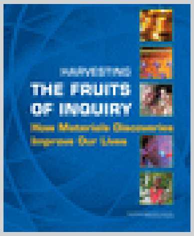

Harvesting the Fruits of Inquiry: How Materials Discoveries Improve Our Lives

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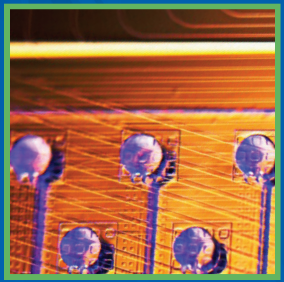

HARVESTING THE FRUITS OF INQUIRY

How Materials Discoveries Improve Our Lives

NATIONAL RESEARCH COUNCIL
OF THE NATIONAL ACADEMIES

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Preface

As discussed in the Physics 2010 decadal survey *Condensed-Matter and Materials Physics: The Science of the World Around Us* (NRC, 2007), the field of condensed matter and materials research (CMMR) has played a key role in meeting our nation's needs in a number of areas, including energy, health, and climate change. In the six years since the release of that report, the impact of CMMR in these areas has continued. The Board on Physics and Astronomy convened this committee, the ad hoc Committee on Societal Benefits from Condensed Matter and Materials Research, to produce a short booklet that highlights a few of the societal benefits that have flowed from research in this field. The full statement of task for this committee is as follows:

> An ad hoc committee will prepare a short report communicating the role that Condensed Matter and Materials Research (CMMR) plays in addressing societal needs. The report will use 5-6 examples to illustrate how research in this area has contributed directly to efforts to address the nation's needs in providing sustainable energy, meeting health needs, and addressing climate change issues. The report will be written at a level that makes its main ideas accessible to key target audiences, including academia, government agencies, and Congress.

This publication, the final report of the Committee on Societal Benefits from Condensed Matter and Materials Research, has been reviewed in draft form and we would like to thank the following individuals for their review comments: Venky Narayanamurti, who coordinated the review, and Sandra Greer (Mills College), Mas Subramanian (Oregon State University), Arthur Ramirez (University of California at Santa Cruz), Barbara Jones (IBM Almaden Research Center), and Jennifer Ouellette. Although the reviewers provided many constructive comments and suggestions, responsibility for the final content of this brochure rests entirely with the authoring committee and the institution.

Andrea Liu, George Crabtree, *Co-Chairs*

Committee on Societal Benefits from Condensed Matter and Materials Research

Overview

We rarely pause to consider the origins of the conveniences that surround our daily lives. Yet we increasingly rely on the fruits of decades of investment in basic condensed matter and materials research to address our day-to-day needs and wants. As an example, breakthroughs in the fundamental understanding of semiconductors led to the invention of the transistor in the late 1940s, which in turn triggered the explosion in microelectronics that has resulted in computers, smartphones, and a host of other devices. Similarly, when liquid crystals were discovered at the end of the nineteenth century, they were little more than geometrically and visually interesting materials. As investment in pure science increased, what began in the post-Sputnik era as curiosity-driven research into liquid crystals grew into the $100 billion per year display industry of today.

Discoveries such as the transistor, laser, and liquid crystal display have permeated almost every aspect of our lives. However, the path that must be followed from basic discoveries such as these to applications that benefit society is often long and many times unclear. With the shortening time horizons of everyone from investors to financial analysts to developers of new products, investments in the basic research needed for future technological discoveries have nearly disappeared from the private sector.[1] Meanwhile, the romantic view of a solitary inventor toiling to develop a light bulb is growing increasingly removed from reality. The materials at the forefront of discovery and their associated phenomena are becoming progressively more complex as science advances. As a result, sustained effort by many researchers covering a wide array of disciplines is needed, not only to make scientific discoveries but also to convert them into prototypes that can attract the capital needed to turn them into marketable products. This calls for significant federal investment in basic research.

Fortunately, such investment pays off handsomely. Basic research has long been recognized as an integral part of the innovation system that leads to economic growth in industrialized nations.[2] Not only can basic research lead to new discoveries, but it also has the added benefit of training young scientists and engineers, many of whom later apply their knowledge and ideas to problems in industry.

Our society faces enormous challenges. We must find ways of satisfying our demand for energy without destroying the environment or risking our security. We must maintain our health as we age without destroying our economy. In this report, we present five vignettes that illustrate just a few of the many instances where recent fundamental discoveries in condensed matter and materials research are transforming current technologies to address these challenges. These discoveries have already created jobs through start-up companies or the expansion of larger ventures; they improve our lives while enhancing the economic competitiveness of our nation.

Solid-State Lighting

It was near dusk as Liu Qi, president of the Beijing Olympic Committee Organizing Group, gazed at the massive "Bird's Nest" Chinese national stadium in front of him. With the 2008 Beijing Summer Olympics scheduled to start in only three months, he was making an inspection tour of the stadium. Construction had just been completed.

But something didn't look right.

Liu Qi looked back over his shoulder at the "Water Cube," China's national aquatic center, standing a few hundred yards from the stadium. The Water Cube gave off an iridescent blue and green glow. Earlier he had toured the facility and been mesmerized by the shifting multicolor patterns that had played across the exterior, provided by computer-controlled light-emitting diodes (LEDs). Looking back at the Bird's Nest, he frowned. "What is the lighting being used for the stadium?" he asked his tour host.

"Why, it's the standard fluorescent lamps called for in the design," the man replied.

"I don't like it; it's too harsh," said the president. He thought for a moment, then said "We want everything for the Olympics to be perfect. I want you to rip out the fluorescents and use LEDs for the Bird's Nest, just like you did for the Water Cube."

The National Aquatic Center of China, also known as the "Water Cube." The LED chips in the exterior architectural lighting were supplied almost entirely by U.S. companies. SOURCE: Courtesy of Cree.

