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The BRIDGE

LINKING ENGINEERING AND SOCIETY

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Editor's Note

Andrew Weiner

The Expanding Frontiers of Engineering

Every year the U.S. Frontiers of Engineering (FOE) Symposium brings together approximately 100 outstanding young engineers, ages 30 to 45, to share ideas and learn about cutting-edge research on a wide range of engineering topics. A unique characteristic of the symposium series is that participants are competitively selected from researchers working across the spectrum of engineering disciplines in academia, industry, and government. FOE provides these emerging engineering leaders with a unique opportunity to learn about exciting research in engineering areas other than their own and to meet and network with promising engineers working in different areas.

The seventeenth U.S. FOE Symposium was held September 19–21, 2011, at Google, Inc., in Mountain View, California. The meeting was organized into independent sessions with the following themes: additive manufacturing, semantic processing, engineering sustainable buildings, and neuroprosthetics. Seven papers based on this year's presentations are included in this issue of *The Bridge*.

The session on additive manufacturing, organized by Carolyn Seepersad of the University of Texas at Austin and Michael Siemer of Mydea Technologies Corporation, focused on layer-by-layer fabrication of complex parts directly from CAD files without part-specific tooling. Additive manufacturing has many strategic advantages over traditional manufacturing processes: the production of complex internal and external part geometries that cannot be made in any other way; rapid iteration through design permutations; and the ability to build customized functional parts in small lot sizes to meet end-users' specifications.

Two presentations from this session are included in this issue of *The Bridge*. Hod Lipson, of Cornell University, describes the evolution of additive manufacturing technologies as a series of milestones in achieving human control over physical matter (p. 5). His article covers additive manufacturing from its current, relatively mature technologies (programming of shape) to new frontiers in which the internal composition, structure, and even the function of materials can be realized through programmable printing technologies.

In the second article, Brett Lyons, a researcher at Boeing, describes aerospace applications of additive manufacturing. Because this industry has an especially demanding manufacturing context that blends low-volume economics, acute weight sensitivity, and the need for highly controlled materials and manufacturing processes to ensure high levels of repeatability and reliability, it has focused directly on transitioning additive manufacturing techniques from the laboratory and model shop to the factory floor (p. 13).

The second FOE session, chaired by Aleksandar Kuzmanovic of Northwestern University and Amarnag Subramanya of Google, featured four presentations on semantic processing. The emergence of the web as a tool for sharing information has led to a massive increase in the size of potential datasets that often include different types of data, such as texts, images, diagrams, music, and others. Recent developments in distributed processing (e.g., cloud computing) have enabled large-scale investigations of statistical machine-learning algorithms to infer meaning from these datasets. Researchers hope to use these algorithms to infer author sentiment from texts, disambiguate references to real-world entities, and perform a variety of other tasks important for web searches and other applications. In "Large-Scale Visual Semantic Extraction," Samy Bengio, of Google Research, describes an approach to automatic image annotation that can scale to very large, varied datasets of images and labels (p. 20).

The focus of the session on engineering sustainable buildings, chaired by Annie Pearce of Virginia Tech and John Zhai of the University of Colorado, was on the emerging integration and transformation of the architecture/engineering/construction industry, which is increasingly building sustainable buildings that benefit the social, economic, and natural environments. Modern design concepts for high-performance buildings, coupled with new building materials and advanced mechanical and electrical systems, require a comprehensive understanding of integrated building elements and systems, including the humans who design, operate, and occupy them. Two articles from this session are included in this issue of *The Bridge*.

In "Challenges and Opportunities for Low-Carbon Buildings," John Ochsendorf discusses cutting-edge benchmarking for building performance and life-cycle-cost. He presents case studies of ultra low-carbon buildings designed by his team at MIT, summarizes key challenges to the design and implementation of low-carbon buildings in the United States, and describes the consequent new opportunities for engineers, whose role is crucial to the success of this changing market (p. 26).

In the next article, "Using Information Technology to Transform the Green Building Market," Christopher Pyke, of the U.S. Green Building Council, approaches the subject from an industry perspective. He describes how location-based services and social networks are driving market transformation for sustainable building. Chris discusses how the development of new tools for identifying, comparing, and rewarding high-achieving projects can drive continuous improvement (e.g., greenhouse gas emissions reductions, water conservation, and public health benefits) in the construction, operation, and life-cycle costs of green buildings (p. 33).

The final session, on neuroprosthetics, chaired by Timothy Denison, Medtronic, and Justin Williams, University of Wisconsin, Madison, focused on the engineering of technologies that can interface with the human body, both for stimulating the nervous system and for processing and acting on signals from the nervous system.

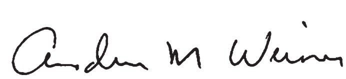
In "The Evolution of Brain-Computer Interfaces," Eric Leuthardt, of Washington University, discusses brain-computer interfaces that can acquire brain signals and translate them into machine commands that reflect the intentions of the user. Eric describes emerging technologies that can help severely impaired individuals communicate and participate more in the world around them (p. 41).

In the final article, "Retinal Prosthetic Systems for the Treatment of Blindness," James Weiland and Mark Humayun, of USC, review the history of electrical stimulation of the nervous system and highlight recent clinical advances in retinal implants for the treatment of blindness. Although much remains to be done, some significant advances have been made that can improve quality of life for some blind people. The authors are optimistic that limited improvements in vision will be possible in the foreseeable future (p. 51).

In addition to the talks, FOE symposia include lively Q&A sessions, panel discussions, and activities that encourage personal discussions and networking. In 2011, a series of five "lightning talks" by researchers from Google, which hosted the meeting, added to the excitement. The dinner speaker, a traditional highlight of FOE programs, was **Alfred Spector**, Vice President of Research and Special Initiatives at Google, Inc. His remarks centered on the evolution of computer science, how it has influenced the world, and how it will help humankind manage the grand challenges that lie ahead.

It has been my great privilege to serve as chair of the Organizing Committee for the U.S. FOE symposia for the last three years. The interdisciplinary approach of FOE events and the diversity of participants have made these meetings truly stimulating and memorable. I know I will miss participating in them in the future.

In closing, I want to express my gratitude to Janet Hunziker, NAE senior program officer, Elizabeth Weitzmann, program associate, and Lance Davis, NAE Executive Officer, for their contributions to the planning and implementation of this unique series. I also want to thank the sponsors of the 2011 symposium—Google, Inc., The Grainger Foundation, the Air Force Office of Scientific Research, the Department of Defense ASDR&E Research Directorate-STEM Development Office, the National Science Foundation, Microsoft Research, and Cummins Inc.



Additive manufacturing is the ultimate tool that may change human life in ways we can barely imagine.

Frontiers in Additive Manufacturing

The Shape of Things to Come

Hod Lipson is associate professor, School of Mechanical and Aerospace Engineering, Cornell University.

Hod Lipson

Additive manufacturing technologies—machines that can automatically fabricate arbitrarily shaped parts, pixel by pixel, layer by layer, from almost any material—have evolved over the last three decades from a limited number of expensive prototypes to widely available, small-scale commodity production tools. But this trend is only the tip of a technological iceberg, a burgeoning "second industrial revolution" that is expected to transform every aspect of our lives. It is easy to predict that, like any other new manufacturing technology, additive manufacturing will lead to more material options, better resolution, faster production, easier and more reliable operation, and lower costs. But it is less obvious where this technology will go next. We can look at the evolution of additive manufacturing technologies past, present, and future as a series of milestones in human control over physical matter.

Printing Forms: Programming the Shape of Matter

The first milestone, which is maturing today, has been unprecedented control over the shape of objects. Machines can now fabricate objects of almost any material—from nylon to glass, from chocolate to titanium—and with any complex geometry. This capability is transforming not only engineering, but also many other fields, from biology to archaeology to education to the culinary arts.

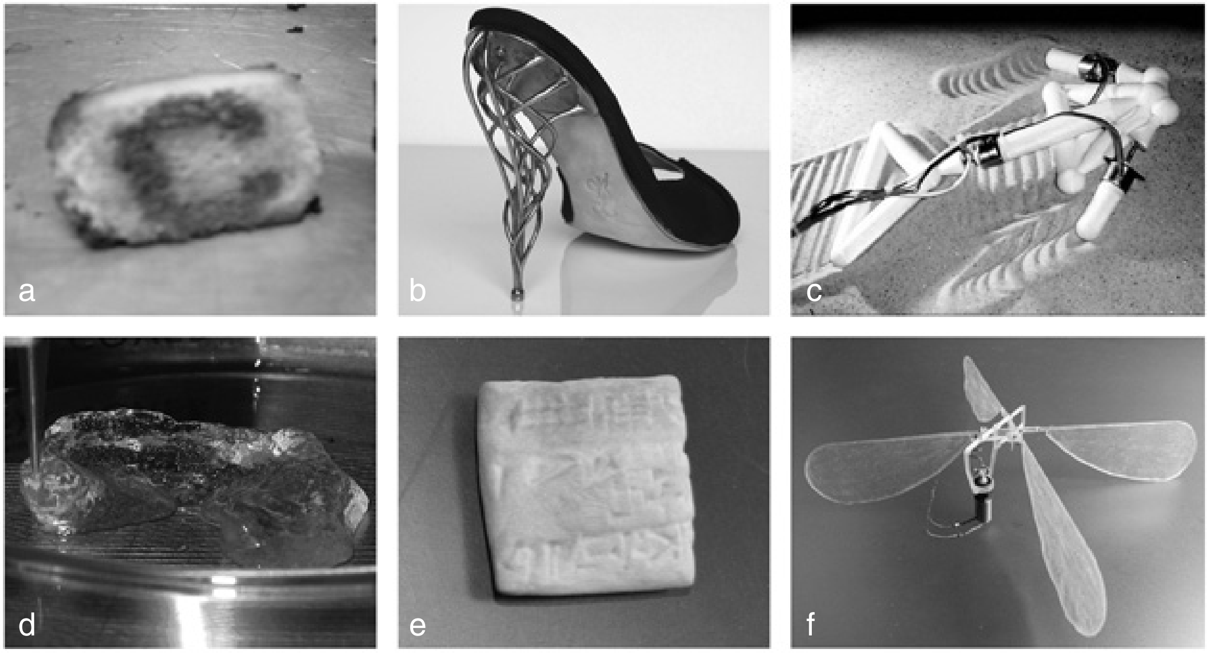


FIGURE 1 3D printing is a universal technology that will impact every industry and discipline. (a) Complex cookie with interior letter in chocolate. (b) Woman's shoe with elaborate titanium heel. (c) A printed robot that was designed automatically. (d) A bio-printed bovine meniscus printed with live cells according to a CD scan. (e) A printed clay copy of a 3,000 year old cuneiform tablet. (f) A 90 percent printed 3-gram flapping, hovering ornithopter. Sources: Figures 1a, 1c, 1d, 1e, and 1f, courtesy of Cornell University and *http://creativemachines.cornell.edu*. Figure 1b courtesy of WTWH Media.

Complexity for Free

Perhaps the most dramatic impact of 3D printing is that it can manufacture objects without factoring their complexity. Fabricating a solid block costs almost the same as fabricating an oddly shaped object with curved surfaces and notches. In either case, the printer scans back and forth, depositing material one layer at a time. The only difference is in the pattern of material deposition. Just as printing a picture of a circle takes no longer than printing a picture of the map of the world, printing a mousetrap takes no longer and requires the same skills and resources as printing a paperweight.

Regardless of how we measure it—in production time, material weight, energy waste, or production planning—the addition of features hardly changes cost. In some cases, added complexity can even reduce cost. For example, printing a block with a hole in it is cheaper and faster than printing a solid block. Therefore, in stark contrast to conventional manufacturing where every additional hole, surface, protrusion, and corner requires more planning, takes longer to produce, and consumes more energy and possibly more raw material, the marginal cost of added complexity with additive manufacturing is near zero.

Why should we care about the marginal cost of complexity? Lowering the cost of manufacturing complex products is obviously a good thing, but the consequences have profound implications. Industrial revolutions are triggered when a fundamental cost associated with production drops to zero, essentially taking that factor out of the cost equation.

The industrial revolution of the nineteenth century occurred when steam engines replaced horses and waterwheels, dramatically reducing the cost of power to near zero. Not only were traditional power sources replaced, but the types of work that machines could perform led to a cascade of innovation, such as railroads and factory automation. Similarly, the Internet reduced the cost of disseminating information to near zero. As a consequence, it also expanded the range and types of media that could be distributed—not just online newspapers, but also wikis, blogs, and user-generated content.

One could argue that additive manufacturing has drastically reduced the cost of complexity, bringing it to near zero. Initially, this simply implies that new technology will gradually replace older, more expensive ways of making things. But in the long term, the range and types of objects that can be manufactured will also increase dramatically.

Personalized Manufacturing

In addition to vast new design possibilities, manufacturing will be personalized. This trend has profound economic implications for how future products will be designed and used, who will design them, and where they will be made (Lipson and Kurman, 2010). Most important, the opportunity for anyone to design and produce complex products without the need for the resources and skills of traditional manufacturing will democratize innovation and unleash the long tail of human creativity. Look online today, and you will see thousands of objects for sale ready to be printed on demand, from custom-shaped hearing aids to flapping, hovering micro air vehicles (Figure 1f), to authentic-looking replicas of ancient cuneiform tablets (Figure 1e).

Printing Composition: Shaping the Internal Structure of Materials

The second milestone, which has just appeared on the horizon, is controlling the composition of matter—not just shaping external geometry, but also shaping the internal structure of materials with unprecedented fidelity. Using multi-material additive manufacturing technologies, we can make materials within materials, embed and weave multiple materials into complex patterns, and co-fabricate entangled components. For example, we can print hard and soft materials in patterns that create materials with bizarre new structural behaviors, such as materials that expand laterally when pulled longitudinally.

We are eliminating traditional limitations imposed by conventional manufacturing when each part had to be made of a single material. Instead, microstructure can now be specified with micron-scale precision. This will make it feasible for you or me to print a custom tennis racket to enhance our backhands or for a doctor to produce a replacement spinal disc implant tailored for a specific patient.

The number of possibilities is enormous, but so far few theories can predict the properties of these new materials, and few designers are prepared to exploit the new design space. Clearly, we will need new design tools to augment human creativity.

From Bio-printing to Food Printing

Every discipline will be affected by the unprecedented control over the shape and composition of matter. Imagine the implications for any field that involves the design and fabrication of physical objects—from mechanical engineering to art and architecture. But additive manufacturing technology can also change fields with no immediate connection to engineering or manufacturing. Take, for example, the emerging field of 3D printing for medical applications.

Custom-Shaped Prostheses. One of the earliest applications of health-related 3D printing was the fabrication of custom-shaped, complex prosthetic limbs and devices, particularly to address the key challenge of the interface point with the body. For example, a good match between the socket of a limb prosthesis and a patient's bony prominences or muscular tissue can greatly improve both functionality and comfort.

When the aesthetic appearance of a prosthesis is a factor, the exterior can be custom shaped to blend with its surroundings or to match symmetrical features. In addition, the ability to shape internal cavities, add strengthening girders, and shave material off non-load-bearing components can all improve the weight-to-strength ratio of the device and make it both stronger and lighter. With sophisticated, multi-material fabrication, the mechanical performance of prosthetic devices could be tailored even further to improve elasticity, shock-absorbance, and energetic performance.

> *Every discipline will be affected by unprecedented control over the shape and composition of matter.*

Another type of shaped prosthesis is the hearing aid. A major factor in the comfort and effectiveness of hearing aids is how they fit in the aural canal. With 3D printing, the patient's canal can be optically scanned, and a tailored soft prosthesis can be fabricated almost instantly.

Custom-Shaped Implants. One-size-fits-all is not a good compromise when it comes to hip replacements. The idea of using 3D printing to fabricate custom-shaped implants dates back to the earliest days of freeform fabrication. Today, custom-shaped titanium or platinum implants can be fabricated with exactly the right size and shape, either parametrically scaled to fit the patient or produced directly from CT scan geometry of the original bone or a symmetrical healthy bone. Because complexity does not increase cost, printed implants can not only match the standard bone shape, but can also include various cavities and connection points to make bonding with existing tissue more compatible, reliable, and effective.

Printing with live cells makes it possible to fabricate heterogeneous tissue implants.

Bio-printing. Instead of using titanium and other engineering materials, implants (and other constructs) can be fabricated directly from biological materials. Early experiments involved 3D printing of biocompatible scaffolds, which were later infused with live cells and incubated before implantation. The live cells gradually replaced the scaffold, resulting in a custom-shaped live tissue-engineered implant.

Printed scaffolds are still prevalent, but printing with biological cells directly, with no scaffold at all, is now possible. In this case, cells are first immersed in a biocompatible hydrogel ink—a *bio-ink*—and then printed into their target form. The bio-ink has two key, contradictory properties that make it tricky to develop. On one hand, it must be fluid enough to be printed—to flow through the nozzle without damaging cells that are subjected to severe shear forces as they come out of the printhead. On the other hand, bio-ink must be stiff enough to hold its shape after printing to prevent the material from oozing into a shapeless mass. To address this double challenge in fabricating cartilage implants in the shape of a meniscus directly from CT data (Figure 1d), we used a variety of chemical and optical cross-linking agents.

Unlike scaffold-infusion techniques, printing with live cells directly makes it possible to fabricate heterogeneous tissue implants. Imagine the fabrication of a form as complex as a spinal disk or a heart valve, which involves multiple cell types in a complex spatial arrangement that is critical to its proper functioning (Cohen et al., 2006).

Drug-Screening Models. An exciting opportunity for fabricating complex, multi-cell heterogeneous tissue arrangements in three dimensions is the fabrication of models for drug screening. Traditionally, drugs and other treatments are tested in petri-dish-like environments that are meant to replicate the anticipated target environment in which the drug or treatment will be used. However, these petri-dishes or test-tubes are relatively simple compared to the real environment, both in the range of cell types and their spatial distribution. This mismatch often necessitates the use of animal models and other sophisticated, high-throughput testing procedures.

With 3D bio-printing, however, 3D spatially heterogeneous tissue models can be fabricated to more closely resemble the target application of a drug. For example, if cancer cells can be fabricated directly in the shape and distribution of a tumor, the effectiveness of treatments could be tested in vitro. Such experiments could provide a more realistic prediction of drug effectiveness and shorten the cycle of drug development.

Surgical Planning. A less obvious, but equally important application of 3D printing is preparation for surgery. Non-routine, complex surgical procedures often involve manipulation of tissue and tools through an intertwined, unknown environment. Some operations also require the preparation and attachment of permanent or temporary plates or other devices in the patient's body. Just as it is easier to put a puzzle together the second time around, surgeons can substantially reduce the time and improve the reliability of an operation if they practice it beforehand. This is especially important for complex, non-routine procedures being attempted for the first time.

For example, the veterinary school often asks us to bio-print a 3D set of shattered or deformed bones from a CT scan of an injured animal that needs emergency surgery. With the printed bones, surgeons can practice the operation—learning to identify fragments, optimize reconstruction, and prepare plates and jigs in advance. Informally, surgeons have reported that surgery time can be reduced by half and that the quality of care is greatly improved.

Surgical Training. Surgeons in training often have access to state-of-the-art surgical equipment and tools, but they rarely have a chance to practice on realistic cases. For example, a surgeon in training is unlikely to be able to practice removing a brain tumor on an animal model, a human cadaver with this condition, or a synthetic training model. With 3D printing, however, relevant, typical cases from real patients can be recorded and reproduced on demand for practice.

With some modeling, it is even possible to combine cases and adjust their severity on demand to challenge surgeons-in-training at the appropriate level for the best learning experience. With multi-material bio-printing, training models could be fabricated with biological materials to provide realistic experience that also provides the feel and responsiveness of real wet tissue.

Custom Medications. An excellent example of an application of 3D printing is the fabrication of medical pills on demand. A growing challenge for both doctors and patients is the administration of multiple medications simultaneously. Instead of keeping track of a dozen pills daily, a printer can now fabricate a single, custom-made pill for each patient. The pill could have an identification marking, which would eliminate the confusion and uncertainty associated with conventional delivery methods.

