. And of course, robots require advanced technology skills for their design, deployment, operation, and maintenance, increasing the advantages of locating production facilities where highly skilled engineers and technicians are more readily available. Moreover, there is a new generation of robots coming that are smaller, more flexible, voice-controlled and safe enough to collaborate with human workers—as teammates rather than as replacements. These robots are likely to increase human productivity and thus save jobs.

Increasingly, robots are no longer confined to factory floors but finding use in homes (to clean floors), in healthcare and other service sectors (to deliver files or materials within a facility), and in transportation and logistics (think of Amazon's robot-powered distribution warehouses). Google has recently acquired several robotics companies and has made headlines with its efforts to develop robotic, driverless cars. This evolution may help provide solutions for labor-scarce jobs, as well as lowering consumer costs. For example, driverless cars could not only help avoid accidents but could also make car sharing an attractive alternative to car ownership, providing personal mobility with the convenience of private transportation and the sustainability of public transportation (Uber without drivers). The size of such a shared fleet would vastly outnumber the number of available taxi drivers in most cities in the U.S. (ever tried to find a taxi in the late evening of a rainy day?), and would generate a variety of new jobs, ranging from servicing and maintenance to the development of the back-end operations structure.

The research opportunities include putting still more flexibility, sensing capabilities, and intelligence into robotic devices, to make them still

No U.S. company is a market leader in designing and manufacturing industrial robots. And current U.S. investment in robotics research is dwarfed by new initiatives in other countries.

more capable of helping people and organizations accomplish routine daily tasks or function at times and under conditions that people don't want to work.

Unfortunately, while the U.S. is a leading country in the use of industrial robots, no U.S. company is a market leader in designing and manufacturing them. Most come from Japanese or European companies, with South Korea and especially China quickly on the rise. The U.S. is at present more competitive in research-oriented domains (domestic robots, driverless cars, drones, etc.), but that may not last in the current global landscape.

The U.S. National Robotics Initiative, launched in 2011, includes the National Science Foundation, the National Institute of Health, NASA, and the Department of Agriculture; the Department of Defense is also supporting robotics research and DARPA is sponsoring a Robotics Challenge with a focus on humanoid robots. But the combined U.S. investment is dwarfed by similar new initiatives worldwide. The European Union's new program, for example, commits about $3 billion in a combined public-private effort designed to ensure that the EU retains a 30-40% market share in the global robotics industry, estimated to reach $70 billion by 2020.

The U.S. is already relying on other countries to provide industrial robots. Staying competitive in rapidly growing and evolving new markets for robotics will require larger investments.

BATTERIES

Will Asian countries dominate the next generation of batteries, as they do the current one?

Batteries are ubiquitous and indispensable in modern society. Without them, no smartphones or tablets, no flashlights, no cars. With improvements, batteries could do much more: transform our use of electric power by enabling a more efficient and resilient grid, more widespread use of wind and solar energy. Advanced batteries may in some cases transform whole industries—they are likely to become the car engines of the future and hence central to the entire automotive sector, as well as a critical component of the smart, energy-efficient houses of the future.

These changes are not possible with today's lithium-ion batteries for both cost and safety reasons. Indeed, what is needed are batteries that are less expensive (e.g., use cheaper ingredients than in those in the now ubiquitous lithium-ion kind) but have five times better performance—a huge jump.

If that seems an insuperable goal, consider one example, a battery based on sulfur. Elemental sulfur is produced in enormous quantities as a byproduct of oil and natural gas production, and as a result costs about 1000 times less, weight for weight, than the electrode compound typically found in cellphone batteries. Yet sulfur as a battery electrode can store a great deal of charge—theoretically more than 10 times as much as the electrodes it would replace. And sulfur is not the only possibility—solid state batteries based on other materials besides lithium, metal-air batteries, and likely still others whose chemistry remains largely unexplored.

Of course, even realizing the potential of sulfur-based electrochemistry or other new chemistries in practical batteries is extremely challenging, because nearly all components would differ from those in a lithium-ion battery and must be re-invented, requiring expertise from multiple scientific disciplines. And there are other constraints—durability over thousands of recharge cycles and multiple years of use, safety, limited environmental impacts. But there are also opportunities to be explored, including:

- Using computational first-principles design to accelerate discovery of new compounds, such as storage materials that store dramatically higher energy than today's electrodes while remaining structurally stable, or nonflammable solid electrolytes with the ion conductivity of liquids.
- Adapting lessons from nanotechnology developed over the past two decades to the design of nanoscale structures with fast, reversible, stable charge storage.

The international competition is fierce, and U.S. efforts are lagging. Japan, China, and Korea have all initiated national research programs on next generation batteries that are already yielding discoveries.

- Controlling the atomic-scale structure of the interfaces between key components of the battery, in order to stabilize highly reactive compounds in contact with each other and allow safe, controlled delivery of electricity from very energetic electrochemical reactions.
- Developing new experimental tools to probe and observe the internal workings of batteries in real time at unprecedentedly small size and time scales.
- Development of entirely new battery designs and advanced manufacturing methods. Today's lithium battery manufacturing infrastructure evolved from decisions made two decades ago to utilize large-scale reel-to-reel winding methods derived from the magnetic tape industry. More efficient, lower cost, easily scaled manufacturing techniques are needed to enable the 100-fold increase in production volume anticipated over the next 20 yrs.

The international competition is fierce, and U.S. efforts are lagging. In fact, while lithium battery technology was conceived and researched in the U.S., today Japan, China and Korea dominate production and harvest the economic benefits. Those same countries have all initiated national research programs focused on next generation batteries that are already starting to yield discoveries. For example, Japanese universities and auto companies have made critical new discoveries in solid sulfide electrolytes that could be the key to all-solid-state batteries with several-fold better performance than lithium designs but with none of lithium's potential for flammability. The research lead has already translated to an enormous head start on commercialization. Germany has also invested in a large national battery program and created new laboratories. Pan-European research programs have been in place for several years. To compete, the U.S. will have to markedly step up its game.

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