The "Bird's Nest" Chinese national stadium in Beijing. SOURCE: Courtesy of Cree.

And that's how the American company Cree was contracted to light the last important LED venue at the Olympics in Beijing. They had already supplied LEDs for the Water Cube, every video display in the main Olympic complex, and the tens-of-meters-long rolling video display depicting the era of the Silk Road for the opening ceremony. All told, the entire event consumed millions of LEDs worth many millions of dollars.

An LED is a semiconductor device, related to the transistor, which directly converts electricity into light. In principle, close to 100 percent efficiency in the conversion of electricity to light is possible. This is radically different from conventional incandescent and fluorescent lamps, which have been limited for many decades, despite much effort, to about 5 percent and 25 percent efficiency, respectively.

The first practical LEDs had very low efficiencies and were extremely expensive, about $200 each. During the 1970s efficiencies improved a little, but the price dropped dramatically—to a few pennies each. And so LEDs became widely used as indicators in clock radios and consumer electronics.

LEDs suitable for lighting only became possible when new semiconductor materials investigated by scientists in academia and in industry reached sufficient maturity. The development of gallium nitride materials enabled the world's first practical blue LEDs in 1993. Blue was the missing color—the holy grail—and its appearance on the scene finally enabled white LED light to be created, by mixing the blue with other colors.

As researchers made progress, LED technology rapidly advanced and began to conquer incumbent technologies such as those for traffic lights. Red, yellow, and green LEDs used as little as 1/10 the electricity of the existing traffic light incandescent bulbs, saving roughly $1,000 of electricity per intersection each year. Today, roughly 80 percent of the traffic lights in the United States use LEDs.

During the past decade, improvements in LED technology have followed a kind of Moore's law (called "Haitz's law"[3] in the case of LEDs), rapidly increasing in performance and dropping in cost. Today, white LED lightbulbs are widely available in stores across the country.

The economic impact of these developments on employment will be significant. In 2007, the U.S. lighting industry employed 60,000 people nationwide and shipped $13.5 billion in lighting products.

These products have good color quality and an extraordinarily long life (50,000 hours as compared to 5,000 hours for fluorescent lights and only 1,000 hours for incandescent lights). And LED lighting energy efficiencies are now surpassing those of fluorescents.[4] Best of all, the costs continue to plummet with the passage of time: Bulbs that cost as much as $100 each when introduced in 2008 have seen their price drop to $10 per bulb by 2013.[5]

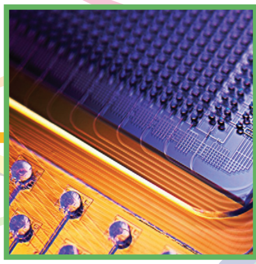
The development of this revolutionary new technology was supported by the National Science Foundation, the Department of Defense, and the Department of Energy. "There's no doubt that Cree wouldn't exist if it weren't for the sustained frontier research funding that we received from the federal government in the early years, and the foresight and vision of the government program managers who realized the potential," says Chris James, Cree's vice president for strategy. "No venture capitalist would ever make the kind of high risk, decades-long investment that we needed."

What does the future hold? Current scientific research and development promises future LED lighting that is even more efficient and less costly. Research topics include how to allow electrons to move more easily in the LED layers (to reduce electrical resistive losses), how to reduce defects in the semiconductor material (to reduce parasitic channels in which electrons lose energy without emitting light), and how to "extract" more light from the LED once the light is created inside it—that is, to reduce the amount of light that is trapped and re-absorbed in the LED.[6] While the best products currently on the market have energy efficiencies of around 25 percent, cool white LEDs have already demonstrated 50 percent in the lab.[7] Ultimately, the industry believes it may achieve energy efficiencies of 70-80 percent, although much basic research will still be needed to reach those levels.[8]

According to a recent study for DOE by Navigant,[9] by the year 2030, LEDs are expected to reduce the electricity used for U.S. lighting by 46 percent, resulting in annual savings of $30 billion, eliminating the need for ~50 large (1,000 megawatt) power plants, and reducing the emissions of 210 million metric tons of carbon every year. Moreover, the costs of LED lighting will continue to drop, as more light is coaxed out of every LED chip and as improvements in manufacturing techniques continue. It is believed that in the next dozen years the purchase price of LED bulbs will drop by a factor of 10.[10]

The economic impact of these developments on employment will be significant. In 2007, the U.S. lighting industry employed 60,000 people nationwide and shipped $13.5 billion in lighting products.[11] LED lighting is an exciting new technology that is expected to have tremendous economic benefit for the lighting industry, which until recently had essentially been reduced to selling products virtually indistinguishable from each other. The new performance possibilities represented by LED lighting should rejuvenate the industry as well as enhance human productivity and create wealth.

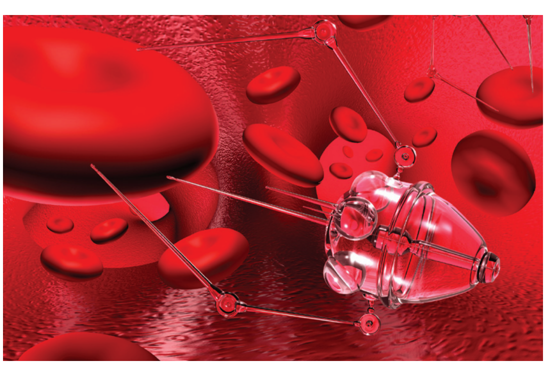
And this is only the beginning. The very form and functionality of our lighting is destined to evolve into something difficult for us to currently imagine. Researchers are beginning to look at how to incorporate micromechanical optical components—electrically activated miniature mirrors and lenses—into the LED chip surface. This could allow beams of light from a lamp to be focused from a wide area to a spotlight. When combined with sensors, such lamps of the future could track peoples' locations and activities as they move about a room, and adjust the intensity and distribution of the light to match the activities of a room's occupant. Imagine living in such a world: instead of flicking on a light switch or adjusting a dimmer as you enter a room, the lamp could automatically adjust the color and spectral content of the light it emits to match the ambient light coming through the windows. Perhaps the lighting system could also respond to the mood and day/night biological rhythms of the perceiver—arriving home on a cold winter's night, your home would be bathed in a warm, inviting glow as you stepped through the door. Or imagine how, as you enjoy the sunset of a summer evening, the lighting system might adjust to complement the orange and pink tones that streak the sky. This more intelligent and judicious allocation of light—the right photon in the right place at the right time—will not only improve the efficiency of our lighting but will also improve our everyday lives.