Food Printing. Food printing is to 3D printing what video gaming is to computers. Based on the same technology as bio-printing, food printing is the fabrication of edible items from raw edible inks. "Edible inks" include chocolate and peanut butter, cookie dough and frosting, as well as organic pesto and locally made goat cheese. It doesn't really matter: Download the recipe, load in the frozen food cartridges, and hit print.

The recipe dictates which material goes where and which in-line-cooking procedure is applied during deposition and after. We have printed foods with all of the materials mentioned above and more, creating chocolate confections with frosted decorations and vanilla cookies with chocolate vertical text lettering inside (Figure 1a). Imagine a cookie printer with sliders to adjust crispiness, flavor, color, and texture. Imagination is the only limiting factor.

Although some may consider printed foods the epitome of processed foods, others are fascinated by the opportunities for almost unlimited innovation. You can download and share recipes, tailor variants as you wish, and produce freshly made dishes to your exact liking.

Printing Function: Programming the Behavior of Active Materials

The third and final milestone, of which we are just beginning to see early signs, is control of behavior. At this point, we will not only control the shape of matter and its composition, we will also be able to program materials to function in arbitrary ways—to sense and react, to compute and behave. This last step entails a blurring of the line between material and code (Gershenfeld, 2005), leading to what is essentially *programmable matter*, including everything from controlling the mechanical functionality of an object to controlling how it processes information and energy.

When we reach this milestone, we will be able to print virtually anything—from a cell phone to a robot that walks out of the printer, batteries included. But the robot will not look at all like today's robots, because it will not be limited by the constraints imposed by conventional manufacturing, and it won't be designed directly by humans (Figure 1c). The ability to manufacture arbitrary active systems comprising both passive and active substructures will have opened the door to a new space for designs and a new paradigm of engineering—one that is not unlike biology.

The New Computer-Aided Design

For the last four decades, computer-aided design (CAD) tools have played a critical role in product design. But the role and format of CAD tools have remained relatively unchanged. Although user interfaces have improved, geometric manipulations have become faster and more reliable, and graphics have become three-dimensional and photo-realistic, conceptually CAD software remains a passive 3D drawing board that records intentions but offers little insight or ideas of its own.

The last step will blur the line between material and code leading to essentially programmable matter.

As 3D printing technologies become more abundant, traditional barriers of resources and skills are all but vanishing. The limit is now our imaginations, but, unfortunately, our imaginations *are* limited. Over and over again, I have seen students faced with the blank page of CAD and the unlimited capability of a 3D printer design rectangular objects with a few linear notches.

To a large extent, this cultural blindness is the result of years of observing mass-produced objects subject to traditional manufacturing constraints. However, it also reflects design thinking imposed by conventional CAD tools and the lack of new tools that can take advantage of the vast new design space offered by 3D printing capabilities. Clearly, the classical CAD paradigm will be dominant for the foreseeable future, but new paradigms for design tools are beginning to emerge.

Function Representations. As our ability to control the shape, composition, and behavior of materials advances, it becomes more appropriate to think about geometry and material specification as programming rather than drawing. For example, say you want to fabricate a spherical surface with periodic patterned protrusions (Figure 2b). Fabricating such an object using traditional manufacturing techniques would be a complicated, expensive nightmare. As a result, such a capability is buried far down the advanced CAD options menu, if it can be found at all.

The spherical surface might be more easily described using algorithmic rather than descriptive geometry, a procedural construction process rather than a target geometry (Pasko et al., 2011)—much the way a biologist describes phenotypes using a developmental process or a software engineer describes the appearance of a dynamic web page.

In fact, there are many more crazy shapes than regular shapes (Figure 2a), but they are currently difficult to explore. If designers were unencumbered by traditional manufacturing constraints, a growing number of them would be anxious to explore these kinds of geometries.

Matter Compilers. An alternative approach to design is to specify what the design should accomplish rather than what it should look like and then let the machine compile the design to meet your specifications. Some products, especially products with purely functional roles, would fit well into such a design process.

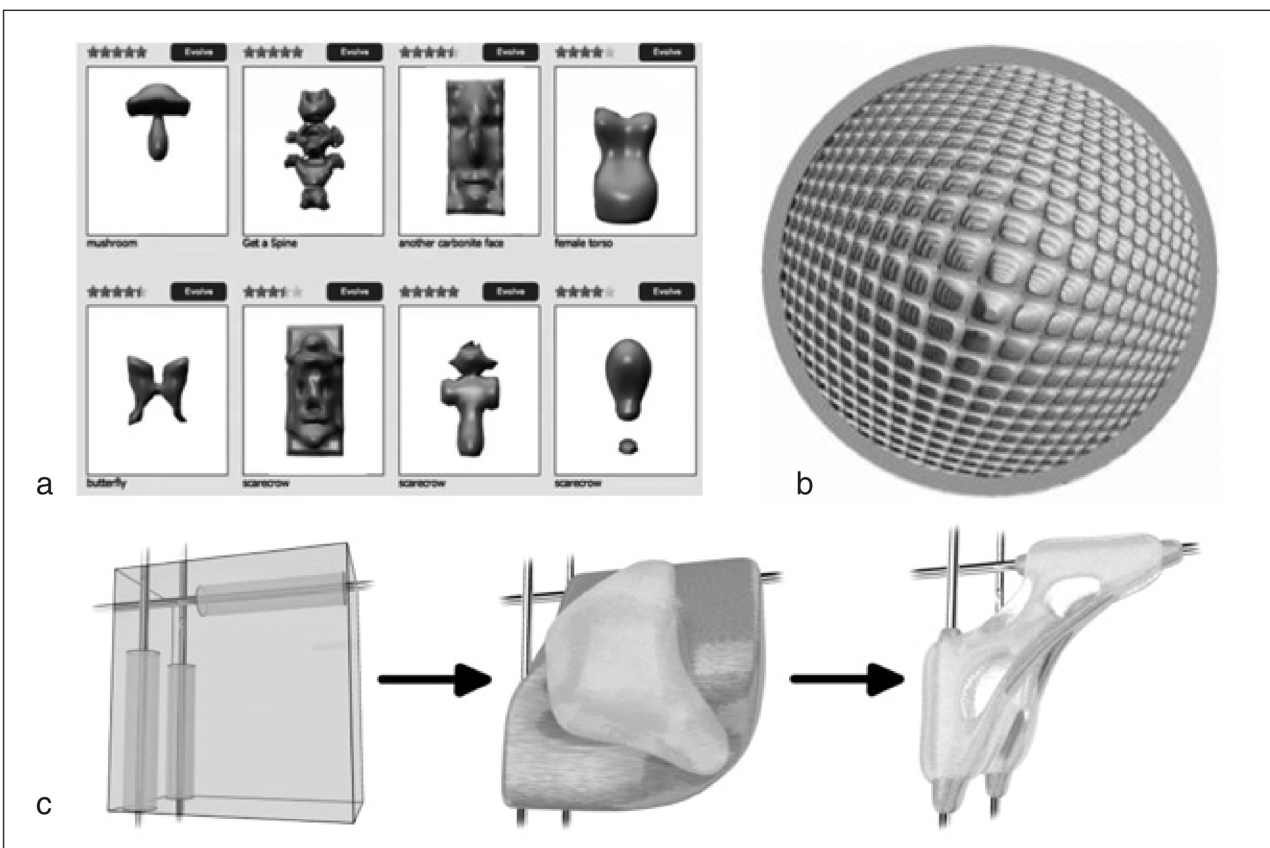


FIGURE 2. The New CAD. Beyond geometric modeling, products are described automatically by interactive evolution, through procedural construction algorithms, or by compiling high-level requirements and constraints. Sources: Figure 2a courtesy of Cornell University and *http://endlessforms.com.* Figure 2b: Pasko et al., 2011. Courtesy of Turlif Vilbrandt. Figure 2c designed by Jon Hiller. Reprinted courtesy of Cornell University and *http://creativemachines.cornell.edu.*

Consider, for example, designing a supporting bracket. We know the geometric constraints of the load and support contact points, the weight to be carried, and the material properties. Specify those requirements, hit the design button, and watch the optimal design emerge automatically. I guarantee that it will not be a block with rectangular notches and holes, but an organic-looking optimal structure with beautifully shaped cavities, a design that would take a human designer years to come up with manually.

Now imagine that the bracket can't be installed because of a protruding pipe. No problem—just add the pipe protrusion constraint and recompile (Figure 2c). Programming by specifying target behavior and constraints, then compiling it into functional geometry, can address complex requirements, while simultaneously exploiting the new manufacturing capabilities afforded by multi-material 3D printing as they become available. In a way, the designer becomes the customer, and CAD software becomes the designer.

Interactive Evolution. What happens when a desired design goal can't be described quantitatively, such as an object that has an aesthetic component that defies quantification? Imagine, for example, designing a perfume bottle. Some aspects of the design, such as volume and size, can be specified quantitatively, but others, such as the look and feel, are more difficult to describe. Moreover, people skilled in the art of assessing perfume bottles may have no inclination to dabble in "CAD speak."

Instead, a new type of CAD software can display a range of initial design concepts and allow an expert to indicate the ones he or she likes best or dislikes least. With this information, the machine can automatically infer a sense of the aesthetic the designer has in mind and generate new solutions that meet the quantitative requirements but are also closer to the designer's aesthetic preferences. By repeating this process through a sequence of solutions and selections, a designer with little CAD expertise might design a complex perfume bottle.

In addition, the designer might come across new ideas and be provoked into exploring corners of the design space where no one else has been. Using this same process, visitors to the EndlessForms website (Clune et al., 2011) have collaboratively designed a variety of objects, from furniture to faces and from bottles to butterflies.

FabApps. What if I want to design a toothbrush to print on my 3D printer today? It is unlikely that I will be able to design a good, ergonomic, safe toothbrush. Even though a toothbrush seems like a simple product, it takes years of experience and know-how to design a successful one. Nevertheless, with 3D printers, people with almost no experience and little patience to learn are likely to want to design their own.

The solution may be simple CAD applications for a specific product that encapsulate all relevant knowledge, yet provide just the right level of flexibility to the user. Such FabApps (a term coined by Daniel Cohen and Jeffrey Lipton), similar to the iPhone apps you can download for 99 cents, could guide you through the design process and make you look like a pro. A toothbrush app could ask for the dimensions of your hand and mouth, process pictures of your face and palm, walk you through 50 different options, ask 20 more questions, and then produce a toothbrush that fits your unique needs perfectly and is guaranteed to be a success.

Conclusion

Tool-making is one of the characteristics that distinguishes modern humans from their evolutionary ancestors. Additive manufacturing, the ultimate tool, has the potential to change human culture forever in ways we can hardly anticipate.

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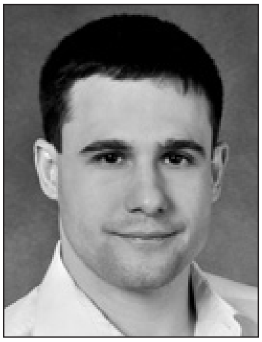
Additive manufacturing has the potential to revolutionize the production of aerospace and defense components.

Additive Manufacturing in Aerospace
Examples and Research Outlook



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Brett Lyons

The advantages of additive manufacturing are now widely recognized, even in the general media, and are predicted to revolutionize manufacturing processes for many industries (Economist, 2011). For aerospace, complex additive manufacturing processes must be developed to meet the industry's stringent requirements and to ensure that products can achieve the robust performance levels established by traditional manufacturing methods. This article provides an overview of additive manufacturing technologies being used for the production of aircraft components and examples showing the direction of ongoing research and related developments.

Aerospace Requirements for Manufacturing

To meet the stringent conditions necessary to ensure safety in air travel, aerospace manufacturers must satisfy a long list of complex requirements for even the simplest part. The consistent production of parts with identical, well-understood properties requires that both materials and production processes be understood to a very high level. This complicated manufacturing context, which blends low-volume economics, acute weight sensitivity (weight is often the deciding factor in choosing materials and manufacturing processes for aerospace and defense components), and the need for highly controlled materials and manufacturing processes, has led Boeing to focus on transitioning additive manufacturing techniques from the laboratory and model shop to the factory floor.

Requirements for commercial aircraft parts are based on U.S. Federal Aviation Regulations, which must be met before a Type Certification can be issued for a given aircraft series; this certification is required for service with any airline (FAA, 2011). The regulations are extensive and detailed, but the single most pertinent language in the context of additive manufacturing can be found in Title 14, Section 25, Subpart D, Subsection 25.605:

> The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must (a) Be established on the basis of experience or tests; (b) Conform to approved specifications (such as industry or military specifications, or Technical Standard Orders) that ensure their having the strength and other properties assumed in the design data; and (c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service.

This brief, but clear requirement is just one of many that have not only contributed to the incredible safety record of commercial air transportation, but have also provided the impetus for studying new fabrication methods. Every aerospace and defense manufacturer either has internal specifications or looks to established standards organizations for data that can support the accurate design of components from a given material, based on minimum allowable performance levels. Factors that must be considered for the material performance of even the simplest components include specific strengths, fatigue resistance, creep resistance, use temperature, survival temperature, several tests of flammability, smoke release and toxicity, electric conductivity, multiple chemical sensitivities, radiation sensitivity, appearance, processing sustainability, and cost.

Despite increased rates of production, the aerospace industry must still produce many parts in very small quantities (Boeing Company, 2011). Additive manufacturing processes, which can form finished parts without intermediate tooling, thus eliminating the associated costs and delays, are extremely attractive to the industry (Ruffo et al., 2006).

Selective Laser Sintering

One of these processes, selective laser sintering (SLS), begins with a computer-generated, three-dimensional design of a given part. The part is then digitally segmented into very thin layers that are selectively solidified in the machine, layer by layer. Essentially, the machine "grows" the part. With this capability, SLS can produce components with complex designs that would be extremely complicated and expensive to produce by other processes.

SLS can produce economical thermoplastic parts that are lightweight, nonporous, thin-walled, and highly complex geometrically. Since the first implementations of SLS on Boeing aircraft, this process has been adopted by a large number of programs, both military (Wooten, 2006) and commercial (Lyons et al., 2009), as well as by producers of unmanned aerial vehicles.

SLS produces lightweight, highly integrated systems and payload components (Figure 1) and, at the same time, eliminates non-recurring tooling costs and provides for life-cycle production flexibility. Because weight is often a critical factor, SLS, which can produce very thin walls and complex designs, is also attractive for replacing parts that are typically produced using established processes, such as rotational, injection, or polymer matrix composite molding.

Drafting commercially efficient specifications in the unique context of aerospace manufacturing requires that a company develop in-depth knowledge of materials and processes. For example, to take advantage of SLS, one must have a firm understanding of the extreme four-dimensional energy input gradients during processing. Typical SLS machines use 75-Watt carbon dioxide (CO_2) lasers that have a 500-μm spot size. The laser spot moves at speeds of up to 10 meters per second over layers of nylon powder only 100 μm thick; each layer is completed in approximately 60 seconds. A thorough

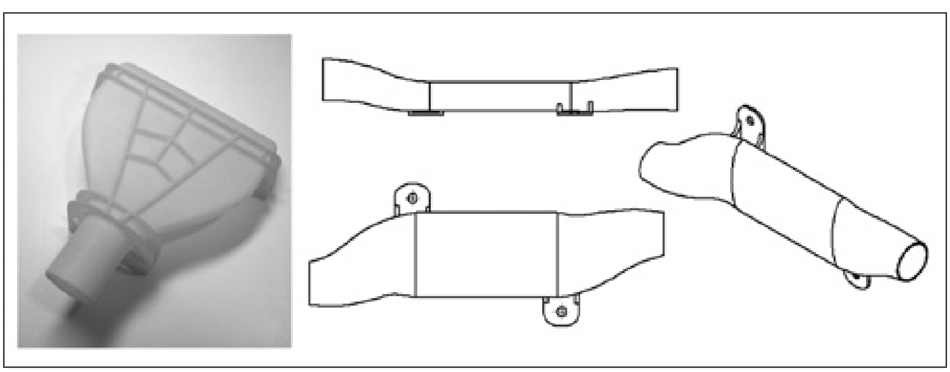

Figure 1. Photograph and illustration of laser-sintered air ducts.

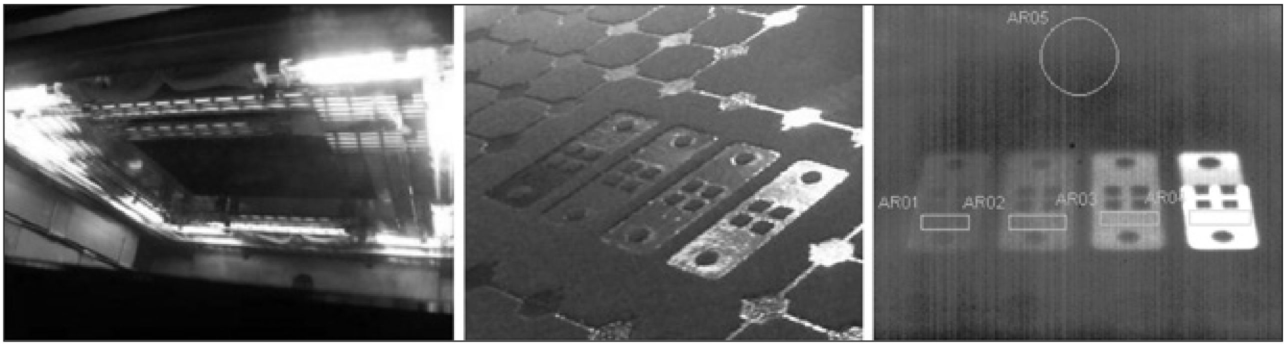

Figure 2. Multi-zone heating (left), SLS part bed (center), and the same parts seen via infrared thermography during laser scanning (right).

description of both the SLS process and efforts to simulate details of the energies present can be found in the literature (Franco et al., 2010).

Examples of Aerospace-Driven Research

Controlling Temperature in the Part-Building Platform

To build parts with repeatable mechanical properties and dimensional control, the temperature distribution across the part-building platform must be as even as possible. To accomplish this and reduce scrap rates, Boeing and its partners at the University of Louisville and Integra Services International (Belton, Texas) developed a patented method for zonal control of the temperature of the part bed in SLS equipment (Huskamp, 2009). Multi-zone, near-infrared (IR) wavelength heating elements (Figure 2) provide the rapid response and spatial resolution necessary to maintain a steady, even temperature. This invention, when paired with real-time IR imaging, has improved thermal control to a more advanced level than is required for most other thermoplastic processing methods.

The Development of Flame-Retardant Polyamides

Another aerospace-driven need that researchers have addressed is for flame-retardant polyamides. Considering that many polymers are derived from fossil fuel-based hydrocarbon feedstocks, the requirement that a related chemistry be self-extinguishing when exposed to flame poses a serious challenge. Nevertheless, flame-retardance is necessary to a greater or lesser degree for all polymer materials used in the interiors of commercial aircraft. To take advantage of the weight and manufacturing benefits of SLS on its commercial aircraft, Boeing collaborated with its suppliers to develop the first laser-processed material that could pass the required flammability tests (Booth et al., 2010).

New Performance Challenges

As the number of potential additive manufacturing applications in aerospace has increased, three new performance challenges have arisen for SLS polymer materials. Operating requirements for the F-35 and B787 have challenged researchers to develop materials that (1) can operate at higher temperatures, (2) have significantly better flame resistance, and (3) offer adjustable electrical conductivity (Shinbara et al., 2010).

To add to these challenges, the new physical performance targets must be met while maintaining as many of the attributes already established for SLS polyamide materials as possible. These attributes include mechanical toughness, resistance to chemical attack, resistance to ultraviolet radiation, dimensional fidelity, and viable economics.

Historically, when a new technology is enabled and nears transition to useful service, researchers in many industrialized nations tend to work on the same technical problems simultaneously. In this case, researchers in the United States, Germany, Japan, and the United Kingdom have conducted in-depth investigations into high-performance polymers for SLS (Hesse et al., 2007; Kemmish, 2010).

If such a material were developed successfully, it could have a wide range of applications in and beyond aerospace. Two notable non-aerospace applications for new high-performance, SLS-produced polymers are for medical implants and devices (Schmidt et al., 2007) and the production of low-volume automotive parts.