Nanoparticle Drug Delivery and Diagnostics in Health

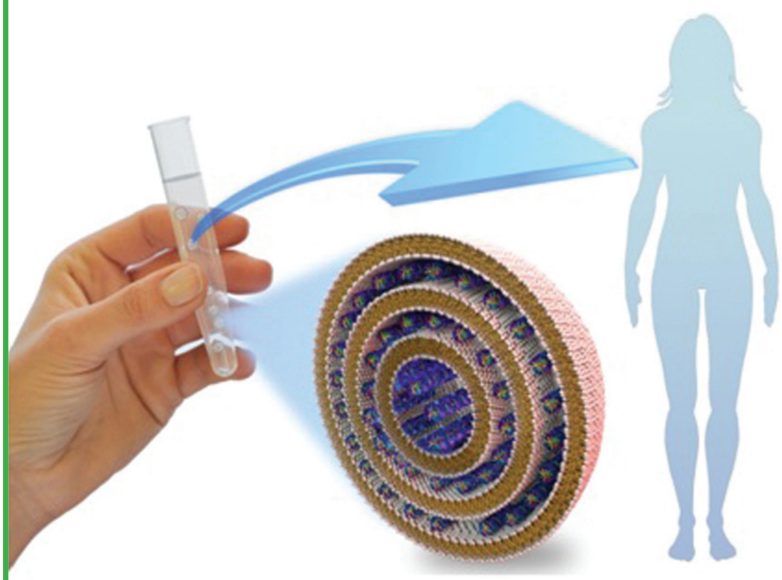
Imagine a medical patient suffering from cystic fibrosis, a disease caused by a faulty gene in the patient's cells, or from cancer, a multigene disease. Then imagine the patient being cured by a new class of treatment, gene therapy, which replaces or supplements the patient's own faulty or diseased genes with new therapeutic nucleic acids, DNA or RNA. These nucleic acids may be encapsulated with carrier molecules such as lipids (fat molecules), which protect them from destruction by the patient's own immune system. The carrier lipids are designed to deliver their cargo specifically to the patient's lungs or to a tumor, allowing for small dosages and reducing harmful side effects.

The delivery of drugs where they are needed is not an empty dream; more than 1,800 human clinical trials are ongoing, with over 110 of them employing lipid carriers.[12] Many of these clinical trials, including those for treating cystic fibrosis as well as cancer, have been aided by the recent discoveries of condensed matter and materials researchers at the University of California, Santa Barbara. These researchers, funded by the National Science Foundation and the National Institutes of Health and using synchrotron facilities funded by the Department of Energy, have uncovered the internal structures of lipid-nucleic acid nanoparticles (NPs)—that is, the arrangement of the lipid and nucleic acid molecules inside



and on the surface of the NP. This new knowledge promises to dramatically raise the success rates of clinical trials because it gives scientists crucial insights into how to design new variations of the lipids that are more efficient at carrying the NP to the diseased cells of interest (which depends on lipids with a special chemical structure being present at the surface of the NP) and at releasing the therapeutic nucleic acid cargo molecules upon cell entry (which depends on the lipid and nucleic acid arrangement inside the NP).

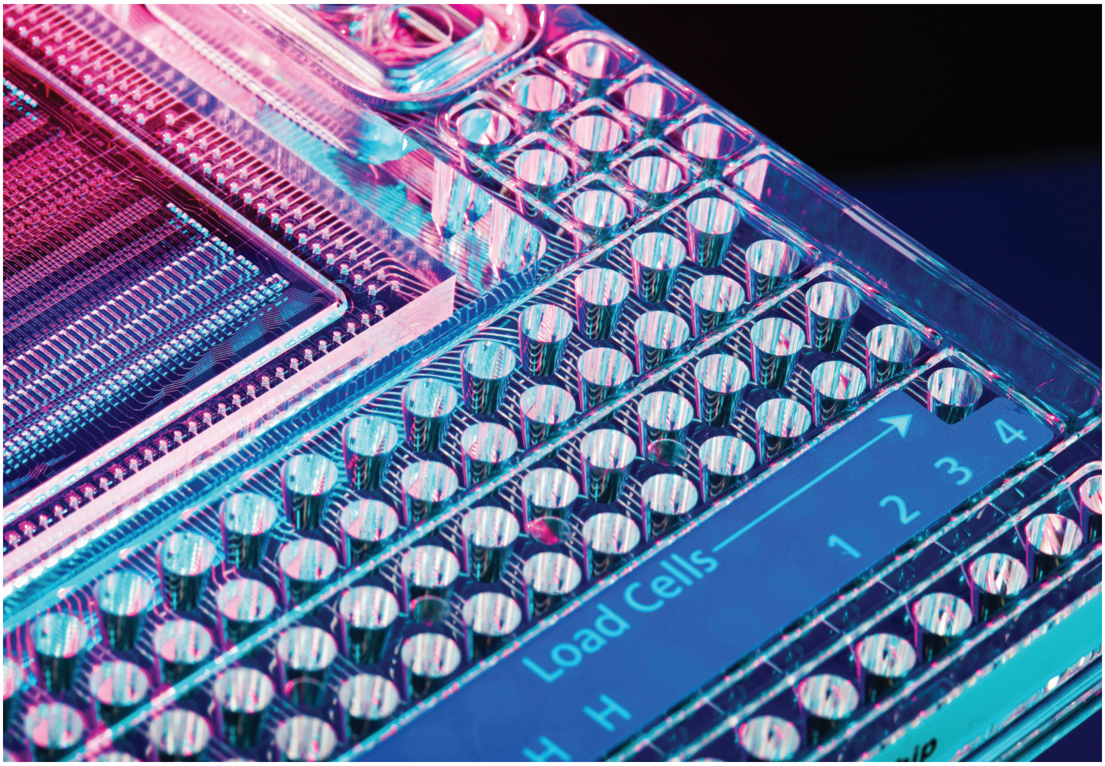
Much of the development of new nucleic-acid-based gene therapies is occurring in small start-up companies, whose technology may be traced to research concepts realized at universities and national laboratories in the course of research supported by federal funding agencies. For example, DNA-chewing enzymes in the blood normally destroy DNA, but materials researchers found that the DNA is protected when grafted to gold nanoparticles.[13] DNA-functionalized gold nanoparticles provide an alternative route to gene therapy as well as high sensitivity to new protein markers for bladder, kidney, prostate, and other cancers. Small businesses such as Nanosphere, based in Illinois, are developing these new technologies for medical applications.



Ongoing clinical trials aim to efficiently deliver therapeutic DNA or RNA molecules for treating a wide range of human diseases. In the figure a human hand is shown holding a vial containing a liquid suspension of lipid-nucleic acid (DNA or RNA) nanoparticles intended for delivery through direct injection into tissue or intravenously or orally. The blow-up of one such lipid-nucleic acid nanoparticle (with a diameter between 100 and 200 nanometers) reveals the internal onion-like structure consisting of lipid bilayers (mustard tails attached to white spheres forming the onion layers) wrapped around therapeutic nucleic acids (DNA or RNA, helically shaped purple molecules). The multi-layered onion structure significantly increases the therapeutic loading capacity (the number of nucleic acids) per particle, thus improving the therapeutic effectiveness of each particle entering a diseased cell. SOURCES: Rädler, J.O., I. Koltover, T. Salditt, and C.R. Safinya, 1997, Structure of DNA–cationic liposome complexes: DNA intercalation in multilamellar membranes in distinct interhelical packing regimes, Science *275: 810-814; Ewert, K.K., A. Zidovska, A. Ahmad, N.F. Bouxsein, et al., 2010, Cationic liposome–nucleic acid complexes for gene delivery and silencing: Pathways and mechanisms for plasmid DNA and siRNA,* Topics in Current Chemistry *296: 191-226.*

This technology could truly level the field, bringing modern, state-of-the-art diagnostics to every doctor's office, even in the poorest countries.

To achieve their full potential, gene therapy and DNA-based disease diagnostics face a huge challenge—to deliver nucleic acids to specific diseased cells within the body. Reaching the holy grail of therapeutic efficacy through precise targeting will require continued sustained research efforts by multidisciplinary teams of researchers, including condensed matter and materials scientists.



Lab-on-a-chip devices such as the integrated fluidic circuit (IFC) shown above can be considered the biological equivalent of the integrated circuit. These devices provide a simple, fast, and cheap system for streamlining genetic research. SOURCE: Courtesy of Fluidigm Corporation.

During the same time that these new targeted delivery systems were being developed, there has been a veritable revolution in disease diagnostics that mirrors the revolution in microelectronics. This revolution exploits microfluidic technologies to develop lab-on-a-chip devices that provide miniature and much simpler diagnostic systems for point-of-care deployment. Condensed matter and materials research has been instrumental in the development of these new technologies. For example, a California company, Fluidigm, founded by a Stanford professor, is developing lab-on-a-chip diagnostics based on soft lithography. Even more easily distributable diagnostic devices are being developed by a Harvard start-up, Diagnostics for All; these devices are printed directly on paper, making their cost very low and thus affordable throughout the world.[14] The rapid ongoing development of this new technology is expected to lead to a suite of patterned paper devices able to assay for a range of organ functions, as evidenced by the recent introduction of such devices for cost-efficient liver function assays.[15] This technology could truly level the field, bringing modern, state-of-the-art diagnostics to every doctor's office, even in the poorest countries.

Rechargeable Batteries

On a Manhattan street corner in April 1973, Motorola engineer Martin Cooper made history. Holding the world's first cell phone—a 9 in. long, 2.5 lb brick of beige plastic—he strode out across Sixth Avenue and made the world's first cell phone call.

Until that point, most cell phone research was focused on developing car phones, which were powered by heavy equipment that could be stored in the car's trunk. But Cooper had other ideas. "People want to talk to other people—not a house, or an office, or a car. Given a choice, people will demand the freedom to communicate wherever they are, unfettered by the infamous copper wire," he explained.[16]

The main challenge lay in developing a suitable energy source: To be truly portable, a mobile phone would need a small, light, and quickly rechargeable battery. The 1973 prototype cell phone contained a large and heavy battery that took 10 hours to charge and provided just 35 minutes of talk time. A breakthrough came in 1976, with the development of the lithium-ion battery, which boasted a high energy-to-weight ratio and could hold a charge for a long time. The lithium-ion battery helped bring down the weight of the first commercially available cell phone—the 1983 DynaTAC—to 1.75 lb. Since then, continued improvements to lithium-ion batteries have allowed cell phones—and a host of other modern devices such as tablets, laptops, and digital cameras—to become ever smaller, lighter, and more portable.