The Focus in Aerospace Research

Although many high-performance polymers are attractive from a cost perspective, the high cost of testing for aerospace applications makes focusing on multiple materials simultaneously cost prohibitive. Unlike injection molding and other methods of polymer processing that rely on both heat and pressure to form a part against the surface of a mold, additive manufacturing processes rely primarily on the input of thermal energy. Thus, viable materials for additive processes must have very specific viscosity and other properties to be processed successfully.

Polyaryletherketone (PAEK) Materials vs. Polyamides

Because of their known performance, the polyaryletherketone (PAEK) family of materials is considered the lowest risk option for current development for aerospace applications. The PAEK family includes different chemistries (e.g., polyetherketone, polyetheretherketone, and polyetherketoneketone). The choice of a PAEK as the next material to be developed is based on inherent factors, including very good flammability and chemical resistance, low moisture sorption, good mechanical performance, good resistance to creep and fatigue, compatibility with several methods of sterilization, and numerous material grades and suppliers to choose from. In light of the comparatively small size of the SLS market and the cost of developing new polymer chemistries, raw materials for SLS are typically selected from commercial off-the-shelf grades of PAEKs, which have been designed for coatings, films, rotational molding, and other applications.

At the time of this writing, the development of a viable PAEK-SLS material is an area of competitive industrial research, so specific information from any one party is generally not published. However, a comparison of established, well-understood polyamides and the PAEK family of materials shows the problem space for engineers working in this field.

Table 1 shows comparative thermal properties of lower temperature polyamides and PAEK materials, as found in the literature and in manufacturer-published information (Kemmish, 2010; Kohan, 1995). By comparing the bulk thermal properties of these two material families, one can begin to understand how differently they will behave in the SLS process.

One important difference is the amount of energy required to heat the material. To process a polyamide powder, the lower melt temperature combined with the lower specific heat (the amount of energy required to heat a given mass of material one degree Kelvin) indicates that the effort required to achieve a given viscosity with heat input is much lower for a polyamide than for a PAEK. The PAEK must be heated to twice the temperature just to approach melt and requires almost twice the energy per degree of heating. This is further complicated in SLS processing because the transient heating requirements of each layer must not change drastically.

A second difference is the ratio of specific heat to the heat of fusion (the energy flux exhibited in the transition from solid to liquid, and vice versa). In the SLS process, the polymer powder is heated in stages from ambient conditions to very near the melt point. Polyamide material has a lower ratio of specific heat to heat of fusion than PAEK materials (1.26/226 compared to 2.20/130). This is important because, despite our best efforts, there is still some gradient of energy input and temperature across the building area at any given time. If a material very gradually transitions into melt, as fully amorphous polymers do, it can be difficult to feed the material smoothly onto the machine's part-building area.

The ratio of specific heat to heat of fusion gives an indication of how easily a given material can be heated to near the melt point, across the whole part bed, without fusing particles together. The closer to the melt point the material is when fed into the machine, the lower the energy input requirements on the laser for heat input to transition the material into the melt region. The lower the requirement on the laser for

TABLE 1 Comparison of the Thermal Properties of Polyamides and PAEK Family Materials

Material	Melt Temperature (°C)	Glass Transition Temperature (°C)	Specific Heat (J/g-K)	Heat of Fusion (100 percent crystalline) (J/g)	Thermal Conductivity (W/m-K)	Thermal Expansion (ppm/Tg °C)	Specific Gravity (g/cc) (crystalline)
Polyamide	180–186	42–55	1.26	226	0.19	85	1.03
PAEK family materials	300–375	145–165	2.20	130	0.26	60	1.30

Note: J/g-K = joules per gram-Kelvin. J/g = joules per gram. W/m-K = watts per meter-Kelvin. Ppm/Tg °C = parts per million per transition in degrees centigrade.

energy input, the lower the risk of polymer degradation. This is because in the CO_2 laser spot there is a roughly Gaussian distribution of energy, the peak of which can cause degradation.

With a given energy input requirement on the laser (per the comparison above), the layer can be drawn with faster or slower laser scan speeds. The scan speed affects the overall per-layer time, which, in addition to the proportion of preheat to laser energy required, results in a variable temperature distribution and cooling rate for a cross section of the part, per given layer.

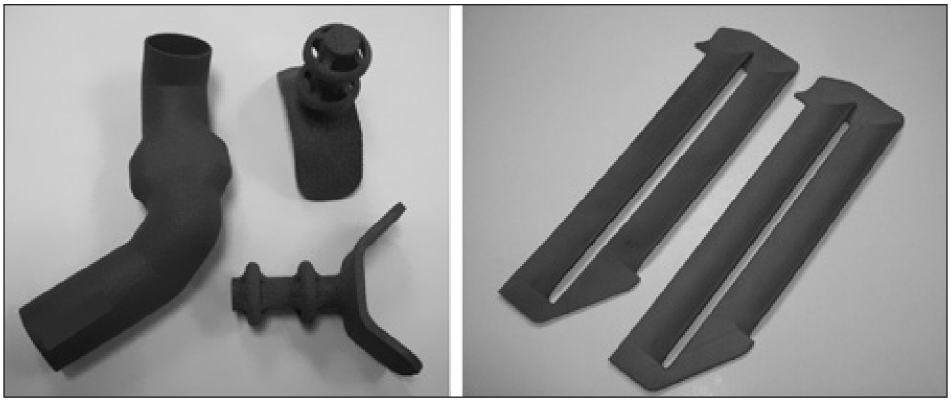

FIGURE 3 Examples of parts made of PAEK materials processed via SLS.

If too much time passes between the start and stop of a given layer and the energy demand on the laser is too high, some sections of that layer will cool faster than others and the layer will not shrink uniformly. Dimensional distortion can result if the cooling gradient is too high relative to the recrystallization temperature, thermal conductivity, coefficient of thermal expansion, and a host of other factors.

A thorough description of the interaction, just for the properties shown in Table 1, is beyond the scope of this paper, but these examples provide a window into the problems currently being addressed by researchers. Thankfully, despite the complexities, several research teams are reporting success with the processing of PAEK materials via SLS (Figure 3).

Moving Forward

Transitioning from the Laboratory to the Factory

Numerous research frontiers lie beyond the development of higher performing polymers. For one thing, additive manufacturing equipment must transition from comparable low-reliability laboratory-grade equipment to hardened, cost-effective, high-temperature, industrial-grade machines. The additive manufacturing industry can look to its predecessors in injection molding and computer numerical-control machining for examples of establishing new manufacturing technology and developing a supporting business case.

So far, in the infancy phase, the unique material requirements of additive manufacturing processing have limited machine manufacturers to selling materials and some parts. Although this has provided a good source of revenue to support new companies, it has also impeded new applications by making the development of new materials difficult for all but the largest users and material companies.

Dependence on the sale of materials and parts, as well as nonproductive patent litigation, have also distracted machine manufacturers from improving upon their equipment with an eye toward higher volume, economical, industrial manufacturing. Equipment manufacturers (e.g., Toshiba, Haas Automation, MAG, Husky, and Arburg) cannot rely on the sales of materials or parts to bolster their businesses. Thus for the additive manufacturing industry to grow, it might look to the business models and history of such machine manufacturers for reference.

Manufacturing Metal Parts

The use of metals in additive manufacturing for aerospace is as complex and exciting as the development of polymers. So far, engine manufacturers have shown leadership in the direct manufacturing of metal parts, which is a highly dynamic field. However, leveraging the capabilities of additive manufacturing to create components with highly complex shapes also lends itself to tool production, for both metal and composite components. In fact, new tooling-focused machines and materials are being actively developed to leverage the process benefits of additive manufacturing for faster production of metal castings (Halloran et al., 2010) and long-fiber-reinforced composites (Wallen et al., 2011).

Analysis of Complex Geometries

Independent of material and processing conditions, the analysis of complex geometries that can be built

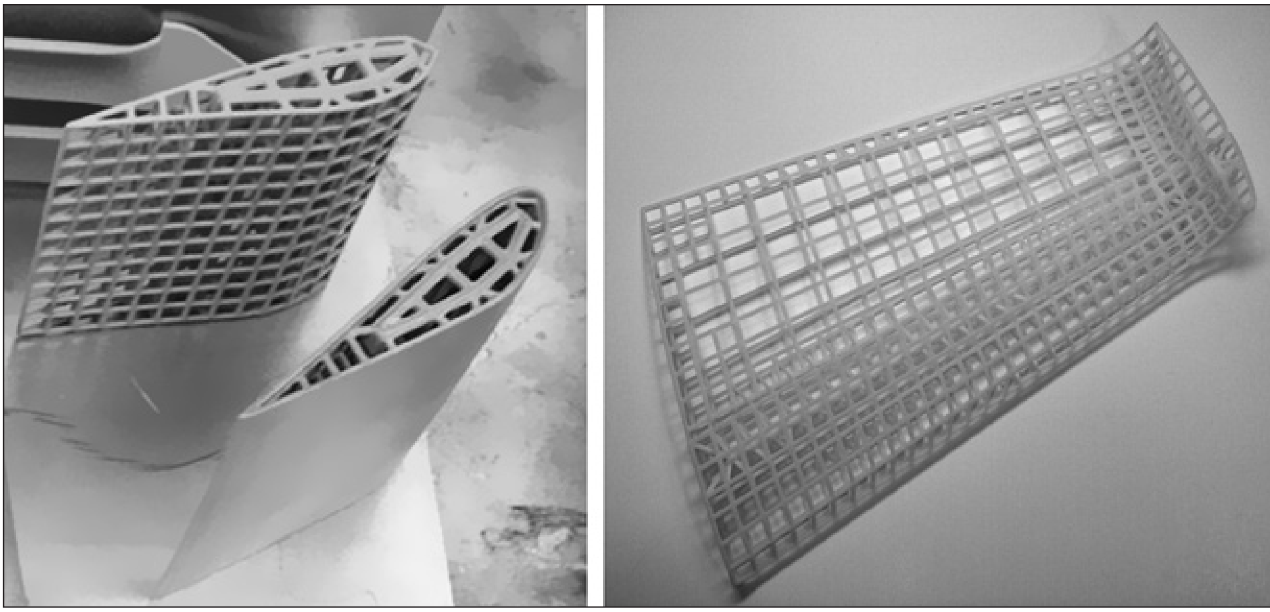

FIGURE 4 Two complex trusses suggest the difficultly of predictive analysis.

only with additive methods is another important area of active research. Even with material test data, the predictive behavior of the types of structures additive manufacturing can build, such as trussed airfoils (Figure 4), is difficult to analyze. This field of study is focusing on developing new software tools for the generation and predictive analysis of complex structures, such as three-dimensional trusses (Engelbrecht et al., 2009).

Conclusion

The descriptions of current research, along with examples, such as Boeing's use of SLS for producing parts for commercial and military aircraft, show that the aerospace industry has the opportunity to lead, and the responsibility to contribute to, this revolutionary field of manufacturing technology. Technologies that provide this level of manufacturing flexibility will greatly contribute to meeting burgeoning global demands for energy, transportation, defense, and medical technologies here on earth and may even prove to be enabling technologies for exploring horizons beyond our planet.

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Machine-learning algorithms for image annotation can enable the classification of huge amounts of different types of data.

Large-Scale Visual Semantic Extraction

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The emergence of the web as a tool for sharing information has led to a massive increase in the size of potential datasets. Millions of images on web pages have tens of thousands of possible meanings that can be associated with labels, or annotations, in the form of HTML tags. These tags are used by webpage authors to describe the content of sections of web pages and by search engines or other web pages to link to them. Thus, HTML tags can be conveniently collected by querying search engines, such as *www.flickr.com* (Torralba et al., 2008), or human-curated labels, such as *www.image-net.org* (Deng et al., 2009).

Clearly, we need machine-learning algorithms for image annotation that can learn from and annotate data on this large scale. The algorithms must include (1) scalable training and testing times and (2) scalable memory usage. The ideal algorithm would be fast and would fit on a laptop, at least at annotation time. Although many models have been proposed and tested on small datasets, it is not clear if any of them satisfies these requirements.

In the first part of this article, we describe models that can learn to represent images and annotations jointly in a low-dimensional embedding space. The low dimension simultaneously implies fast computations for ranking annotations and small memory usage. To ensure good performance for such a

[1] This article is based on Weston et al., 2010, and Bengio et al., 2010.

model, we propose estimating its parameters by learning to rank annotations and optimize the process so that at least the top ranked annotations are relevant for a given image (this process is often called optimizing precision-at-top-k).

In the second part of the article, we propose a novel algorithm for shortening testing time in multi-class classification tasks in which the number of classes (or labels) is so large that even a linear algorithm can become computationally infeasible. Our proposal is for an algorithm for learning a tree structure of the labels in the joint embedding space. We believe that by optimizing the overall tree loss (i.e., the loss one would incur by using the tree to retrieve the top-k labels for any given image), such an algorithm would be more accurate than existing tree-labeling methods.

Joint Embedding of Images and Labels

Imagine that one could transform different types of objects—images, videos, music tracks, or texts—into a common representation (such as a vector of real numbers) that could be used by machines to compare them. One could then look for the nearest image similar to a given text label or videos similar to a given image and so on. Each type of object (image, video, music, text) could have a different transformation, or mapping function, and these could be learned using appropriate training data.

Figure 1 illustrates our idea for a simple case that involves two types of objects—images and text labels. We propose to learn two mappings (or transformations) jointly into a feature space (which we call *embedding space*) where the images and labels are both represented. Even though the mapping functions for images and text labels are different, they can be learned jointly to optimize the objective of our final task—annotating images with appropriate text labels.

The first step consists in transforming images, which are often available in jpg, gif, and similar file formats, into more appropriate representations. Years of research in computer vision have yielded several alternatives.

Most recent approaches start by detecting so-called *interest points,* which are positions in the image considered important to analyze (e.g., Dalal and Triggs, 2005; Lowe, 1999). Features are extracted from these interest points using well-known methods, such as scale-invariant feature transforms (SIFT) or histograms of oriented gradients (HOG). Finally, the features are aggregated into a single fixed-length vector representing the image.

One common approach includes (1) learning a dictionary of common features from a large repository of images; (2) using an unsupervised clustering approach, such as K-Means; and (3) representing the image as a histogram of the number of times each feature of the dictionary is present in the image.

Assuming the image representation is a d-dimensional real-valued vector, we denote it by $x \in \Re^d$. Furthermore, let us assume our annotation task can consider up to Y possible text labels (or annotations). We can then represent each annotation as a unique integer $i \in \Upsilon = \{1,\ldots,Y\}$ index into the dictionary of all possible annotations.

Finally, consider an arbitrary D-dimensional embedding (or target) space into which we want to map both images and labels. Our goal is then to learn to transform images, represented in their original image-feature space $\Re^d$ into a new representation in the joint space $\Re^D : \Phi_I(x) : \Re^d \to \Re^D$ while jointly learning a mapping for annotations (i.e., a position in the new joint space for each annotation):

$$\Phi_W(i) : \{1,\ldots,Y\} \to \Re^D$$

In the simplest case, we assume that both mappings are linear, that is:

$$\Phi_I(x) = x^T V$$

and

$$\Phi_W(i) = W_i$$

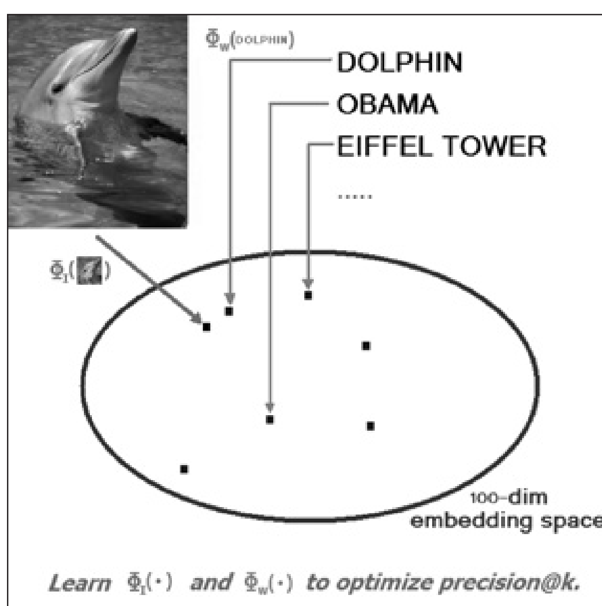


Figure 1 Joint embedding space.

where V is a matrix of size $d \times D$ mapping images into the embedding space, W is a matrix such that line i, W_i is a D-dimensional vector that represents the label in position i in the dictionary, and T means "transpose" and applies to the matrix that precedes it. For example, x^T means that the lines and columns in matrix x are transposed.

The goal for a given image is to rank all possible annotations so that the highest ranked annotations best describe the semantic content of the image. Consider the following model:

$$f_i(x) = \Phi_I(x)\Phi_W(i)^T = x^T V W_i^T$$

where the possible annotations indexed by i are ranked according to the magnitude of $f_i(x)$, largest first.

Image Labeling as a Learning-to-Rank Task

Labeling an image can be viewed as a ranking task. Given an image, one must order labels so that the ones at the top of the list best correspond to the image and the ones at the end of the list are unrelated to it. Various learning-to-rank methods have been proposed in the machine-learning literature over the years, some of which can scale to large datasets and some, such as SVM-Rank, that cannot (e.g., Joachims, 2003).

Here is the simplest scalable approach. One can decompose the ranking task into several smaller tasks:

$$loss = \sum_x \sum_{y^+} \sum_{y^-} \left|1 - f_{y^+}(x) + f_{y^-}(x)\right|_+$$

where the notation $|a|_+$ is a if $a>0$, 0 otherwise, and for each training image x, we want the score of each appropriate label y^+ for that image to be higher than the score of any inappropriate label y^- for that image by a margin of at least one. Otherwise we will incur the corresponding loss.

This loss can be minimized very efficiently on very large datasets using stochastic gradient descent. In this case, one randomly selects a triplet (x, y^+, y^-) from the training set and computes its loss. If the loss is 0, then nothing changes. Otherwise, one can compute the gradient of the loss with respect to the parameters (in this case, V and W) and use it to modify the parameters in the direction opposite the gradient with some fixed but small learning rate, which amounts to a slight improvement in the model with respect to that triplet. By doing so repetitively, this procedure can be shown to converge to the nearest local optimum of the global loss.

However, note that most of the chosen triplets will yield a 0 loss (e.g., it very quickly becomes easy to say that a given image is more like a dolphin than a truck), hence not improving the model, which can lead to very

TABLE 1 Nearest Labels in the Embedding Space Learned on the Web-data

Target Label	Nearest Labels
barack obama	barak obama, obama, barack, barrack obama, bow wow, george bush
david beckham	beckham, david beckam, alessandro del piero, del piero, david becham
santa	santa claus, papa noel, pere noel, santa clause, joyeux noel, tomte
dolphin	delphin, dauphin, whale, delfin, delfini, baleine, blue whale, walvis
cows	cattle, shire, dairy cows, kuh, horse, cow, shire horse, kone, holstein
rose	rosen, hibiscus, rose flower, rosa, roze, pink rose, red rose, a rose
pine tree	abies alba, abies, araucaria, pine, neem tree, oak tree, pinus sylvestris
mount fuji	mt fuji, fujisan, fujiyama, mountain, zugspitze, fuji mountain
eiffel tower	eiffel, tour eiffel, la tour eiffel, big ben, paris, blue mosque, eifel tower
ipod	i pod, ipod nano, apple ipod, ipod apple, new ipod, ipod shuffle
f18	f 18, eurofighter, f14, fighter jet, tomcat, mig21, f 16

slow progress. A faster alternative would be a loss that concentrates on the top of the ranking instead of considering all triplets $(\boldsymbol{x}, \boldsymbol{y}^+, \boldsymbol{y}^-)$ uniformly.

In Weston et al., 2010, we proposed the weighted approximate rank loss (WARP), which can weigh each triplet according to the estimated rank of appropriate labels and still yield an efficient implementation. In order to estimate the rank of appropriate labels efficiently, we used the following trick: for a given image $\boldsymbol{x}$ and its correct label $\boldsymbol{y}^+$, we randomly sampled several incorrect labels, from $\boldsymbol{y}^-$ up, until we found one that yielded a non-negative loss.