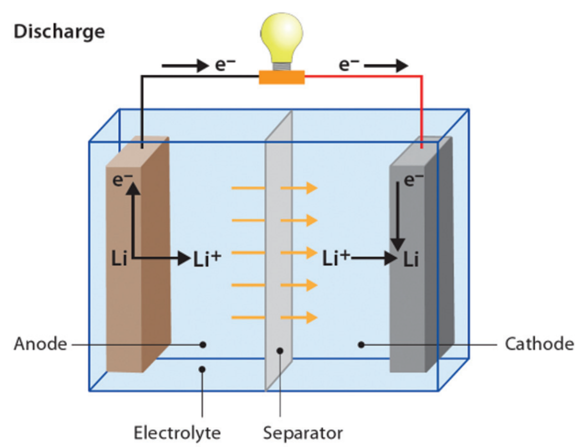
The size of mobile phones decreased drastically from the time that the first commercially available cell phones were released in the mid-1980s through the mid-2000s, owing in large part to improvements in battery energy density. Further improvements in batteries and other technological advances have led to the introduction of phones with greater capabilities (accompanied by growth in size to accommodate those capabilities). Shown are (from left to right): (1) Motorola DynaTEC (1983), (2) Nokia Mobira cityman 900 (1987), (3) Motorola MicroTAC (1994), (4) Motorola StarTAC (1996), (5) Nokia 7110 (1999), (6) Samsung SCH-A650 (2004), (7) Nokia E71 (2008), and (8) Samsung Galaxy S4 (2013). SOURCES: 1, 3, and 4, courtesy of Motorola; 2, 5, and 7, courtesy of Nokia; 6 and 8, courtesy of Samsung.

So, what makes a good battery and why is lithium the battery of choice for so many devices? Among the most important criteria used for evaluating the effectiveness of a battery are (1) its (weight-based) energy density (the amount of energy deliverable per unit volume or per unit weight), (2) its (weight-based) power density (the rate of energy deliverable per unit of time and weight), (3) safety, (4) costs, and (5) reliability. It turns out that lithium offers significant advantages judged by some of these criteria but drawbacks as judged by others. Because lithium, with a density of 0.53 g cm^{-3}, is the lightest of metals—even lighter than water, which has a density of 1.00 g cm^{-3} at room temperature—it allows the building of batteries with a high energy density. Lithium is also among the most electropositive of metals, a measure of its ability to donate electrons and therefore form positive ions. Consequently, the change in the potential energy of lithium ions as they undergo chemical reactions at the anode and cathode is significant, translating into a higher voltage across the battery than in batteries that use other elements. However, a characteristic of lithium closely related to its electropositive nature (tendency to release an electron) is that it is highly reactive and flammable, which must be considered in the safe design of batteries that use lithium as a component.

The exploitation of lithium for use in batteries can be traced directly back to a materials discovery, the so-called "lithium intercalation compound," which accommodates lithium atoms into its structure without tightly binding them so that they can be released during the charging process.[17] This scientific discovery was followed by more discoveries, such as the high-cell-voltage cathode material $LiCoO_2$, developed by John Goodenough,[18] which is still one of the most common cathode materials in portable consumer electronics today.

How Do Batteries Work?

Batteries are made up of cells that contain two electrodes—a negatively charged anode and positively charged cathode—and an electrolyte that separates the electrodes and allows for the flow of charged atoms (ions) between them. Once the electrodes are connected to an external circuit, chemical reactions take place at the two electrodes, resulting in the release of electrons able to travel along the connected path and ions that travel through the electrolyte from one electrode to the other.



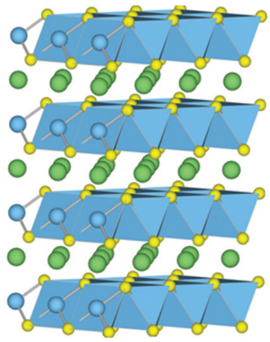
During charging, lithium is brought to the anode, where it is stored. When electricity is needed, lithium ions flow from the anode (negative electrode in which lithium is in a higher energy state) to the cathode (positive electrode, where lithium is in a lower energy state) just as water would flow from higher to lower ground. As a lithium ion leaves the anode, an electron is collected and then flows through the device (the light bulb, in this schematic).

In these compounds, lithium and other elements (such as cobalt and oxygen in $LiCoO_2$) are combined in such a way that the atoms form a layered structure in which the lithium is loosely bound and therefore is easily available to participate in the chemical reactions and transportation that make the battery work. The architecture of the material is designed so that the material's structure remains unaffected as the lithium atoms engage in the repetitive process of releasing electrons, traveling out of the material as ions and being replaced by lithium atoms from the electrolyte, allowing the process to be repeated many times.

Much of the materials research that has taken place over the last 35 years in refining the lithium battery (or trying to replace it with something even better) has focused on taking advantage of what lithium has to offer while satisfying the other needs for a good battery. Cobalt, for example, is a relatively expensive mineral and so materials researchers have worked to find alternatives that still meet standards of safety, reliability, and high energy densities.[19]

The payoff for significant improvements in energy and power densities extends well beyond personal electronic devices.

Other efforts have gone into developing alternative architectural structures that provide even greater energy densities or allow for cheaper synthesis and even replacing lithium itself with elements having similar chemical properties.[20]



A schematic of the crystal structure of lithium cobalt oxide, $LiCoO_2$, where single layers of lithium atoms (green balls) are loosely arrayed between cobalt oxide layers, made up of cobalt atoms (blue balls) and oxygen atoms (yellow balls). SOURCE: Courtesy of Anton Van der Ven, University of Michigan.

The payoff for significant improvements in energy and power densities extends well beyond personal electronic devices. To take advantage of renewable solar or wind energy, we need to store electricity collected when the sun shines or the wind blows, for use when night falls or the wind calms. Battery-driven electric vehicles could replace foreign oil with domestic electricity and reduce our emission of greenhouse gases. Scientists are now working toward the next-generation batteries for these energy applications with up to five times better performance and costing one fifth the cost of the best batteries available today. Discovering novel materials is key to achieving this visionary goal.