The number of samples that had to be drawn from the set of possible labels to find one that yielded a non-negative loss is a good indicator of how well-ranked the correct label is. If it is very well ranked, one will have to sample many incorrect labels before finding one that is ranked higher. If it is poorly ranked, one will quickly find an incorrect label that is ranked higher.

In fact, a good estimate of the rank of the correct label is simply the number of incorrect labels in the dictionary divided by the number of samples needed in the proposed approach. One can then use this estimate to weigh the gradient update accordingly. The resulting model can be trained much faster and will perform at a much higher level of precision at the top of the ranking.

Large-Scale Learning

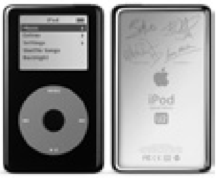
We trained an embedding model with the WARP loss on a very large dataset of more than 10,000,000 training images and more than 100,000 labels. The labels correspond to queries people have tried on Google Image Search, and images attributed to these labels were the ones they often clicked on. This made for a very noisy dataset in which queries were written in several languages with many spelling mistakes and many apparently similar queries (although there are often subtle differences between apparently similar queries, like *dolphin*, which usually means the sea animal, and *dolphins*, which often also means the football team in the United States).

An interesting side effect of training such a model is that looking at the nearest labels to a given label in the embedding space provides a natural way of organizing labels. Examples in Table 1, which show the nearest labels to a given label, include several misspellings, translations, and semantically similar labels. Table 2 provides examples of images from our test set of 3,000,000 along with the nearest 10 labels in the embedding space. In both tables, one can see that the model is not perfect (e.g., the image of the dolphin was labeled "orca" in position 2, before "dolphin" in position 3). However, given the difficulty of the task, the model works quite well.

Learning Label Trees

Real-time applications are not effective for labeling images when the number of labels is large (in our testing dataset we had about 100,000 labels). A naive approach would be to compute a score for each potential label, then sort them, and finally show the top few.

TABLE 2 Examples of the Top 10 Labels Obtained for Some Test Images

Target Image	Nearest Labels	Target Image	Nearest Labels
	delfini, orca, dolphin, mar, delfin, dauphin, whale, cancun, killer whale, sea world		barrack obama, barack obama, barack hussein obama, barack obama, james marsden, jay z, obama, nelly, falco, barack
	eiffel tower, statue, eiffel, mole antoneliana, la tour eiffel, londra, cctv tower, big ben, calatrava, tokyo tower		ipod, ipod nano, nokia, i pod, nintendo ds, nintendo, lg, pc, nokia 7610, vino

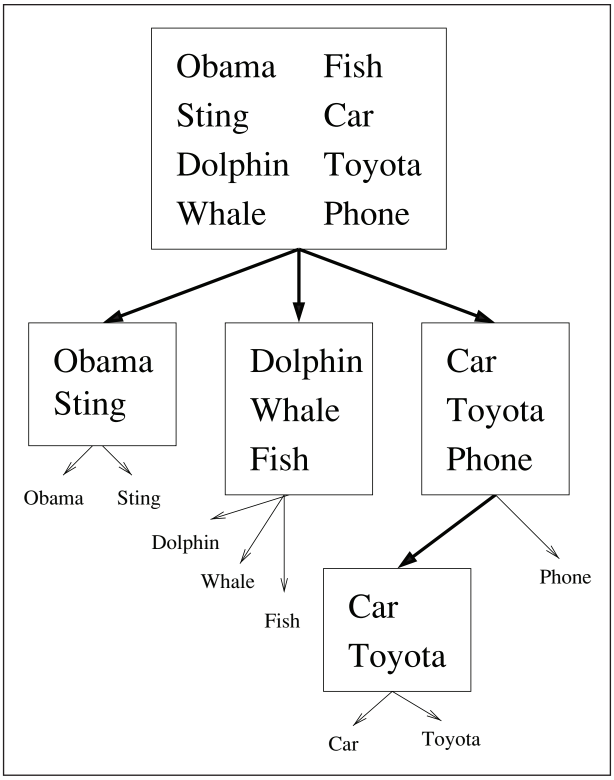


Figure 2 Example of a label tree.

However, as the number of potential labels increases, this procedure becomes infeasible in real time. Ideally, the labeling time should be, at most, proportional to the log of the number of labels.

Existing tree-based approaches (Beygelzimer et al., 2009a,b, Hsu et al., 2009) are typically less accurate than naive linear-time approaches. We have proposed a novel approach for learning a label tree, in which each node divides the set of potential labels into multiple subsets and a local decision is made to choose which subset of labels the current image is most probably associated with (Bengio, 2010). Figure 2 shows an example of a label tree. If the subsets are balanced (i.e., approximately the same size), this procedure decreases the number of labels to consider at a logarithmic rate until a prediction is reached.

In our model, we apply the following two steps: (1) learning a label tree, and (2) learning predictors for each node of the tree. These steps are described in the following subsections.

Learning the Label-Tree Structure

To learn a label tree such as the one in Figure 2, we proceed as follows. Given a set of labels in a node, we look for a partition of that set into subsets. Within the subset, labels are difficult to distinguish with classifiers trained on their corresponding images. However, it is easier to distinguish images belonging to labels of one subset from images belonging to labels of another subset.

This basic rule enables us to postpone difficult decisions (e.g., is this an ipod nano or an ipod touch) and make easy decisions first (e.g., is this about either [dolphin, whale, shark] or about [ipod touch, ipod nano, iphone]). We can do this by computing the confusion matrix between all labels to count the number of times our classifiers confuse class i with class j on a test set of images not used to train the classifiers.

We then use the resulting matrix to apply spectral clustering (Ng et al., 2002), a technique that can cluster objects (in this case labels) using a given similarity (or distance) matrix between them, instead of using, say, the Euclidean distance between two labels. This procedure can then be used recursively to create a complete label tree. Table 3 shows an example of labels that were clustered together using this technique.

Learning a Label-Embedding Tree

Once labels are organized into a tree, one can retrain a new embedding model (using the algorithm described above) in which each image can be labeled either with its original set of labels or with reference to the nodes of the tree that contain them. Thus, the embedding space contains representations of all labels, as well as all nodes of the tree.

At each training iteration, one selects an image at random and then selects one of its correct labels at

TABLE 3 Examples of Obtained Clusters of Labels

great white sharks, imagenes de delfines, liopleurodon meduse, mermaid tail, monstre du loch ness, monstruo del lago ness, oarfish, oceans, sea otter, shark attacks, sperm whale, tauchen, whales	apple iphone 3gs, apple ipod, apple tablet, bumper, iphone 4, htc diamond, htc hd, htc magic, htc touch pro 2, iphone 2g, iphone 3, iphone 5g, iphone app, iphone apple, iphone apps, iphone nano	chevy colorado, custom trucks, dodge ram, f 250, ford excursion, ford f 150, mini truck, nissan frontier, offroad, pickup, toyota tundra

random, including the nodes of the tree where the labels appear. Whenever an internal node is selected as a positive label for a given image, we select the competing negative label as one of the sibling nodes in the label tree. This corresponds to how the tree would be used at test time.

This repetitive procedure results in a structure of labels based on both semantic and visual similarities. In addition, using this method, the performance of a label-embedding tree, on average, performs both faster and slightly better at test time (Bengio et al., 2010).

Conclusion

The problem of image annotation for very large numbers of possible labels is very challenging. In recent years, significant progress has been achieved by proposing progressively better feature-extraction techniques from images to solve problems like rotation and translation invariances. In this article, we focus on the modeling aspect of the problem, particularly for very large, varied datasets of images and labels.

The proposed approach (learning a joint embedding space) achieves a performance level that is at least as high as performance levels on a similar task at that scale. In addition, the approach described above yields a novel visual semantic space in which images and text labels coexist and their relative distances in that space reflect both semantic and visual differences.

We also propose a method, an additional tree-based structure over the labels that learns from data, so that a given image can be annotated quickly in a time frame proportional to the log of the number of potential labels. With its improved performance and quick reactions, this approach may prove to be very efficient.

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Improving the construction and performance of buildings could lead to huge reductions in carbon emissions.

Challenges and Opportunities for Low-Carbon Buildings

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John Ochsendorf

Buildings account for a higher proportion of greenhouse gas emissions than any other economic sector, and emissions attributable to building construction and operation have been increasing in recent decades. These emissions can primarily be traced back to heating, cooling, and lighting systems, although emissions from embodied materials are also significant.

Major new initiatives are under way to reduce the amount of energy consumed by buildings, but numerous technical, economic, and policy barriers will have to be overcome. This article provides summaries of some key challenges to the design and implementation of low-carbon buildings in the United States and describes the resulting opportunities for the engineering professions.

Introduction

Although buildings have major environmental impacts in terms of water use, consumption of raw materials, and the depletion of other natural resources, the focus of this article is on reducing greenhouse gas emissions for mitigating climate change. Carbon dioxide equivalence (CO_2e) provides a simple metric for determining the environmental performance of buildings, including both embodied emissions and operating emissions.

As the largest source of carbon emissions in the United States, buildings also represent a significant target of opportunity for carbon reductions (Figure 1). In a landmark paper, Pacala and Socolow (2004) identified improvements in building efficiency as one of seven "stabilization wedges" that could help offset global increases in carbon emissions over the next 50 years.

The Intergovernmental Panel on Climate Change has identified buildings as the sector with the greatest potential for carbon reductions, particularly because reductions that result from improved building performance also yield substantial economic benefits (IPCC, 2007). The World Business Council for Sustainable Development has concluded that the energy use of buildings worldwide could be reduced by 60 percent by 2050 using existing technologies (WBCSD, 2009). McKinsey Consulting has identified the building sector as the most cost-effective target for carbon abatement. According to McKinsey's analyses, carbon reductions for most buildings could be achieved at a negative cost (McKinsey, 2007).

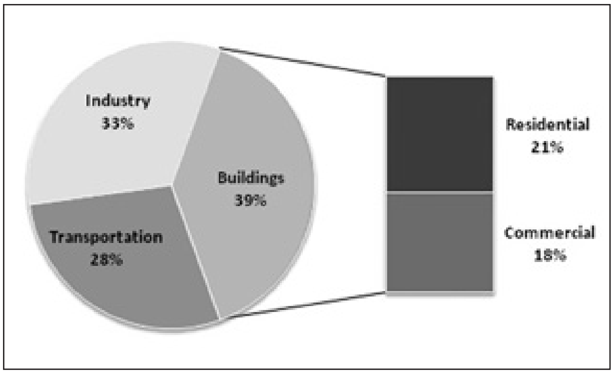

Figure 1 U.S. energy consumption by sector. Source: Energy Information Agency.

Current Initiatives

Several current initiatives in the United States have established target levels for improved carbon performance of buildings. The best known initiative is the LEED (leadership in energy and environmental design) rating system developed by the United States Green Building Council. The exponential growth of the LEED system has dramatically increased the market share of green construction over the last decade. However, although the LEED system promotes a variety of environmental improvement strategies for many different types of buildings, it does not explicitly address carbon emissions.

The 2030 Challenge

The 2030 Challenge developed by Architecture2030 establishes rigorous targets for reducing carbon emissions from new buildings, and in the next two decades, these standards will become increasingly stringent (Architecture2030, 2012). The current goal is to design buildings that use 60 percent less annual energy than average for that building type. For example, to satisfy the 2030 Challenge, a new hospital must emit 60 percent lower emissions than the current national average for hospitals. The reduction targets will decrease by 10 percent every five years (e.g., a decrease in emissions of 70 percent by 2015), until, by 2030, new buildings will be carbon neutral.

There are three primary approaches to meeting these design goals: (1) improving design strategies; (2) improving the efficiency of technologies and systems; and (3) using off-site renewables, such as offshore wind energy (up to a maximum of 20 percent). Although the 2030 Challenge is voluntary at present, many city governments have committed to pursuing its goals, and a number of engineering and architectural firms are already tracking energy consumption and carbon emissions for their new buildings in relation to the 2030 Challenge goals.

National and State Initiatives

Some countries are developing binding legal requirements for dramatic carbon reductions in new buildings in the coming decades. For example, in the United Kingdom (UK), the Climate Change Act of 2008 mandates 80 percent carbon reductions on a 1990 baseline by the year 2050 (Crown, 2008). To help achieve this goal, the target for new residential construction in the UK will be zero carbon emissions by 2016.

The most aggressive legal target for carbon reductions in the United States is California's Assembly Bill 32 (AB32), which mandates reductions to 1990 emissions levels by 2020 (Assembly Bill 32, 2012). Improved building efficiency is a major component of California's road map toward lower greenhouse gas emissions.

Improving Building Codes

Other policies, such as more stringent building codes, can be important motivators for engineers and architects and can move markets toward lower carbon buildings. An extensive study by the World Business Council for Sustainability has shown that more stringent building codes are the most effective way to reduce carbon emissions from buildings and to transform the market for a low-carbon future (WBCSD, 2009).

Challenges for Low-Carbon Buildings

The Role of Engineers

Engineers, who are crucial to designing more sustainable buildings, often become involved too late in the design process to make all of the necessary decisions. Many key decisions, such as building orientation, glazing ratio (i.e., area of glass/area of opaque wall), and the overall form of the building are made in the earliest design stages. Once these critical decisions have been made, engineers can attempt to optimize a poor design, but it is difficult at that point to achieve a low-carbon design.

The engineering of sustainable buildings is not being taught in most U.S. schools of engineering.

The challenge is to integrate engineering analysis in a way that provides rapid feedback to architects and the rest of the design team early in the process. For this, engineers must be trained as designers, so they can propose multiple solutions to open-ended problems. In short, the design of high-performance buildings requires integrated systems thinking beginning in the earliest conceptual design stage.

To ensure that engineers with the necessary skills are available, more of them must be trained in building science and sustainable design. However, most engineering schools do not directly address the design and operation of buildings, because sustainable building design involves aspects of mechanical engineering, civil engineering, and architecture.

The few existing programs in architectural engineering are turning out graduates, but in numbers far below those of traditional engineering disciplines. Thus, despite the dramatic economic and environmental impacts of buildings and the growing need for engineers in this field, the engineering of sustainable buildings is not being taught in most schools of engineering in the United States.

Funding for Research

Finally, there is an acute lack of spending on research and development (R&D) for sustainable buildings. It has been estimated that only 0.25 percent of gross sales in construction are spent on R&D in the United States, much less than is spent by industries in other economic sectors, such as the automobile and electronics industries (Gould and Lemer, 1994). Furthermore, only 0.2 percent of federal research funding is spent on topics related to green buildings (USGBC, 2008).

The scarcity of research funding means that fewer researchers are working on this vital topic, despite the urgency of climate change and the favorable economics for carbon reductions through improved buildings. Increased research funding would not only attract more students, but would also attract leading engineers to this important field.

Opportunities for Low-Carbon Buildings

More efficient building design is one of the most cost-effective opportunities for large-scale reductions in carbon dioxide emissions on a national and global scale. Thus more emphasis on integrated building design for the full life cycle of a building can lead to dramatic improvements in building performance. The key is to incorporate systems thinking *at the conceptual design stage*, taking into account climate-specific factors and regional climate.

The choice of materials for a building can not only determine the embodied carbon of a building, but also has implications for the carbon emissions from building operations, through thermal mass and improved daylighting. For example, appropriate building materials can moderate diurnal temperature swings or help to distribute daylight deeper into interior spaces. In addition, decisions about building orientation, façades, heating and cooling strategies, and glazing ratios, which must be made early in the design process, are crucial factors in the final energy performance of a building.

New Design Tools

Most traditional architectural design software does not have the capacity to analyze energy or environmental performance in the conceptual design phase. However, in the last decade, several tools have been developed to assist architects and engineers by providing architects with rapid feedback on environmental performance.

For example, the MIT Design Advisor enables the rapid estimation of building energy use based on massing, orientation, climate, glazing ratios, and other factors (Design Advisor, 2012). More recently, the DIVA platform has been developed to enable architects to run basic performance simulations in the early design stage using existing architectural design software (DIVA, 2012). Although such programs are being developed quickly, there is still an urgent need for improvement, as well as for engineers capable of systems-level building design.

Educating Architectural Engineers

A multidisciplinary education focused on sustainable design can attract a new generation of engineers to the profession. In addition to expertise in heat transfer, thermal science, materials engineering, and other traditional building sciences, sustainable buildings require expertise in design thinking and creative problem solving.

There is also a strong demand in the market for increased literacy in rigorous sustainability metrics and for expertise in the life-cycle environmental and economic performance of buildings. Integrated graduate education in the built environment, such as the Solving Urbanization Challenges by Design, a program at Columbia University, combine engineering, architecture, and planning to provide a broad-based education for sustainable building designers and researchers (IGERT, 2012).

Funding for Research and Development

Increasing funding for R&D on sustainable buildings will require new partnerships among industry, academia, and government. Some current examples are (1) the Greater Philadelphia Innovation Cluster for Energy Efficient Buildings supported by the U.S. Department of Energy (DOE) and numerous academic and industry partners (GPIC 2012); (2) the Center for Architecture Science and Ecology supported by Rensselaer Polytechnic Institute and Skidmore Owings and Merrill (CASE 2012); and (3) the Advanced Building Systems Integration Consortium at Carnegie Mellon University (ABSIC, 2012).

Increased federal funding could be provided by the National Science Foundation and the DOE, both of which are appropriate agencies for promoting research on sustainable buildings. In addition, new graduate research fellowships for students working in building science would help attract more researchers to the field.

Case Studies

Many low-carbon buildings constructed in recent years can serve as models to inspire engineers, architects, building owners, and policy makers. Noteworthy examples of a residential building development, a school, an office building, and a cultural building are described below.

BedZED, Beddington, England, 2002

The Beddington Zero Energy Development, known as "BedZED," is a pioneering low-carbon residential development outside London, England, made up of 99 homes of various sizes (BedZED, 2012). Opened in 2002 and designed by a team of architects, engineers, and developers, these low-rise buildings have passive heating, cooling, and lighting strategies that dramatically reduce residential energy requirements (Figure 2).

However, the BedZED concept goes beyond the design of buildings to include transportation, food production, and other holistic urban-design strategies. For example, photovoltaic arrays and biofuel incinerators are designed to generate 100 percent of on-site electricity demand.

Although the initial cost of construction was slightly higher than for conventional construction, occupants are realizing substantial annual energy savings, and the

FIGURE 2 Beddington Zero Energy Development, Beddington, England, 2002. Source: WikiPedia "BedZED."

FIGURE 3 Richardsville Elementary School, Richardsville, Kentucky, 2010. Source: Sherman Carter Barnhart Architects.

resale value of homes has exceeded the local average housing market by 10 to 20 percent (BedZED Toolkit II, 2003). Now 10 years old, BedZED continues to set an international standard for developers and designers to learn from and emulate.

Richardsville Elementary School, Richardsville, Kentucky, 2010

Richardsville Elementary School is an 82,000 square foot net-zero-energy educational building for 600 students (Sherman, 2012). Like other low-carbon buildings, Richardsville's initial design was significantly more efficient than the design of typical school buildings (Figure 3). For example, annual energy demands are only 5.3 kilowatt hours per square foot per year (kWh/ft^2/yr), about 75 percent lower than the national standard for elementary schools. In addition, a 348 kW photovoltaic array generates on-site renewable energy to meet this demand.

At a cost of approximately $190 per square foot, the school's construction costs are competitive with those of other schools around the country. Insulated concrete form (ICF) construction provides improved insulation and reduces air infiltration through the exterior envelope of the building, and geothermal technology generates heating, cooling, and hot water. Overall, Richardsville has dramatically lower annual operating costs than traditional school buildings, resulting in equally dramatic reductions in life-cycle economic costs.

Advanced building technology in schools also has pedagogical benefits. For example, it can motivate students to learn about green building design and construction. Students and teachers also actively monitor the energy performance of the building, and green technologies are incorporated into lesson plans. Richardsville is an example of how an integrated design team can dramatically reduce the energy demands of a building to achieve a zero-energy school.

Research Support Facility, National Renewable Energy Laboratory, Golden, Colorado, 2010

The Research Support Facility of the National Renewable Energy Laboratory is a 222,000 square foot, net-zero-energy office building located at an altitude of 5,300 feet in the Rocky Mountains of Colorado (NREL, 2012). Home to 800 employees, this federal office building is both a showcase for low-energy building technology and a living laboratory for ongoing research and for monitoring the performance of green technologies (Figure 4).

Equipped with day-lighting and passive heating and cooling strategies, the building requires only 10.3 kWh/ft^2/yr, which is 50 percent less than the national standard for office buildings. The energy demand is met by an on-site 1.6 megawatt photovoltaic array, which

FIGURE 4 Research Support Facility, National Renewable Energy Laboratory, Golden, Colorado, 2010. Source: NREL/Dennis Schroeder.

also helps power an on-site energy-intensive data center. Even at an altitude of one mile above sea level, the building does not require conventional heating. Instead, it is warmed by the data center and by transpired solar collectors, which were originally developed at NREL.

Interpretive Centre, Mapungubwe National Park, South Africa, 2009

The Mapungubwe National Park Interpretive Centre is both a museum and a visitor's center at a World Heritage site in a remote area of northeast South Africa (Figure 5). The client for the project, South Africa National Parks, required a building with minimal environmental impact to be built, as much as possible, with local materials and labor. In this harsh climate, where daytime summer temperatures can reach 110°F, the design team was determined to use passive strategies to maintain a comfortable interior temperature.

Using on-site soil and stones, the advanced structural design of the building consists of massive masonry walls and load-bearing vaults that increase thermal mass. The soil-cement vaults were built with minimal formwork and no interior steel reinforcements, thus reducing the amount of embodied carbon in the building materials by approximately 80 percent compared to conventional steel and concrete construction (Ramage et al., 2010).

Because of the remote location, on-site energy demands were kept to a minimum, and daylighting is the primary lighting source. For its radical approach to design and construction with local materials, the building was honored as the 2009 World Building of the Year at the World Architecture Festival.

Lessons Learned

In these and most other low-carbon buildings, the crucial design strategies were developed by collaborative teams of architects and engineers early in the design process. In addition, owners or clients often played a central role in establishing a vision for each project, essentially setting a challenge for the design team to meet. By setting clear targets for energy consumption, these designs were achieved at costs similar to those of conventional construction. However, as a result of reduced operating energy requirements, they have significant life-cycle economic benefits. These and other projects clearly show that the carbon intensity of new buildings can be dramatically reduced using existing technologies.

FIGURE 5 Interpretive Centre, Mapungubwe National Park, South Africa, 2009. Source: James Bellamy.

Conclusions

Buildings are widely recognized as the most significant opportunity for cost-effective carbon reductions in the United States and around the world. To take advantage of these opportunities, engineers must continue to play a vital role in transforming the built environment for a low-carbon future.

Numerous areas for improvement remain. An intensive emphasis on conceptual design, life-cycle thinking, and innovative research partnerships will be necessary to advance the field, reduce carbon emissions, and train a new generation of engineers. We now know from experience that dramatic improvements in the design and operation of buildings are possible. Our hope is that well trained engineers will provide leadership for the United States and the carbon-constrained world of the future.

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The green building community is using information technology to drive fundamental changes in the real estate market.

Using Information Technology to Transform the Green Building Market

Christopher Pyke

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The built environment shapes our lives both as individuals and as a society. It is not only a tangible library of our history, a reflection of our technology, and a window into our values and priorities, but also a platform for the future. The built environment greatly affects our health and well-being and is a major factor in our collective impact on the environment.

Today's buildings are marvels of security, comfort, and accessibility, but we are becoming increasingly aware of their limitations in terms of energy and water consumption, greenhouse gas (GHG) emissions, and storm water runoff, as well as their contributions to diseases (e.g., asthma and obesity), exposure to toxic materials, and physical impairments. The impacts are felt both locally and over large geographic areas that are dependent on global supply chains. In fact, buildings are associated with 40 percent of *global* primary energy consumption—50 percent if we include the energy consumed in the production and distribution of steel, concrete, aluminum, and glass (IPCC AR4 WG3, 2007).

The negative impacts of buildings have historically been considered economic externalities, and, therefore, were unregulated and isolated from competitive forces in the real estate market. Nevertheless, their pervasive, often invisible, and unaccounted-for impacts have far-reaching implications. Ultimately, reducing the drivers of climate change, enhancing energy security, promoting public health, improving quality of life, and improving the health and well-being of current and future communities will hinge on our ability to create (and re-create) built environments.

In the last 20 years, efforts by the green building community in the United States to respond to these challenges have been led by interdisciplinary, practitioner-led coalitions seeking to advance the design, construction, and operation of built environments to promote human health, well-being, and the protection and restoration of the environment. The movement began with an image and a simple idea, a classic market-adoption curve (a conceptual illustration of the distribution of practice or performance in an industry, ranging from a few scofflaws on the low end through the average-performing majority, to a small group of innovators on the high end [Roger, 1962]). The idea was to use strategic market interventions to permanently shift distributions of practice toward higher performance and greater achievement.

Although the concept attracted some attention, the image lacked substance, mostly because very little information was available to describe distributions of practice and performance over relevant populations for real-world buildings. Empirical evidence for understanding or predicting the real-world impacts of potential market interventions and green building practices was also scarce. We simply did not have the data or tools we needed to provide an empirical foundation to support the founding vision.

Green building projects are becoming the currency of data-driven market transformation.

Fortunately, the lack of experience and data did not delay action. Leaders of the movement first defined "green" and set an initial direction by defining "good," "better," and "best" practices and preferred levels of performance. In this way, they provided a credible directional signal to the industry—not perfect and not always rooted in data, but useful as a basis for action. The next steps were to develop a workforce and assess tools, policies, and programs for recognizing and rewarding high performance.

As a result of efforts by thousands of organizations, the movement soon made a real impact on the building industry. Today, hundreds of thousands of professionals have received green building training and personal accreditation, and thousands of individual projects have been evaluated and certified against third-party standards (Watson, 2011).

The next generation of green building will return to its beginnings, propelled by an emerging foundation of data and analytics that provide empirical support for the original vision. We can now cite data to describe the prevalence of performance and the distribution of actions among market participants. We can create the "curves" we have been talking about and promoting, powered by a state-of-the-art information ecosystem rooted in project performance and evidence-based practice.

Measuring Green Performance and Achievement

We now have tools and processes for designing and assessing high-performance green buildings and communities. The concept of a green building "project" has evolved to encompass commercial interiors, homes, commercial buildings, and even entire neighborhoods—ranging from less than 1,000 square feet to more than 50 million square feet. With thousands of projects completed and thousands more in the pipeline, green building projects are becoming the currency of data-driven market transformation.

Recognition for projects is typically based on the implementation of specific design and operational strategies (e.g., integrative design, energy efficiency, water conservation), the achievement of milestones (e.g., facilities management policies), and, increasingly, the performance of whole systems, ranging from interior spaces to neighborhoods (e.g., whole-building energy performance).[1]

Project-rating systems, such as the U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED™)[2] and a number of analogous systems around the world define required levels of achievement and performance to meet a wide range of criteria (Cole,

[1] The term "performance" refers to a measurement, typically a quantitative metric, such as energy efficiency, renewable energy generation, water consumption, or occupant satisfaction. The term "achievement" refers to binary or qualitative activities, such as policies, procedures, or discrete choices (e.g., green cleaning, commissioning, or the use of third-party certified building products). The two terms are often used together as "performance and achievement" to reflect the typical range of green building practices.

[2] See *www.usgbc.org/leed* for more information.

1999). Projects that meet or exceed requirements are recognized by LEED certification and other designations.

In effect, assessment systems and third-party certification tools have responded to historic deficiencies in information and market failures (e.g., the lack of information about energy efficiency or GHG emissions) by providing credible information about practices and performance levels. For example, LEED certification brings transparency to many aspects of green building, including location and transportation, design and engineering processes, construction activities, site planning, energy consumption and supply, water use, indoor environmental quality, and innovation. Such transparency improves the flow of information among market participants and creates opportunities for competitive differentiation. Fundamentally, the LEED standard provides the long-sought distribution of market conditions and rewards projects that demonstrate leadership in prevailing practices.

Over the past decade, the day-to-day tools for ensuring transparency have been rudimentary—a simple scorecard and, at the end of the process, a glass plaque displayed in a building lobby. Nevertheless, these simple steps have had a remarkable impact on the industry.

Using information technologies, we can now vastly accelerate and scale up the impact of our fundamental goals and concepts. In addition, we can now treat individual projects and collections of projects as testable hypotheses of the efficacy of green building processes, products, and services. Emerging information technology and data sources provide opportunities for reinforcing connections between design intent and real-world impact. The remainder of this article describes a preliminary vision for information-powered, data-driven market transformation.

Information and Efficiency

Classical economics begins with the assumption that market participants have equal and immediate access to relevant information (Fama, 1970; Malkiel, 2003), which is the basis for setting prices and valuing assets. Real estate markets, for example, have developed sophisticated tools that provide information on financial aspects of individual buildings and portfolios, and commercial information services provide benchmarking data related to capital costs, sales prices, tenancy, and numerous other factors. Markets for this information are mature and highly segmented, and market responses are complex, but reasonably predictable (Gatzlaff and Tirtiroglu, 1995).

However, comprehensive information on non-financial dimensions of properties, such as energy use, water consumption, and occupant experience, or on the efficacy of green building practices, such as energy efficiency technologies and water-conserving products is not readily accessible. The absence of this information contributes to inefficient markets, inhibits innovation, and sometimes contributes to market failures (Gillingham et al., 2009).

We can now treat individual projects and collections of projects as testable hypotheses of the efficacy of green building processes, products, and services.

For example, inefficient, polluting assets may be overvalued, while cleaner, more efficient buildings are overlooked. The most effective practices may be undervalued, and less effective actions may be overrated. The resulting misallocation of resources is a predictable result of the absence of information, and this is now the defining challenge and opportunity for the green building movement.

The most direct remedy is to create public and private mechanisms to provide information on non-financial aspects of assets, such as the green dimensions of homes and commercial buildings, along with information about the contributions of specific practices. This can be accomplished through public labeling programs and private efforts to create information markets and analytical services. Some public programs have been initiated, such as the European Union's building-level Energy Performance Certificates, green building certifications, and, in a few metropolitan areas, municipal energy benchmarks (IEA, 2010). Complementary private efforts may also be in the offing, but only a few have emerged publicly (e.g., Bloomberg New Energy Finance).

Taken together, however, these efforts barely scratch the surface. Ultimately, we must connect information about performance with essential contextual information in three essential areas: design intent (e.g., original plans), implementation actions and practices (e.g., technologies, management strategies, etc.) and normalization factors (e.g., occupancy schedules, occupant density, etc.).

Accelerating Innovation

Real-world data on how operational performance relates to design intentions and specific strategies, people, products, and services will be the foundation and currency for the next generation of green buildings. However, data per se will not necessarily lead to change. To accelerate market transformation, information must be interpreted and linked to mechanisms that create market opportunities for high-performing projects and, by extension, competitive risks for low performers.

At this point, the interests of the green building movement diverge from those of agnostic market analytics. Rather than improving reporting on the status quo, our goal is to use information to drive permanent, self-sustaining change in entire industries. Success will be measured by the rate and magnitude of those changes.

We intend to use data and information technology to accelerate the diffusion of innovation and the rate of market evolution, that is, the rate at which new practices are taken up by market participants and, critically, their impact on the performance of individual assets and the built environment as a whole. Our goal is to achieve a permanent, positive shift in prevalent practices and performance.

Although the building sector as a whole has not yet embraced these concepts, new data sources and information technologies are creating opportunities for scalable, information-based market interventions. However, realizing these opportunities will require three key components in the design of emerging data streams and information technologies for green buildings:

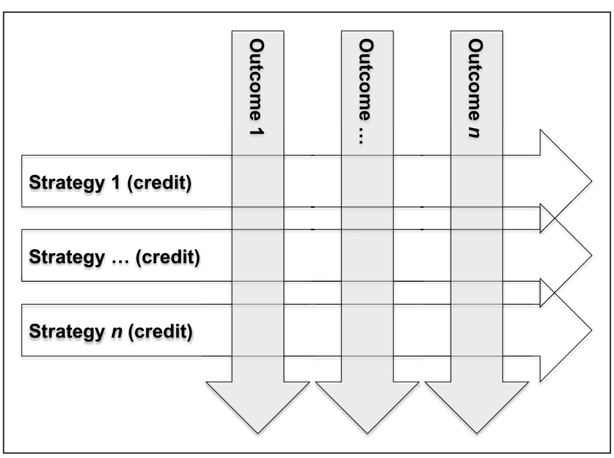

Figure 1 LEED is an outcome-oriented rating system. Points (relative weights) are assigned based on the association between credits (a.k.a., strategies) and outcomes (e.g., reductions in greenhouse gas emissions).

- **Define outcomes** (i.e., performance dimensions subject to evaluation). "Green building" per se is not an outcome. It is a process and an evaluation framework. The next generation of assessments must strengthen connections between desired outcomes (intentions) and operational performance measures, which will lead to more specificity in design, engineering, operations, and evaluations.
- **Understand and reward relatively high performers.** Data-driven evaluations of new performance dimensions can provide a basis for sorting and ranking projects; drawing inferences about underlying practices, products, and services; and creating performance-based reward systems.
- **Inspire and assist relatively low performers.** Information creates opportunities to identify and improve low-performing projects and strategies in comparison to higher performing peers.

Outcomes

For the past decade, green building has been determined by a single performance dimension—the number of points a project achieves on a rating system. This dimension is typically divided into categories, such as LEED Certified, Silver, Gold, and Platinum levels. Sometimes, the act of certification itself or the level of certification becomes a goal in itself.

We have been exploring ways to expand the traditional focus by developing and implementing a multidimensional framework linking green building outcomes and practices. An initial framework was released with LEED 2009 (USGBC, 2008), in which every green building "credit" (a.k.a., optional strategy) was quantitatively associated with 13 environmental "impact categories," such as GHG emissions, resource depletion, and smog formation (Figure 1). On this basis, weights (points) were assigned to individual credits. In addition, credit achievement could be used to track specific outcomes—literally unpacking the information collected during the certification process.

LEED 2012, which has seven core green building outcomes supported by more than 30 metrics (e.g., energy efficiency, renewable energy production), will be designed from the bottom up to associate actions with outcomes. In addition, every action can be critically evaluated with respect to operational performance. The outcomes or performance dimensions can be as "simple" as intensity of energy use (e.g., annual energy use per square unit of floor space) or much more complicated, synthetic measures, such as the 29 weighted factors included in the LEED 2009 GHG Index. Each metric provides a new dimension for ranking and sorting green building projects in terms of goals and outcomes.

High Performers

Each performance dimension is populated with real projects based on third-party verified data collected during the certification process giving us an opportunity to identify and reward high performers. The first test is simple scoring based on performance (e.g., an Energy Star score). However, the confluence of service-based, information technology architectures, highly scalable databases, and pervasive data collection is creating unprecedented opportunities for connecting design and engineering intent with execution and outcomes. Based on these data, we will be able to identify factors that contribute to different levels of performance and achievement (Figure 2).

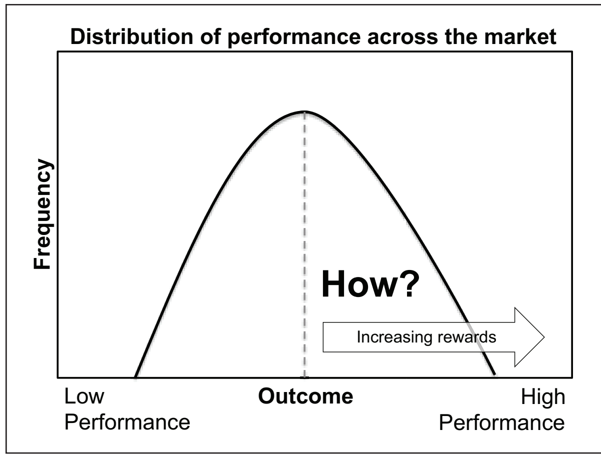

Figure 2 The Green Building Information Gateway (GBIG) provides data on the distribution of performance across populations of green building projects. GBIG information can be used to improve our understanding of "how" high-performing projects deliver above average results. Placing a project in context provides a basis for recognition and competitive advantage.

Fundamentally, we want to understand how projects achieve a given level of relative performance. This will require identifying and tracking relationships among people, organizations, practices, technologies, and many other factors. Each high-performing project can then provide a benchmark for lower performing projects. Data on projects can be combined to evaluate the relative efficacy of green building practices.

Today, we can use a demonstration system called the Green Building Information Gateway (GBIG) (*www.gbig.org*) to begin to identify and explore high-performing projects based on multiple outcomes. For example, Table 1 shows the performance and achievement in six categories of an exemplary office building in Chicago, Illinois. The accompanying density plots compare the selected project (the dark triangle) with other projects certified on the same rating system, in this case LEED for Existing Building: Operations & Maintenance (more information is available from *http://www.gbig.org/projects/10049661*).

Our goal is to use this data and information technology to shorten cycles between innovations, market uptake, operational performance, and positive recognition. This will require creating highly scalable information systems to collect data on performance, practices, and technologies in near real time and provide dynamic, context-relevant benchmarking and recommendations. These data will provide decision makers with timely information for market and green "comparables," which are not currently available in the real estate industry.

CATEGORY	POINTS	RANKING ?
Energy and Atmosphere	25/30	
Materials and Resources	10/14	
Indoor Environmental Quality	17/19	
Sustainable Sites	8/12	
Water Efficiency	7/10	
Innovation in Operations	7/7	
Total	74	

TABLE 1 A Basic "Nutrition Label" for an Exceptionally High-Achieving LEED-Certified Project. Conceptually similar to food labeling, the "nutrition label" can be created by GBIG to summarize information for six LEED credit categories and place achievement in the context of all others using the same rating system. Source: Green Building Information Gateway (*www.gbig.org*) or *http://www.gbig.org/projects/10049661*.

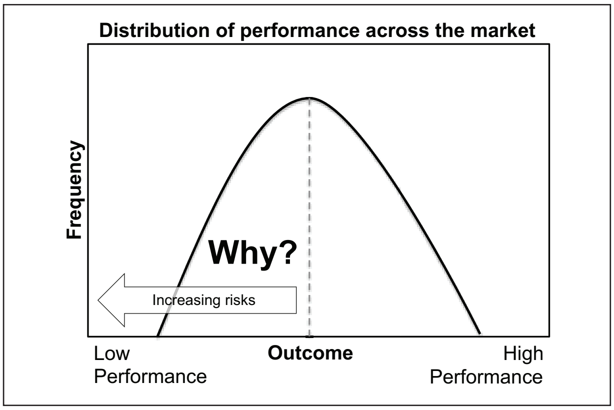

Figure 3 Information in GBIG can be used to understand "why" relatively low-performing projects deliver below average results. This understanding can inform critical evaluation and subsequent improvements.

Low Performers

The green building community has always been comfortable recognizing high performers, but for every high performer there are a commensurate number of underperformers. Outside of Lake Woebegone, underperformers are statistically inevitable.

Nevertheless, we have generally been less aggressive in searching out underachievers and trying to understand and assist them. To ensure continued progress, we recognize that we must pursue an understanding of these projects with energy equal to or greater than our pursuit of high performers.

Fortunately, we can adapt the same basic information technologies to identify underperforming projects (Figure 3), determine the factors that affect their practices, and recommend specific strategies for improvement based on practices by comparable higher performing projects. We may also be able to identify specific actions and circumstances that compromise outcomes. Our goal is to understand the challenges and, if necessary, create new or improved interventions to overcome barriers, such as technological limitations, lack of technical understanding, or cost.

GBIG can help identify and explore many outcome dimensions for relatively low-achieving projects. Table 2 shows selected metrics for a LEED for New Construction (version 2.2) project in Washington, D.C. (more information is available from *http://www.gbig.org/projects/10100317*).