Renewable energy such as wind and solar requires storage of energy to be used when the sources are not available.

Spintronics

As dusk fell one spring evening in 1820, Hans Christian Oersted bustled round his laboratory preparing for a lecture. Oersted, a professor of natural philosophy at the University of Copenhagen, planned to teach his students about the heating of a wire by an electric current and to demonstrate magnetism using a compass needle.

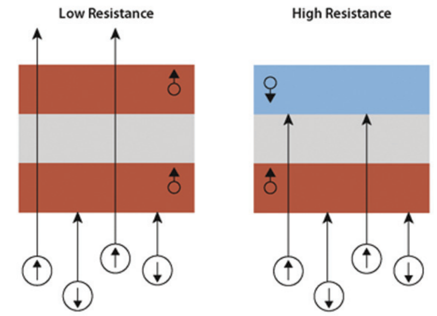
But as he gathered materials for the demonstrations, Oersted noticed something surprising: When electricity flowed through the wire, the compass needle moved. When he reversed the polarity of the battery providing the current, the compass needle pointed in the opposite direction.

Oersted's seemingly simple discovery—that electricity creates a magnetic field that will deflect a compass—launched the study of electromagnetics and sowed the seeds for a scientific revolution. Over the next century, great advances were made in the understanding of how magnetism and electrical currents interact, from Faraday's discovery that a varying magnetic field induces a potential difference, to Lord Kelvin's finding that a magnetic field can change the electrical resistance of a material. This scientific understanding provided the foundation for the development of the electric motors, generators, transformers, and electromagnets that revolutionized the way we live and work.

Today, scientists are still unraveling the mysteries of electricity and magnetism, but now their focus has zoomed in to the microscopic level, to investigate the interaction between the tiny electrical currents and the quantum-mechanical magnetism (spin) possessed by individual electrons. Technology that harnesses spin and uses it to control the movement of charge is called spintronics.

One spintronics device already in use is the hard disk drive, which stores digital information and delivers it to the rest of the computer system when needed. Since 1997, hard drives have used a spin-based phenomenon to cram gigabytes of songs, documents, photos, and movies into ever smaller spaces.

The information in hard disk drives is stored in small magnetic bits, like tiny compass needles that can be switched between pointing north and pointing south. To read the information from an individual magnetic bit, one must have a sensor, or read head, that is capable of detecting the minute magnetic field emanating from that bit. As hard drives get smaller, the data must be packed more densely, making a mass of magnetic bits (almost one trillion per square inch) that is difficult to decipher.



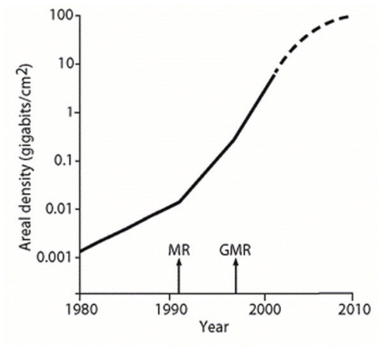
GMR consists of two extremely thin layers of magnetized material separated by a layer of non-magnetized material in the middle. Each electron can exist in one of two spin states: up or down. Within the atoms of the magnetic material, all the electrons' spins become oriented the same way, parallel to the magnetic orientation of that particular layer. That affects how electrical current passes through the system: If the two magnetized layers are polarized in the same direction, then electrons spinning in that direction will pass through both layers with little resistance, whereas electrons spinning in the other direction will not. If, however, the layers are magnetized in opposite directions, then all the electrons will face high resistance, regardless of the direction of their spin.

This is where electron spin enters the picture. In 1988, scientists Albert Fert and Peter Grünberg each independently discovered the phenomenon of giant magnetoresistance (GMR), a technology that uses the properties of spin to convert small fluctuations in magnetic field into large changes in resistance (for more explanation, see box). Other scientists quickly saw the potential of the technology for creating read heads sensitive enough to read data stored on miniaturized hard drives: The tiny magnetic fields from each data-storing bit would slightly reorient the magnetizations in a GMR-based read head, creating a significant change in the electrical resistance that could convert the data into an electrical read-out signal.

The problem was that the techniques used to make the GMR structure were time-consuming and required very low temperatures and high magnetic fields, making mass production difficult. A breakthrough came when scientists at IBM tried a fast, inexpensive technique called sputtering to create the thin layers of material needed for a GMR system—and it worked. This work paved the way to manufacturing readout heads based on GMR technology that could operate at room temperature.

The era of GMR-based hard disk drives lasted only about a decade, but the spintronics revolution continues. Today's hard disk drives are based on a newer spintronic technology called the magnetic tunnel junction. Similar in appearance to GMR, magnetic tunnel junctions consist of two magnetic layers separated by a layer of insulator. Most electrical current cannot pass through the insulating layer, but a quantum mechanical property called tunneling magnetoresistance allows electrons of one spin direction to "tunnel" through. That means the current that flows through is almost entirely either spin-up or spin-down, depending on the magnetic polarization of the surrounding layers. This produces even greater sensitivity to small magnetic fields than GMR and therefore these magnetic tunnel junctions can be used to build even more sensitive read heads.

Spintronic read heads have allowed vast increases in the capacity of digital data storage over the past 15 years (see box) and vast decreases in its cost—for example, it now costs less than one cent to store fifty songs. However, the impact of spintronics reaches well beyond the personal computer. The ability to store and access huge amounts of data has helped to usher in the information age: Most of the information accessible through the Internet is stored on banks of hard disk drives.



With the introduction of readout heads based on the spintronic properties of magnetoresistance and giant magnetoresistance, the density of data storage on hard drives has increased. SOURCE: The Royal Swedish Academy of Sciences.

The future of spintronics offers other equally exciting opportunities. Currently, a global race is taking place to commercialize a spintronics technology that if successfully developed could remove one of the biggest aggravations of computers—the time it takes a computer to "boot up."