Testing and Evaluation

The ability to understand, stratify, rank, and interpret performance and outcomes with respect to processes, products, and services creates immediate opportunities for encouraging constructive competition and competitive differentiation. It also contributes to a new framework for testing and evaluating green building strategies using projects as natural experiments.

However, realizing these opportunities will require a change in perspective. Today, the implementation of strategies is often considered a mark of achievement—an outcome in its own right. However, in the near future the value of green building strategies will be based on the reliability of their contributions to operational performance and intended outcomes. In this emerging, performance-oriented perspective, every project becomes a real-world experiment representing a unique combination of circumstances, intentions, strategies, and outcomes.

Many sectors have embraced such frameworks, sometimes called evidence-based practices, adaptive management, or continuous improvement (e.g., the familiar "Deming Cycle"). Typically, the goal is to treat practice as iterative experimentation. Every action has an intent, implementation strategy, and anticipated outcomes. The objective is to incrementally strengthen connections between intentions and outcomes.

For example, some physicians practice evidence-based medicine by using data on health outcomes to inform treatment decisions. Similarly, conservation biologists practice adaptive management using information about population trends to refine restoration and

CATEGORY	POINTS	RANKING ?
Energy and Atmosphere	1/17	
Materials and Resources	7/13	
Indoor Environmental Quality	5/15	
Sustainable Sites	7/14	
Water Efficiency	2/5	
Innovation in Design	5/5	
Total	27	

TABLE 2 A Sample GBIG "Nutrition Label" for a Relatively Low-Achieving LEED-Certified Project. This label places LEED credit category achievement in the context of all other certified projects using the same rating system. Source: Green Building Information Gateway (*www.gbig.org*) or *http://www.gbig.org/projects/10100317*.

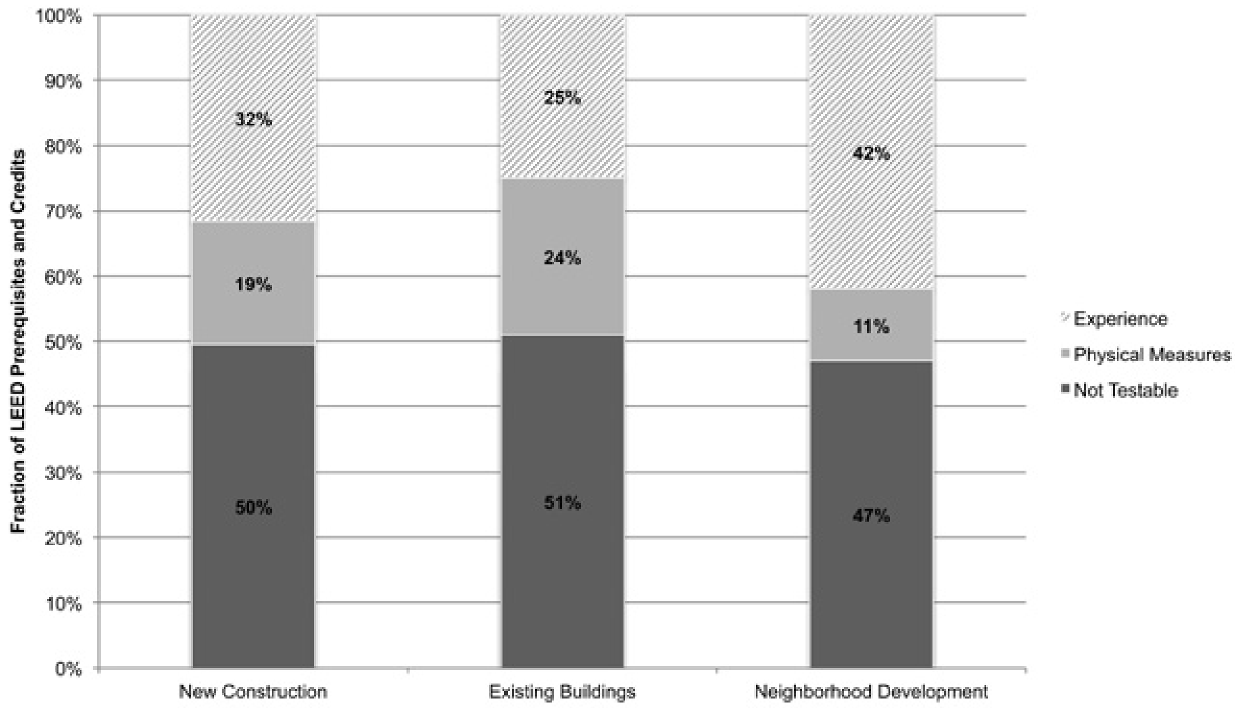

Figure 4 Proportion of LEED credits associated with different evaluation methods and rating systems. The x-axis categories reflect three LEED rating systems: LEED for New Construction, LEED for Operations and Maintenance, and LEED for Neighborhood Development. The y-axis indicates the fraction of prerequisites and credits intents that can be directly evaluated in operation based on physical measures (e.g., meters), occupant experience, or "not testable" (e.g., reference to a third-party standard or criteria). Source: Data from Pyke et al., 2010.

protection practices. Evidence-based practice in these domains is supported by closely coordinated monitoring, evaluation, and surveillance programs.

The architectural community is just beginning to recognize similar opportunities for "evidence-based design" (Mortice, 2009). Unfortunately, this industry generally lacks corresponding systematic data collection and systems, and interconnected data and analytics are prerequisites for evidence-based practice. This community will require an information infrastructure like the one envisioned for GBIG.

Green building will help lead this revolution. Every credit in every LEED rating system is defined with respect to a specific intent and documentation. Today, more than 1,000 credits are in regular use for nearly 100,000 projects, representing real-world opportunities for testing a wide range of hypotheses, some of which are more testable than others (Pyke et al., 2010).

In a recent study, we found that 50 per cent of LEED credit intents are currently evaluated based on consistency with a third-party authority or rule, such as purchase of a certified material or implementation of a specified policy (Figure 4). The intentions of the other 50 per cent of LEED credits require evaluations of operations, most often using information from physical measures or human experience in or around projects. Physical measures include energy use, energy production, water consumption, temperature, runoff, and other factors. Human experience reflects the health and well-being of occupants, which can be measured through physiological responses or opinions and perceptions.

Every time we link design or engineering intent and real-world actions with outcomes, we create new performance dimensions that can be used to stratify and compare projects. Combinations of intent, actions, and outcomes are enabled by search, compare, and benchmarking information technologies. The integration of these new streams of data and analytical tools will provide a foundation for the next generation of performance-oriented, evidence-based practices.

Clearly, we will have to place more emphasis on the management of information for the entire life cycle of a project, design and engineering intentions, documentation of actions and implementation strategies (e.g., service providers, products, etc.), and performance monitoring and evaluation systems explicitly linked to intended outcomes. All of these elements will be built into increasingly integrated information ecosystems that span the life cycle of built environments and the length and breadth of the supply chains that support them. This emerging ecosystem will support a pervasive network of data producers and information consumers seeking to create value and gain competitive advantage through superior performance.

Conclusion

The success of green building over the past decade attests to the efficacy of using relatively simple information-based interventions to produce demonstrable market transformations. In the coming decade, we will need new tools and approaches to bring these concepts to scale and to generate the pace of change necessary to achieve our mission of creating sustainable, healthy, high-performance built environments.

I believe this change will be powered by a new generation of data and information technologies specifically designed to promote market-based competition across multiple performance dimensions, to understand and learn from high performers, and to recognize and improve low performers. Every performance dimension we track provides an opportunity for competitive differentiation. Every high-performing project we identify and rank provides an opportunity for learning, recognition, and reward. Every low-performing project we touch provides an opportunity for education, investment, and improvement.

The critical technologies, such as customized search engines, distributed sensors, social media, service-based software architectures, and cloud solutions, are either already in hand or are rapidly emerging. With these tools, we will be able to engage orders-of-magnitude more projects and, ultimately, move from episodic certification to continuous performance and real-time monitoring. We can already see the contours of this new world, its sweeping implications for green building practices, and the built environments we may someday inhabit.

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Brain-computer interfaces create alternate communication channels for people with severe motor impairment.

The Evolution of Brain-Computer Interfaces

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The ability to enable the brain to control an external device with thoughts alone is emerging as a real option for patients with motor disabilities. The goal of this area of study, known as *neuroprosthetics*, is to create devices, known as *brain-computer interfaces* (BCIs), that can acquire brain signals and translate them into machine commands that reflect the intentions of the user. In the past 20 years, neuroprosthetics has progressed rapidly from fundamental neuroscientific discovery to initial translational applications.

Seminal discoveries beginning in the 1980s demonstrated that neurons in motor cortex, when taken as a population, can predict the direction and speed of arm movements in monkeys (Georgopoulus et al., 1982, 1986; Moran and Schwartz, 1999b). In subsequent decades, these findings were translated into increasing levels of brain-derived control in monkeys and then to preliminary human clinical trials (Hochberg et al., 2006; Taylor et al., 2002).

In recent years, an emerging understanding of how cortex encodes motor and non-motor intentions, sensory perception, and the role of cortical plasticity in device control have led to new insights into brain function and BCI applications. These new discoveries have greatly increased the potential of neuroprosthetics in terms of control capability and the variety of patient populations that can be helped. This article provides an overview of current BCI modalities and emerging research on the use of motor and non-motor areas for BCI applications and assessments of their potential clinical impact.

Brain-Computer Interfaces: Definition and Essential Features

A BCI is a device that can decode human intent from brain activity alone, thus creating an alternate communication channel for people with severe motor impairment. Explicitly, a BCI does not require the "brain's normal output pathways of peripheral nerves and muscles" to facilitate interaction with the environment (Wolpaw et al., 2000, 2002). A real-world example would be a quadriplegic subject who can control a cursor on a screen with signals derived from individual neurons recorded in primary motor cortex without the need for overt motor activity. It is important to emphasize that a true BCI creates a completely new output pathway for the brain.

As a new output pathway, the user must have feedback to improve how he or she alters electrophysiological signals. Similar to the development of a new motor skill (e.g., learning to play tennis), there must be continuous alteration of the subject's neuronal output.

This requires that the output be matched against feedback from the intended actions so that the output (swinging the tennis racket or altering a brain signal) can be tuned to optimize performance to reach the intended goal (hitting the ball over the net or moving a cursor toward a target). Thus, the brain must change its signals to improve performance.

In addition, a BCI may also be able to adapt to the changing milieu of the user's brain to further optimize functioning. This dual adaptation requires a certain level of training and a learning curve, for both the user and the computer. The better the computer and subject are able to adapt, the shorter the training period to achieve control.

There are four essential elements to the practical functioning of a BCI platform (Figure 1). All four elements must work in concert to manifest the user's intention (Wolpaw et al., 2002):

- signal acquisition, the BCI system's recorded brain signal or information input
- signal processing, the conversion of raw information into a useful device command
- device output, the overt command or control functions administered by the BCI system
- operating protocol, the manner in which the system is altered and turned on and off

Signal Acquisition

Signal acquisition is a real-time measurement of the electrophysiological state of the brain. Brain activity is usually measured by voltage changes recorded via

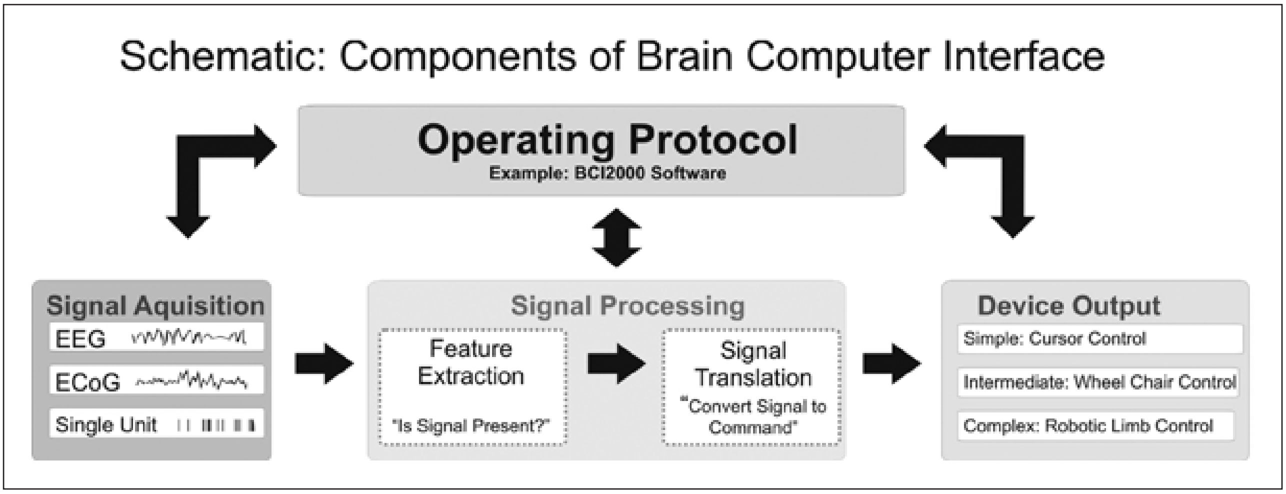

FIGURE 1 Essential features and components of a BCI. There are four essential elements to the practical functioning of a BCI platform: (1) signal acquisition, the BCI system's recorded brain signal or information input; (2) signal processing, the conversion of raw information into a useful device command; (3) device output, the overt command or control functions administered by the BCI system; and (4) operating protocol, the manner in which the system is turned on and off and the way the user or a technical assistant adjusts parameters of the previous three steps to convert intentions to machine commands. All four elements are essential to manifesting the user's intention (Schalk et al., 2004a). Source: Leuthardt et al., 2009. Reprinted with permission.

electrodes, either invasive (under the skin) or non-invasive (on the surface of the skin). Theoretically, other measurements, such as blood flow detected with magnetic resonance imaging (MRI), altered magnetic fields measured by magnetoencephalography (MEG), and optical signals, might be used for signal acquisition. However, none of these non-electrical signals is currently practical or feasible for clinical application.

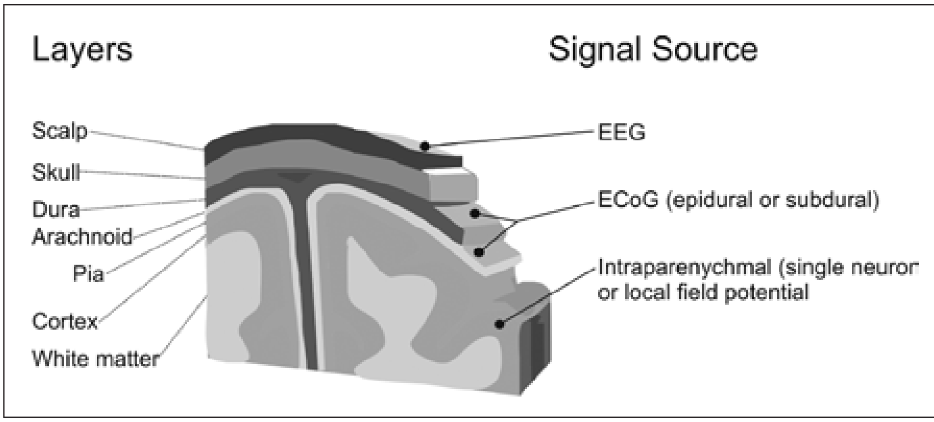

FIGURE 2 Signals for a BCI. The figure shows the three general categories of signals for BCI application and their anatomic location relative to the brain and its respective covering layers. EEG = electroencephalography; ECoG = electrocorticography. Source: Leuthardt et al., 2009. Reprinted with permission.

The most common types of signals include *electroencephalography* (EEG), electrical brain activity recorded from the scalp (Elbert et al., 1980; Farwell and Donchin, 1988; Freeman et al., 2003; Pfurtscheller et al., 1993; Sutter, 1992; Vidal, 1977); *electrocorticography* (ECoG), electrical brain activity recorded beneath the skull (Leuthardt et al., 2004, 2005; Schalk et al., 2004b); *field potentials*, electrodes that monitor brain activity from within the parenchyma (Andersen et al., 2004); and "*single units*," microelectrodes that monitor the firing of individual neuron action potentials (Georgopoulus et al., 1986; Kennedy and Bakay, 1998; Laubach et al., 2000; Taylor et al., 2002).

Figure 2 shows the relationship between various signal platforms in terms of anatomy and the population sampled. Once acquired, signals are digitized and sent to the BCI system for further interrogation.

Signal Processing

In the signal processing stage of BCI operation, there are two essential functions: feature extraction and signal translation. The first extracts significant identifiable information from the gross signal; the second converts that identifiable information into device commands.

Converting a raw signal into a meaningful one requires an array of analyses, from assessment of frequency power spectra, event-related potentials, and cross-correlation coefficients for analysis of EEG/ECoG signals to the directional cosine tuning of individual neuron action potentials (Levine et al., 2000; Moran and Schwartz, 1999b; Pfurtscheller et al., 2003).

The impetus for all of these analyses is to determine the relationship between an electrophysiologic event and a given cognitive or motor task. For example, after recordings are made from an ECoG signal, the BCI system must recognize that an alteration of the signal has occurred in the electrical rhythm (feature extraction) and then associate the change with a specific cursor movement (translation). As mentioned above, signal processing must be dynamic to adjust to the changing internal signal environment of the user.

Device Output

Overt action (actual device output) is then taken by the BCI. As in the previous example, this can result in moving a cursor on a screen, choosing letters for communication, controlling a robotic arm, driving a wheelchair, or controlling an intrinsic physiologic process, such as moving a limb or controlling bowel and bladder sphincters (Leuthardt et al., 2006b).

Operating Protocol

An important consideration for practical applications of BCI devices is the overall operating protocol. This refers to the manner in which the user controls *how* the system functions. The *how* includes, for example, turning the system on or off, controlling the kind of feedback and how fast it is provided, controlling the speed at which the system implements commands, and switching between device outputs.

The way the system functions is critical for BCI functioning in real-world applications. In most current research protocols, the parameters are set by the investigator. In other words, the researcher turns the system on and off, adjusts the speed of interaction, and defines very limited goals and tasks. These are all things the user will eventually have do by him(her)self in an unstructured applied environment.

Current BCI Platforms

To date, three general categories of BCI platforms have been put forward as possible candidates for clinical application: EEG-based systems; single unit systems; and ECoG-based systems, an intermediate modality. The categories are primarily determined by the source from which the controlling brain signal is derived—the scalp, intraparenchymal neurons, or the cortical surface. The current status of each of these platforms is described below in terms of level of control, surgical considerations, and clinical population.

EEG is currently the only modality that has been shown to actually help people with paralysis.

Electroencephalography-Based Systems

EEG-based BCIs derive brain signals from electrical activity recorded from the scalp (Birbaumer et al., 1999; Blankertz et al., 2006; Farwell and Donchin, 1988; Kübler et al., 2005; McFarland et al., 1993, 2008b; Millan et al., 2004; Muller et al., 2008; Pfurtscheller et al., 1993, 2000; Sutter, 1992; Vaughan et al., 2006; Wolpaw et al., 1991; Wolpaw and McFarland, 1994, 2004). EEG-based BCIs are the most common for studies in humans, probably because this recording method is convenient, safe, and inexpensive.

EEG provides relatively poor spatial resolution, because a large brain area must be involved to generate detectable signals (Freeman et al., 2003; Srinivasan et al., 1998). Despite this limitation, signals relevant to BCI research can still be obtained from EEG, including modulations of mu (8–12 Hz) and beta (18–25 Hz) rhythms produced by sensorimotor cortex. These rhythms show non-specific changes (typically decreases in amplitude) related to movements and movement imagery, but they do not provide specific information about the details of movements, such as the position or velocity of hand movements. This may be an important limitation, because signals associated with specific movement parameters are typically used in BCI systems based on action-potential firing rates.

Another limitation of EEG recordings is that the detected amplitudes are very small. This makes them susceptible to artifacts created by sources outside the brain, such as electromyographic (EMG) signals produced by muscle contractions.

Despite these limitations, EEG-based BCIs have been shown to support higher performance than might be expected, including accurate two-dimensional (McFarland et al., 2008b; Wolpaw and McFarland, 2004) and even three-dimensional control of a computer cursor (McFarland et al., 2008a). To date, the large majority of clinical applications of BCI technologies for people with severe motor disabilities have been demonstrated using EEG (Kübler et al., 2005; Nijboer et al., 2008; Vaughan et al., 2006).

Ultimately, however, the intrinsic lack of signal robustness may have important implications for chronic applications of BCI systems in real-world environments. BCI systems based on EEG typically require substantial training (Birbaumer, 2006; Wolpaw and McFarland, 2004) to achieve accurate one- or two-dimensional device control (about 20 and 50 30-minute training sessions, respectively), although some studies have reported shorter training requirements (Blankertz et al., 2006). Nevertheless, noise sensitivity and prolonged training are fundamental limitations in the widespread clinical application of EEG-based BCIs.

In summary, EEG has been shown to support much higher performance than was previously assumed and is currently the only modality that has been shown to actually help people with paralysis. However, because of significant limitations, it is currently not clear to what extent EEG-based BCI performance, in the laboratory and in clinical settings, can be improved.

Single Neuron-Based Systems

From a purely engineering point of view, the optimal method of extracting electrical information from the brain would be to place a series of small recording electrodes directly into the cortical layers (1.5–3 mm) to record signals from individual neurons. In essence, this is what single-unit action-potential BCI systems do. Such systems have been very successful for limited time periods in both monkeys (Carmena et al., 2003; Serruya et al., 2002; Taylor et al., 2002; Velliste et al.,

2008) and humans (Hochberg et al., 2006; Kennedy and Bakay, 1998).

To extract single-unit activity, small microelectrodes with ~20 micron diameter tips are inserted into the brain parenchyma where relatively large (e.g., 300 microvolt) extracellular action potentials have been recorded from individual neurons 10–100 microns away. These signals are usually band-passed filtered from 300–10,000 Hz and then passed through a spike discriminator to measure time intervals between spikes.

The firing rates of individual neurons are computed in 10 to 20 millisecond bins and "decoded" to provide high-fidelity control of either a computer cursor or robot endpoint kinematics (Georgopoulus et al., 1986; Moran and Schwartz, 1999a; Wang et al., 2007). Given its high spatial resolution (100 microns) and high temporal resolution (50–100 Hz), this modality arguably provides the highest level of control in BCI applications.

Unfortunately, there are two major problems with single-unit BCIs. First, the electrodes must penetrate into the parenchyma where they cause local neural and vascular damage (Bjornsson et al., 2006). This can initiate a cascade of reactive cell responses, typically characterized by activation and migration of microglia and astrocytes toward the implant site (Bjornsson et al., 2006).

Second, single-unit, action-potential microelectrodes are very vulnerable to encapsulation. The continued presence of electrodes promotes the formation of a sheath composed partly of the reactive astrocytes and microglia (Polikov et al., 2005; Szarowski et al., 2003). This reactive sheath can have numerous deleterious effects, including neural cell death and tissue resistance that electrically isolates the device from the surrounding neural tissue (Biran et al., 2005; Szarowski et al., 2003; Williams et al., 2007).

Research into novel biomaterial coatings and/or local drug delivery systems that may reduce the foreign body response to implanted electrodes is ongoing. So far, however, the results are far from clinical application (Abidian and Martin, 2008; Seymour and Kipke, 2007; Spataro et al., 2005). The development of a long-term BCI system based on single-unit activity may be delayed until these issues have been resolved.

Electrocorticography-Based Systems

Over the past five years, enthusiasm has been mounting for ECoG, a more practical and robust platform for BCI in clinical application. As detailed above, both EEG and single-unit-based systems have serious limitations for large-scale clinical application, either because of prolonged user training and poor signal-to-noise limitations with EEG or because of the inability of single-unit constructs to maintain a consistent signal (Bjornsson et al., 2006; Szarowski et al., 2003; Wolpaw and McFarland, 2004).

ECoG-based systems might be an ideal trade-off for practical implementation (Leuthardt et al., 2005). Compared to EEG, the ECoG signal is substantially more robust. Its magnitude is typically five times larger, its spatial resolution is much greater (0.125 versus 3.0 cm for EEG), and its frequency bandwidth is significantly higher (0–500 Hz versus 0–40 Hz for EEG) (Boulton et al., 1990; Freeman et al., 2003; Srinivasan et al., 1998). The latter quality, access to higher frequency bandwidths, promises particularly useful information for BCI operation (Gaona et al., 2011).

Many studies have demonstrated that different frequency bands carry specific, anatomically distinct information about cortical processing. Lower frequency bands, known as mu (8–12 Hz) and beta (18–26 Hz), which are detectable with EEG, are thought to be produced by thalamocortical circuits. These bands show broad anatomic decreases in amplitude in association with actual or imagined movements (Huggins et al., 1999; Levine et al., 1999; Pfurtscheller et al., 2003; Rohde et al., 2002).

ECoG-based systems might be an ideal trade-off for practical implementation.

The higher frequencies, also known as gamma activity, are only appreciable with ECoG. Gamma activity, which is thought to be produced by smaller cortical assemblies, shows close correlation with the action-potential firing of tuned cortical neurons in primary motor cortex in monkey models (Heldman et al., 2006). In addition, high-frequency changes have been associated with numerous aspects of speech and motor function in humans (Chao et al., 2010; Crone et al., 1998, 2001a,b; Gaona et al., 2011; Leuthardt et al., 2004; Schalk et al., 2007).

Besides providing more information content, because the ECoG signal is recorded from larger electrodes that do not penetrate the brain, ECoG sensors should have a higher likelihood of long-term clinical durability. This expectation is supported by some pathologic and clinical evidence. For example, in cat, dog, and monkey models, long-term subdural implants showed minimal cortical or leptomeningeal tissue reaction while maintaining prolonged electrophysiologic recording (Bullara et al., 1979; Chao et al., 2010; Loeb et al., 1977; Margalit et al., 2003; Yuen et al., 1987).

So far, ECoG for BCI applications has primarily been studied in motor-intact patients with intractable epilepsy that requires invasive monitoring. Preliminary work in humans using the implantable NeuroPace device for the purpose of long-term subdural electrode monitoring for the identification and abortion of seizures has been shown to be stable (Vossler et al., 2004).

Similar to EEG-based BCI systems, the ECoG approach has primarily focused on changes in sensorimotor rhythms from motor cortex. The major difference has been access to higher frequency gamma rhythms with ECoG, which provide significant advantages in training requirements and multidimensional control.

In 2004, Leuthardt et al. demonstrated the first use of ECoG in closed-loop control in a one-dimensional cursor-control task with minimal training requirements (under 30 minutes). In additional experiments, the same group and others have demonstrated that specific frequency alterations encode very specific information about hand and arm movements (Leuthardt et al., 2004; Pistohl et al., 2008; Sanchez et al., 2008; Schalk et al., 2007). In 2006, Leuthardt et al. (2006a) further demonstrated that ECoG control using a signal from the epidural space was also possible.

Schalk et al. (2008) has shown that ECoG signals can be used for two-dimensional control with performance in the range of typical performance before the testing of invasive single-unit systems. Because ECoG electrode arrays cover broad regions of cortex, several groups have begun to explore alternate cognitive modalities and their cortical physiologies to expand BCI device control. Felton et al. (2007) have shown that, in addition to motor imagery, sensory imagery can also be used for device control. The same group demonstrated that auditory cortex could be trained to acquire simple control of a cursor (Wilson et al., 2006).

Ramsey et al. (2006) showed that higher cognitive functions, such as working memory in the dorsal lateral prefrontal cortex, can also be used for effective device operation. Recently, Leuthardt et al. (2011) demonstrated that phonemic content taken from speech networks could be used for simple device control.

Taken together, these studies show that ECoG signals carry a high level of specific cortical information and that these signals can enable a user to gain control rapidly and effectively. It is worth noting, however, that so far these control paradigms have not been extended to motor-impaired subjects. The effects on cortical signals in the setting of a spinal cord injury or amyotrophic lateral sclerosis (ALS) have not been explicitly tested.

Conclusions

The field of neuroprosthetics is growing rapidly as the cortical physiology that underpins the way a human brain encodes intentions is beginning to be understood. This understanding will have a significant impact in improving function for people with various forms of motor disability. As research moves beyond motor physiology, the field of neuroprosthetics is poised to increase its capabilities and serve the needs of a more diverse clinical population. The evolving understanding of cortical physiology as it relates to motor movements, language function, and plasticity, could all provide higher levels of complexity in brain-derived control.

Given the rapid progression of these technologies over the past decade and the concomitant rapid increase in computer processing speed, signal analysis techniques, and emerging ideas for novel biomaterials, we can be hopeful that in the near future neuroprosthetic implants will be as common as deep brain stimulators are today. The clinical advent of this technology will usher in a new era of restorative neurosurgery and new human-machine interfaces.

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Researchers are working on implantable neurostimulators to treat debilitating neurological conditions, including blindness.

Retinal Prosthetic Systems for the Treatment of Blindness

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Most functions of the human body are controlled by small electrical signals delivered via nerves. Thus, it is no surprise that electrical signals applied to the body from external sources can modulate physiological activity. In fact, reports of physiological electromodulation date back to the eighteenth century, but scientists of that time did not know enough about neurophysiology to understand the basic mechanism by which electricity could modulate biological activity. Today, with many advances in neurobiology, medicine, and engineering, we can inform the design of clinically beneficial, implantable neurostimulation devices to treat a number of debilitating neurological diseases.

Neurostimulators

Implantable neural stimulators activate nerve cells, which are responsible for processing and communicating information between the brain and other parts of the body (Kandel et al., 1991). Specialized nerve cells called sensory receptors convert physical stimuli into electrical signals that can be relayed by other nerve cells to the brain. Because nerve cells are polarized,

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an electrical potential can be measured across the cell membrane. Transient changes in membrane potential signal to other cells that an event has occurred, and neural networks, composed of connected neurons, determine if that event, along with input from other cells, requires action by other parts of the nervous system. Events such as the onset of disease or an injury that damages nerve cells, particularly sensory cells, can result in significant disability for the affected individual, including loss of sensory input, diminished capability to process information, or reduced motor function.

How Electrostimulation Works

Activating a nerve cell by an electrical signal generated by an implanted device is more complicated than connecting two wires. The complexity arises partly from differences in carriers of the electrical charge. In metals, electrons carry the charge, whereas in the body, ions carry the charge. The conversion from electrons to ions occurs at the electrode, typically a metal or metal oxide, in direct contact with the extracellular fluid. An electrical signal applied to the electrode causes current to flow in the tissue via the movement of charged sodium, chloride, potassium, and other ions.

The end effect is to depolarize the nerve cell membrane. Depolarization beyond a certain level results in an action potential (as is the case with natural neural signaling). An electrode has this affect on many neurons in its vicinity, and the summed activity of these neurons is an electrically elicited sensation or modulated function.

Successful Neurostimulators

A number of successful neurostimulators are in widespread use. For example, cochlear implants stimulate the auditory nerve enabling deaf people to hear, often well enough to talk on a telephone. Implantable neurotransmitters can also relieve unrelenting pain that sometimes results from nerve damage or disease. For example, implantable devices that stimulate the lower spinal cord are known to decrease or even eliminate the feeling of pain.

A dramatic example of electrical stimulation is in the treatment of Parkinson's disease. By stimulating a part of the brain called the thalamus, many symptoms of Parkinson's subside almost immediately. Parkinson's patients with uncontrollable tremor or rigidity that severely limits motor function show improved coordination within minutes of commencing stimulation.

Treating Blindness with Electrical Stimulation

Causes of Blindness

The retina is a light-sensitive, multilayer tissue that lines the interior surface of the back of the eye (Figure 1) (see *http://webvision.med.utah.edu/*). Photoreceptors (rods and cones) are the light-sensing cells of the retina; the other cells process photoreceptor signals and send information to the brain via the optic nerve. When photoreceptors degenerate due to disease, the retina can no longer respond to light. However, sufficient numbers of other retinal nerve cells remain so that the electrical stimulation of these cells results in the perception of light.

Diseases such as retinitis pigmentosa and age-related macular degeneration cause blindness for millions of people (Gehrs et al., 2010; Hartong et al., 2006) and are presently untreatable. At first, symptoms are subtle, such as difficulty seeing at night or blurred central vision, but ultimately, these conditions result in blindness. Given that vision is the sense by which people obtain most of their information about their surroundings, blindness has an extremely detrimental impact on the afflicted.

The Development of Electrical Stimulation

Electrical stimulation has been proposed as a treatment for blindness for decades, but only recently have systems consistent with clinical use been developed. The first documented use of electrical stimulation to create visual perception dates to 1755, when Charles LeRoy discharged a large capacitor through the head of

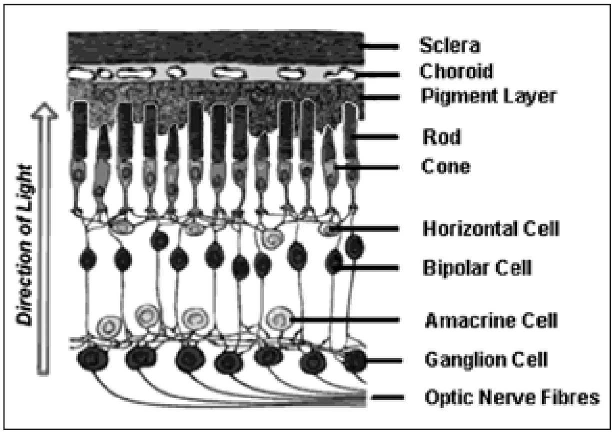

FIGURE 1 Cross section of the retina and other layers of the eye (choroid and sclera). The rods and cones are the photoreceptors that sense light. The other cells process this information and transmit electrical impulses to the brain via optic nerve fibers. Source: Image from *http://www.catalase.com/retina.gif*.

a blind person, who described seeing "flames descending downwards" (Marg, 1991). Over time, as science, medicine, and engineering have progressed, it has become feasible to develop a permanent implant to stimulate the retina.

Initial clinical experiments that provided proof-of-principle involved briefly inserting a handheld electrode into the eye of a blind person, stimulating the retina, and asking the person to describe what he or she saw, if anything, and to describe the sensation (Humayun et al., 1996; Rizzo et al., 2003). These simple yet essential experiments established initial design parameters for a permanent implantable device.

Retinal Prostheses: General Description and Current Clinical Systems

General Description

A retinal prosthesis consists of several components that perform specific functions: a camera that converts photons to digital data; a processing unit that generates stimulus commands based on the image; analog drivers that produce stimulus current; and an array of stimulating electrodes to deliver stimulus current to the retina (Weiland et al., 2005).

As shown in Figure 2, the electrode array can be positioned in two locations in the eye, the epiretinal surface and the subretinal space. These anatomical locations have come to define the two basic approaches being investigated for retinal prostheses. An epiretinal implant would rest on the inner limiting membrane of the retina, whereas a subretinal implant would be inserted into the space occupied by photoreceptors in a healthy retina.

Several clinical trials have been conducted to test systems in blind humans. For the sake of brevity, only the trials that have produced the most significant results are discussed below.

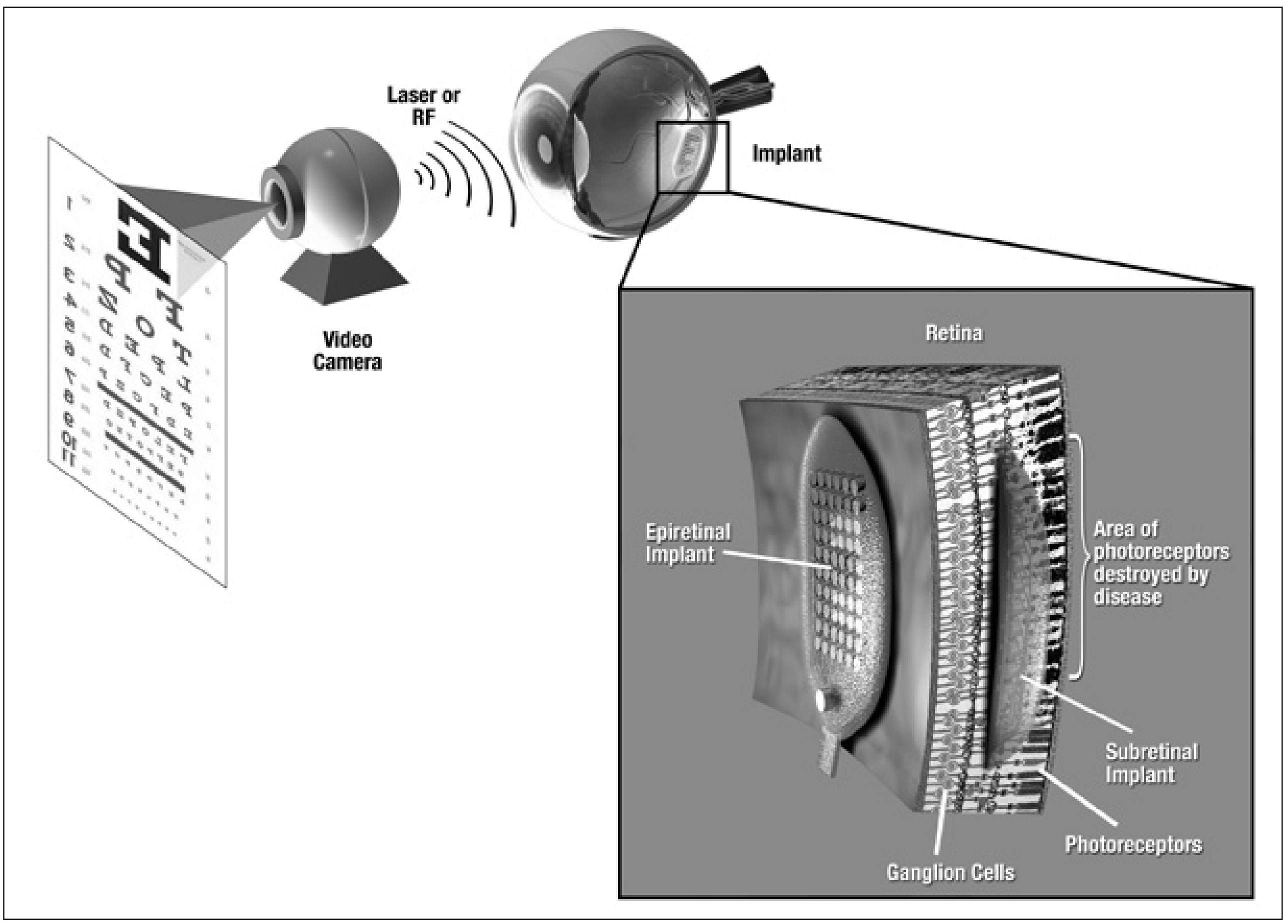

FIGURE 2 The retinal prosthesis concept. An image is captured by a camera and transmitted to an implant. The implant applies a patterned, complex stimulus to the retina via an array of electrodes on the surface of the retina (epiretinal) or underneath the retina (subretinal). Source: Image courtesy of Annual Review of Biomedical Engineering.