Most computers use two types of data storage: a hard disk drive, which provides long-term data storage, and a solid state random access memory (RAM) that runs operations. Both types of memory have advantages and disadvantages. Thanks to spintronics, modern hard disk drives can store large amounts of data very cheaply. However, the basic mechanism of hard disk drives has remained unchanged since the 1950s, and is now considered unreliable and slow. Solid state memories read and write data quickly, but information manipulated within the memory of their chips is volatile—that means the information is lost when the computer is powered off or crashes. It must be reread from the disk drive and restored in memory each time the computer is turned on, giving that irritating delay.

To get around this problem, many computers, smartphones, and tablets now use flash, a nonvolatile solid state memory that uses high-voltage pulses of charge to write memory cells. However, flash memory uses a lot of power, and the cell is damaged each time data is written, becoming unusable after about 10,000 writing operations.

A spintronic alternative called magnetic RAM, or MRAM, offers a nonvolatile, power-efficient form of memory. The technology is based on the magnetic tunnel junction: Data are stored in the magnetic state of the magnetic tunnel junction and can be read by the tunneling magnetoresistance of the same device. Because information is stored using magnetic field not charge, processing chips using MRAM technology are nonvolatile and retain data even when powered off. Not only are start-up delays a thing of the past, but power consumption is significantly reduced compared to current chip memories, which need to use power continuously

The race is on to learn more about these spintronics phenomena and bring them to the marketplace.

to retain stored information, or flash, which requires high-voltage pulses of energy to write information. Unlike flash memory, MRAM chips do not wear out over time.

The first MRAM solid state drives went on sale in 2006, but work continues to develop higher-density MRAM based on a spintronic effect called spin transfer torque, in which the orientation in a magnetic layer is modified using spin-polarized current instead of magnetic fields. First predicted in 1996 by researchers at IBM and Carnegie Mellon University, spin transfer torque has the great virtue of allowing computer chip magnetic memory bits to be scaled down to very small sizes, just a few tens of nanometers across. In this way it can make possible MRAM products with a very high density of memory bits that are fast, nonvolatile, cheap, and never wear out—all of the attributes that one would want in a memory technology. In the United States today, both large corporations (e.g., IBM, Micron Technology, Intel, Qualcomm) and smaller companies (Everspin, Crocus, Avalanche, Spin Transfer Technologies) have devoted significant effort to commercializing this technology.

With portable wireless electronics becoming increasingly popular, there is a growing need for devices that are power efficient. Consequently, much current spintronics research explores new materials or device designs that provide better energy performance, as compared to charge-based devices (see the Rechargeable Batteries section for another example). Lower-power electronics are also important for database server facilities that will require ever more power as big data applications proliferate. Finally, spintronics concepts are expected to continue to exert strong influence on computer memory.

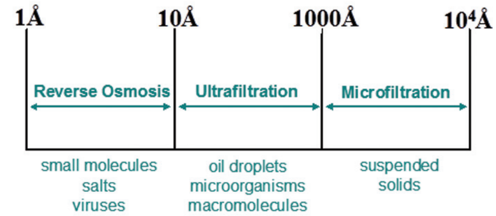
Classes of spintronics materials other than traditional metal ferromagnets—strongly correlated transition metal oxides are one such class—may help scientists learn more about spin and reveal entirely new phenomena. For example, the recently discovered topological insulators are materials that behave like insulators in their interior but have conducting states on their surfaces—a finding that may further revolutionize spin electronics. The race is on to learn more about these spintronics phenomena and bring them to the marketplace. Research in spintronics has exploded in China, Japan, Korea, and Europe, as well as in the United States.

Polymer Membranes for Water Filtration

Today, about 783 million people—11 per cent of the world's population—live without access to clean drinking water.[21] For these people, many of whom live in the developing world, taking a drink of water means risking exposure to bacteria, viruses, arsenic, and other chemicals. Every year, there are 3.4 million deaths from water-, sanitation-, and hygiene-related causes, many of them preventable.[22]

The problem is that for much of the world, sources of clean, fresh water are scarce. About 97.5 percent of the water on our planet is salty, and only 0.5 percent of the fresh water is accessible.[23] Even within the United States, freshwater supplies in places such as the West are rapidly dwindling,[24] and drought threatens agriculture. At the same time, increasing contamination of water supplies from pesticides, fertilizers, hormones, pharmaceuticals, and shale gas extraction is a serious problem that threatens health. A lack of access to water supplies has the potential to trigger conflict, both within the United States and around the world.

To help solve these problems, materials scientists and chemical engineers are working to develop inexpensive, scalable, and sustainable methods to harvest and purify water, for example with new polymer membranes that can filter contaminants from the water[25] (see box). One research team is working on a fuel-efficient method for turning salty seawater into clean, drinkable freshwater. Currently, salt is removed from seawater either by thermal desalination, which involves boiling seawater above 212°F and then distilling the vapors, or by reverse osmosis, which uses hydraulic pressure to force water through a membrane that filters out salt. Both methods require large inputs of energy. In 2011, Oasys Water announced a desalination method that is at least 10 times more fuel-efficient.[26] The new method is based on the principle of simple forward osmosis: Without any input of energy, water molecules will naturally move from fresh solutions to saltier ones. The researchers developed a specially formulated solution that is saltier than seawater, drawing water molecules out of seawater across a porous membrane and leaving the sea salt residue behind. The resulting solution contains a mix of salt compounds that vaporize at much lower temperatures than seawater salts. That means the salty liquid can be made into freshwater by thermal desalination at only 122°F, a significant energy saving over traditional thermal desalination methods.



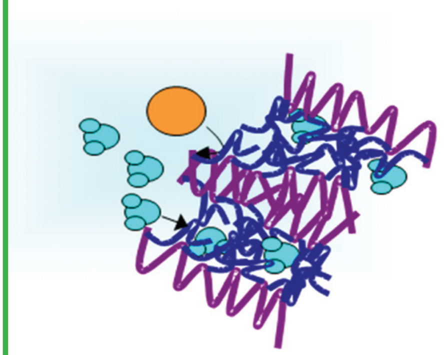
Schematic representation of the processes involved in the cleaning of water. Contaminated water contains many pollutants of various sizes, and an integrated approach is needed to remove them all. Initial states include treatment with sediment filters that remove larger particles and then ultrafiltration with hydrophobic/hydrophilic membranes for the removal of oils and microorganisms. Typically, these steps are followed by subjecting the water to reverse osmosis through membranes that remove the smallest contaminants.

Another team of researchers is developing new membranes that make the process of reverse osmosis more efficient by fabricating a matrix of polymers and nanoparticles that allows water molecules to flow through but repels contaminants.[27] That means less energy is needed to pump water through the membrane.

Striving to develop technologies that could help increase access to clean drinking water was one of the goals of the late MIT polymer science professor Anne M. Mayes. Her research group designed and synthesized novel polymer materials that helped solve one of the more intractable problems of water filtration systems: the buildup of contaminants and salt at the surfaces of the filters and membranes. This fouling can clog membrane pores, decreasing the amount of water that flows through the system. As a result, the membranes must be cleaned and replaced frequently—at a high cost.

Every year, there are 3.4 million deaths from water-, sanitation-, and hygiene-related causes, many of them preventable.

The Mayes group developed copolymers that are studded with "comb" copolymers, which consist of a hydrophobic backbone lined with short hydrophilic extensions, like the teeth on a comb. The teeth attract water molecules and prevent the buildup of contaminants, creating membranes that are remarkably resistant to fouling (see box). Two of Mayes's graduate students founded a new small business in Massachusetts, Clean Membranes (www.cleanmembranes.com) to bring these foul-resistant membranes to the market. With support from the Office of Naval Research, the company has developed membranes as a pretreatment step for shipboard desalination systems, attracting venture investment. Companies like these bring new technologies to help solve global problems, while providing jobs to bolster the U.S. economy.



Efforts to improve water filtration systems include the development of membranes made up of combinations of materials that perform different functions in the filtration process. The example in this figure consists of two types of molecular chains. The first, poly(oxyethylene) side chains (dark blue), provides nanochannels for the selective transport of liquids. They are highly wettable by water and many organics and have low fouling propensity, allowing the passage of water (aqua) through the filter, while pushing away foulant molecules (orange). These are combined with poly(vinylidene fluoride) (PVDF) backbone chains that provide structural integrity and are insoluble in most organic liquids. SOURCE: Reprinted with permission from J.F. Hester, P. Banerjee, Y.-Y. Won, A. Akthakul, M.H. Acar, and A.M. Mayes, 2002. ATRP of amphiphilic graft copolymers based on PVDF and their use as membrane additives, Macromolecules *35: 7652. Copyright 2002, American Chemical Society.*

Concluding Remarks

In these tight budgetary times, the question of whether the nation is benefiting from federal spending on basic research is becoming increasingly important. The amount spent by the federal government for basic research in a given year is approximately $40 billion, slightly more than 1 percent of the total federal budget.[28] Of this, a small fraction is used to support condensed matter and materials research, the subject of this report.

The examples in this report illustrate how advances in basic research lead to tangible products that benefit not only our economy but also our health, the environment, and quality of life. Moreover, these examples represent only a handful of the many recent discoveries in condensed matter and materials research that have affected our lives or that hold considerable commercial promise. From gecko-inspired adhesives based on carbon nanotubes that do not use any liquid glue, to rare earth magnets used in earbuds and the electric motors of hybrid cars, these discoveries have added to the economic strength of our nation by generating new jobs and creating new products. They also help our economy in less direct ways: As mentioned in the first example of this report, $30 billion per year in power savings alone are estimated to flow from advances in solid state lighting by 2030, a more than fair return on our nation's investments in that area.

It is worth noting that most federal grant money is spent on supporting graduate students and postdoctoral fellows, while most of the remainder is spent on scientific equipment. As a result, even money spent on research that does not lead to a useful application is not wasted—it is used to train the future scientific and engineering workforce or to purchase equipment made by high technology companies.

The path from basic research in condensed matter and materials research to new product is often obvious only in retrospect. For example, it might seem frivolous to study how light flickers when bubbles move around in shaving cream or particles move in a colloidal suspension like paint. These optics discoveries from the 1990s, however, have led to new noninvasive and cheap medical devices, now being tested in clinical trials, for monitoring blood flow in stroke patients as they lie in their beds.

It is difficult to predict the time it takes to move from fundamental discovery to indispensable product. Liquid crystals were first discovered in 1888 but did not become ubiquitous in liquid crystal displays until the 1990s. The first LED was made in 1927 but LEDs did not see widespread use as indicator lights until the 1970s and are only now entering our homes as lighting sources. On the other hand, the phenomenon of giant magnetoresistance, the fourth example in this report, was commercialized within 10 years of its discovery in 1988. By now, it forms the basis for the market in computer disk drives and Internet mass storage, a market amounting to many tens of billions of dollars. Even a 10-year path from initial discovery to final product is too long, however, for almost all businesses, especially when the nature of the eventual product is not obvious at the outset. This is why federal funding is essential, particularly in light of the disappearance of almost all basic research in industrial laboratories.[29]

The total amount contributed by condensed matter and materials research to the U.S. economy has not been estimated. But it is clear that the impact is far-reaching, and that these benefits are magnified enormously when discoveries are made in the United States and commercialized here. Federal investment in scientific research in condensed matter and materials research not only pays for itself manyfold but is vitally important in order for our country to maintain its economic leadership of the world.

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