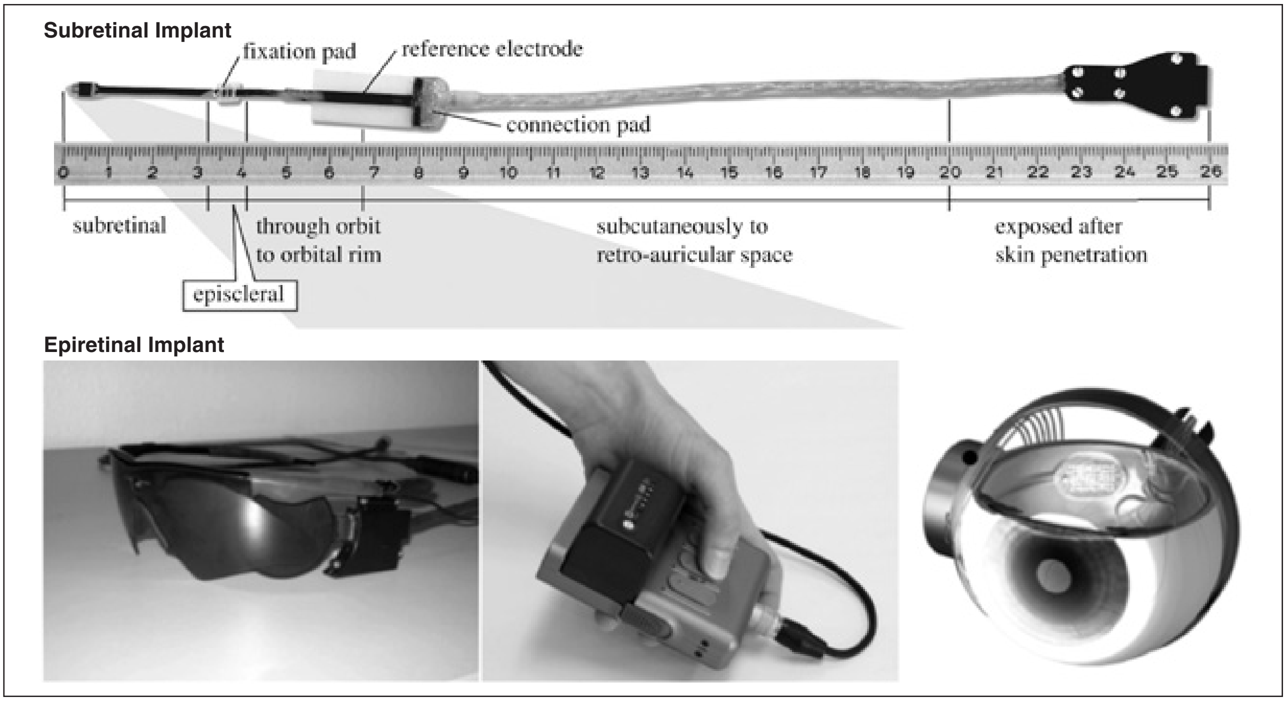

FIGURE 3 (top) A subretinal implant developed by Retina Implant GmbH has been tested in 12 subjects. The microphotodiode array implanted in the subretinal space is to the far left. The remainder of the implant consists of cabling connected to external test equipment. (bottom) The epiretinal implant system developed by Second Sight Medical Products Inc., includes (left) a videocamera mounted in a pair of glasses, (center) a wearable image-processing system, and (right) an epiretinal implant with components inside and outside the eye. Stimulus commands generated by the wearable image-processing system are transmitted wirelessly to the implant via an inductive coil in the glasses frame. Source: Images courtesy of Proceedings of the Royal Society and the British Journal of Ophthalmology.

Subretinal Implant

An externally powered, subretinal microphotodiode array (Figure 3 top), developed by Retinal Implant GmbH, has been tested in 12 subjects (Zrenner et al., 2011). The device has 1,500 repeating units on a single silicon chip. Each unit has the following elements: a microphotodiode that senses light, digital and analog circuitry that scales a voltage stimulus based on the sensed light, and a microelectrode that applies the stimulus to the retina. The voltage stimulus pulse is supplied by a source outside the eye.

The best test subject was able to read large letters (although it took a long time to do so) and demonstrated visual acuity of approximately 20/1,000. Other subjects showed pattern recognition, light detection, and object discrimination.

Epiretinal Implant

The ARGUS II retinal prosthesis (produced by Second Sight Medical Products Inc.)[1] has been implanted in 30 subjects (Figure 3, bottom). The device has 60 electrodes and an external camera unit that delivers image information wirelessly to the implant. The best result to date for visual acuity is 20/1,200 (Humayun et al., 2011).

Twenty-two of the 30 subjects were able to read letters. However, with the ARGUS II device (as with the subretinal device described above), reading letters took much longer than reading with natural vision. ARGUS II subjects also demonstrated improved mobility, could sense the direction of a moving object, and had improved hand-eye coordination (Ahuja et al., 2011).

Assessing the Results

The results described above for both devices have generated considerable excitement among researchers in ophthalmology, vision, and biomedical engineering. The possibility of restoring vision has captured the imagination of many, and reports from the human test subjects testify to the promise of an implantable retinal prosthesis. In controlled tests, improved mobility was clearly evident, and subjects reported more confidence during ambulation.

[1] Dr. Humayun has a financial interest in Second Sight Medical Products Inc.

Nevertheless, based on an objective analysis of the data as a whole, one must conclude that we are a long way from being able to claim "restored vision." By all measures, the tested individuals are still considered blind, even when the devices function well. The best reported visual acuity was 20/1,000, whereas the cutoff for legal blindness is 20/200 (normal vision is 20/20).

In addition, the field of view is limited. The field for ARGUS II extends to 20 degrees (the limit for legal blindness), but natural vision has a 180-degree field of view. The subretinal results were even more limited, with current implants providing a field of view of less than 15 degrees.

Challenges for Artificial Vision

Meeting the Basic Challenges

We will need both technical and biological advances to increase visual acuity with future implants. For instance, simulations of artificial vision project that about 1,000 individual pixels are necessary for visual function such as reading (at near normal speed) and face recognition. To reach this goal, we will need improvements in electronic packaging (the materials and assembly techniques that protect the circuits from saline). This will be particularly important for the subretinal device described above, which now relies on a thin-film approach to protecting the subretinal electronics, because a thick enclosure does not fit in the subretinal space. In addition, low-power integrated circuits must be developed that can both generate an effective stimulus pattern to evoke form perception and use power efficiently to ensure safety.

Connecting Electrodes to the Retina

Even if the barriers described above can be overcome, we need a better understanding of how to connect the device to the retina and how the brain will respond to this type of input.

The subretinal device described above has 1,500 electrodes, but it does not achieve the visual acuity that would be possible if each electrode were acting independently. Higher visual acuity will require electrode arrays that are densely packed with small electrodes. However, to take advantage of this density, the electrode arrays must be consistently positioned in close contact with the retina.

Inconsistent positioning of the electrode array has been a major barrier for epiretinal implants. If electrode arrays can be developed that can conform to the surface of the retina and account for anatomical variations among patients, each electrode will be able to activate a small part of the retina, thereby increasing visual acuity.

Improving Stimulation and Rehabilitation

Better stimulation strategies will be necessary for perceptions to appear more natural. Currently, perceptions fade within seconds as neural adaptation mechanisms attenuate the artificial input. Researchers must focus on optimizing stimulus protocols to maximize user performance. Finally, rehabilitation strategies will be necessary to train users to maximize their performance with the implant.

The "Optogenetic" Approach

A new approach to artificial vision could potentially address some of the problems encountered with electronic retinal prostheses. The "optogenetic" technique would modify individual neurons to incorporate light-sensitive ion channels into the cell membrane; the most common light-sensitive channel is channelrhodopsin2 (ChR2) (Gradinaru et al., 2010). Ion channels are the means by which ions pass through the cell membrane, and membrane potential is influenced by whether channels are open or closed. When light of a specific wavelength is shone on the cell, ChR2 ion channels open, resulting in depolarization of the cell.

> *A new, "optogenetic" approach to artificial vision might address some of the problems encountered with bioelectronic prostheses.*

Bi et al. (2006) first demonstrated that this technique could be used to modify retinal ganglion cells, showing that light-evoked neural responses were present in a mouse model of retinal degeneration when the mouse retinal cells contained ChR2. Others have since expanded on this work.

Advantages

The optogenetic approach has some significant advantages over the bioelectronic approach. By making each cell light sensitive, vision can potentially be restored to near-normal acuity. Also, by using light as the activating signal, the optics of the eye can focus an image on the retina. In other words, the optogenetic technique can come much closer to restoring natural vision than bioelectronic approaches.

Disadvantages

Artificial vision based on optogenetics also has challenges that preclude clinical use. The main issue relates to sensitivity.

Currently, modified cells require that bright blue light (460 nm) be activated, roughly 7 orders of magnitude above the light-sensitivity threshold of normally sighted people. Thus, an external apparatus would still be required to convert an image from a camera into a light stimulus that interacts with the modified cells. In addition, it is not known if cells can be modified permanently, or if repeated injections would be needed.

Finally, it is not clear how such intense light would interact with a diseased retina, which has only remnant light sensitivity. A common symptom of retinitis pigmentosa, for example, is photophobia (discomfort in bright light), which is clearly not compatible with a therapy that requires intense light input into the eye.

Summary

These are interesting times for researchers on retinal prostheses. Clinical trials have shown both the promise and limitations of electrical stimulation as a treatment for blindness. People working in this field are constantly reminded of the wondrous sense of vision available to most of us, how reliant we are on our vision, and the devastating impact of vision loss. Given the complexity of vision, for the foreseeable future, prosthetic vision systems will clearly provide vision that is artificial in appearance and below the resolution necessary for complex, visually guided tasks.

However, even a slight improvement in vision can have a significant impact on quality of life. Restoring a person's ability to see large objects and detect motion can increase confidence for navigating through unfamiliar environments. In addition, the brain has an amazing ability to adapt to new input, and an individual, through experience and training, can use other contextual and sensory information to improve his or her understanding of what is being "seen" via an artificial vision system.

Although important breakthroughs have been made, this field is still in the early stages. Moving toward the restoration of high-acuity vision will require concerted efforts by scientists, engineers, clinicians, and, most important, blind patients.

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NAE News and Notes

Class of 2012 Elected

In February, NAE elected 66 new members and 10 new foreign associates, bringing the number of U.S. members to 2,254 and the number of foreign associates to 206. Engineers are elected to NAE for outstanding contributions to "engineering research, practice, or education, including . . . significant contributions to the engineering literature" and to "new and developing fields of technology, . . . major advancements in traditional fields of engineering, or . . . innovative approaches to engineering education." A list of newly elected members and foreign associates follows, with primary affiliations at the time of their election and brief descriptions of their principal accomplishments.

Mark Adamiak, director of advanced technologies, GE Digital Energy Multilin, Wayne, Pennsylvania. For contributions to power system protection, control, monitoring, and communications.

Robert D. Allen, senior manager, Advanced Materials Chemistry Department, IBM Almaden Research Center, San Jose, California. For innovations in chemistries and materials for semiconductor manufacturing.

Michael I. Baskes, adjunct professor, Department of Mechanical and Aerospace Engineering, Jacobs School of Engineering, University of California, San Diego, La Jolla. For contributions to the embedded atom method for predicting the structure and properties of metals and alloys.

Craig H. Benson, Wisconsin Distinguished Professor, director of sustainability research and education, and chair of Civil and Environmental Engineering and of Geological Engineering, University of Wisconsin, Madison. For improvements in design, construction, and monitoring of earthen liners and covers for municipal, hazardous, and radioactive waste landfills.

Barbara D. Boyan, professor and Price Gilbert Jr. Chair in Tissue Engineering; associate dean for research, College of Engineering; and Georgia Research Alliance Eminent Scholar, Wallace H. Coulter Department of Biomedical Engineering, Institute for Bioengineering and Bioscience, Georgia Institute of Technology, Atlanta. For engineering implant technologies for bone and cartilage repair.

Mary C. Boyce, Ford Professor of Engineering and department head of Mechanical Engineering, Massachusetts Institute of Technology, Cambridge. For contributions to understanding the mechanics of deformation in engineered and natural polymeric solids.

Joan F. Brennecke, Keating-Crawford Professor of Chemical and Biomolecular Engineering and director of the Energy Center, University of Notre Dame, Notre Dame, Indiana. For innovation in the use of ionic liquids and supercritical fluids for environmentally benign chemical processing.

Max William Carbon, Professor Emeritus of Nuclear Engineering, University of Wisconsin, Madison. For establishing engineering educational programs for nuclear reactor design and safety.

George M. Church, director, Center for Computational Genetics, and professor of genetics, Harvard Medical School, Boston. For contributions to human genome sequencing technologies and DNA synthesis and assembly.

Jared L. Cohon, president and professor of civil and environmental engineering, Carnegie Mellon University, Pittsburgh. For contributions to environmental systems analysis and national policy and leadership in higher education.

James J. Coleman, Intel Alumni Endowed Chair in Electrical and Computer Engineering, professor of materials science and engineering, and director of the Semiconductor Laser Laboratory, University of Illinois, Urbana-Champaign. For contributions to semiconductor lasers and photonic materials.

Louis Anthony (Tony) Cox Jr., president, Cox Associates, Denver, Colorado. For applications of operations research and risk analysis to significant national problems.

Robert L. Crippen, former astronaut and director of the NASA Kennedy Space Center; and retired president, Thiokol Propulsion Group, Palm Beach Gardens, Florida. For leadership in human space flight and development of solid fueled rockets.

Supriyo Datta, Thomas Duncan Distinguished Professor of Electrical and Computer Engineering, Purdue University, West Lafayette, Indiana.

For quantum transport modeling in nanoscale electronic devices.

Akhil Datta-Gupta, Regents Professor and L.F. Peterson '36 Chair, Harold Vance Department of Petroleum Engineering, Texas A&M University, College Station. For developing the theory and practice of streamline simulation for fluid flow in heterogeneous reservoirs.

William P. Delaney, Director's Office Fellow, MIT Lincoln Laboratory, Lexington, Massachusetts. For contributions to radar systems for national defense.

Steven P. DenBaars, Mitsubishi Chemical Professor in Solid State Lighting and Displays, Materials Department, University of California, Santa Barbara. For contributions to gallium nitride-based materials and devices for solid state lighting and displays.

Dennis E. Discher, Robert D. Bent Professor of Chemical and Biomolecular Engineering, University of Pennsylvania, Philadelphia. For elucidation of the effects of mechanical forces on cell physiology and stem cell development.

Elazer R. Edelman, Thomas D. and Virginia W. Cabot Professor of Health Sciences and Technology, Massachusetts Institute of Technology, Cambridge. For contributions to the design, development, and regulation of local cardiovascular drug delivery and drug eluting stents.

Gordon R. England, president, E6 Partners LLC, Arlington, Virginia. For advances in digital avionics for aircraft, land, and naval platforms.

Robert W. Farquhar, executive for space exploration, KinetX Inc., Tempe, Arizona. For deep space missions to asteroids and comets and for leading the NEAR mission to Eros.

Peter C. Farrell, founder, chairman, and chief executive officer, ResMed Inc., San Diego, California. For research and development of devices for treatment of sleep disorder breathing.

James R. Fienup, Robert E. Hopkins Professor of Optics; professor, Center for Visual Science; senior scientist, Laboratory for Laser Energetics; and professor of electrical and computer engineering; University of Rochester, Rochester, New York. For development and applications of phase retrieval algorithms.

Huajian Gao, Walter H. Annenberg Professor of Engineering, School of Engineering, Brown University, Providence, Rhode Island. For contributions to micromechanics of thin films and hierarchically structured materials.

William W. George, professor of management practice, Harvard Business School, Cambridge, Massachusetts. For applying engineering principles to manufacturing to advance health care.

Peter W. Glynn, Thomas W. Ford Professor and chair, Management Science and Engineering Department, Stanford University, Stanford, California. For contributions to simulation methodology and stochastic modeling.

Alan H. Gnauck, Distinguished Member of the Technical Staff, Bell Labs, Alcatel-Lucent, Holmdel, New Jersey. For contributions to high-speed, high-capacity lightwave communications systems.

Steven M. Gorelick, Cyrus F. Tolman Professor, Department of Environmental Earth System Science, Stanford University, Stanford, California. For optimization techniques and transport models for groundwater and the remediation of contaminated aquifers.

Alfred Grill, IBM Fellow, IBM Thomas J. Watson Research Center, Yorktown Heights, New York. For contributions to low dielectric constant insulators for the interconnects of very large scale integrated electronic devices.

Victoria F. Haynes, president and chief executive officer, RTI International, Research Triangle Park, North Carolina. For integrating research, economics, and social sciences to solve multidisciplinary problems.

Richard Hogg, Professor Emeritus of Mineral Processing and Geoenvironmental Engineering, Pennsylvania State University, University Park. For contributions to the science and engineering of coagulation and flocculation in particulate systems.

Ray R. Irani, executive chairman, Occidental Petroleum Corporation, Los Angeles, California. For leadership in the petrochemical industry and processes for applications of particulate systems.

James W. Jones, Distinguished Professor, Department of Agricultural and Biological Engineering, University of Florida, Gainesville. For contributions to understanding climate change, environmental impacts, and sustainable agricultural systems.

Mujid S. Kazimi, TEPCO Professor of Nuclear Engineering, professor of mechanical engineering, and director of the Center for Advanced Nuclear Energy Systems, Massachusetts Institute Technology, Cambridge. For contributions to technologies for the nuclear fuel cycle and reactor safety.

Richard Wilker Korsmeyer, senior research fellow and head of business development and licensing for pharmaceutical sciences, Pfizer Inc., New London, Connecticut. For contributions to drug delivery formulations and medical devices.

Helmut Krawinkler, John A. Blume Professor Emeritus of Engineering, Stanford University, Stanford, California. For development of performance-based earthquake engineering procedures for evaluating and rehabilitating buildings.

Fikri J. Kuchuk, fellow and chief reservoir engineer, Schlumberger Testing Services, Clamart, France. For contributions in pressure transient analyses for petroleum reservoirs.

Juan C. Lasheras, Stanford S. and Beverley P. Penner Distinguished Chair Professor of Engineering and Applied Sciences, Distinguished Professor of Engineering, and director of the Center for Medical Devices and Instrumentation, Institute of Engineering in Medicine, University of California, San Diego, La Jolla. For studies of atomization, turbulent mixing, and heat transfer and for the development of medical devices.

Kai Li, Paul M. Wythes '55, P'86 and Marcia R. Wythes P'86 Professor, Department of Computer Science, Princeton University, Princeton, New Jersey. For advances in data storage and distributed computer systems.

Henrique S. Malvar, chief scientist and Distinguished Engineer, Microsoft Research, Redmond, Washington. For contributions to multiresolution signal processing and multimedia signal compression and standards.

Tobin J. Marks, Charles E. and Emma H. Morrison Professor of Chemistry, professor of materials science and engineering, and Vladimir N. Ipatieff Professor of Catalytic Chemistry, Northwestern University, Evanston, Illinois. For innovation in electronic, photonic, and photovoltaic materials and catalytic polymerization.

Jyotirmoy Mazumder, Robert H. Lurie Professor of Mechanical Engineering, professor of materials science and engineering, director of the Center for Laser-Aided Intelligent Manufacturing, and director of the NSF I/UCRC for Lasers and Plasmas for Advanced Manufacturing, University of Michigan, Ann Arbor. For quantitative transport modeling for laser interaction and for the design and commercialization of direct metal deposition machines.

Diane M. McKnight, fellow of the Institute of Arctic and Alpine Research and professor of civil, environmental and architectural engineering, University of Colorado, Boulder. For elucidating the interrelationship between natural organic matter and heavy metals in streams and lakes.

Antonios Georgios Mikos, Louis Calder Professor of Bioengineering and Chemical and Biomolecular Engineering; director, J.W. Cox Laboratory for Biomedical Engineering; and director, Center for Excellence in Tissue Engineering; Rice University, Houston, Texas. For advances in tissue engineering, regenerative medicine, biomaterials, and drug delivery, including development of biodegradable polymers.

Richard K. Miller, president and professor of mechanical engineering, Franklin W. Olin College of Engineering, Needham, Massachusetts. For establishing a new paradigm for undergraduate engineering education and for the establishment of Olin College.

Robert A.K. Mitchell, consultant and retired vice president, Northrop Grumman Aerospace Systems, Redondo Beach, California. For development of autonomous unmanned aerial systems and their applications.

Philip M. Neches, chairman, Foundation Ventures LLC, New York City. For the architecture and software of parallel database appliances.

James J. O'Brien, consulting engineer, James J. O'Brien P.E., Riverton, New Jersey. For development of standards of practice for computerized scheduling of construction projects and capital programs.

Babatunde A. Ogunnaike, interim dean; William L. Friend Chair of Chemical Engineering; and professor, Center for Systems Biology-DBI; University of Delaware, Newark. For advances in process systems, process engineering practice, and systems engineering education.

Norbert Joseph Pelc, professor and associate chair for research of the Radiology Department, and professor of electrical engineering (by courtesy), Stanford University, Stanford, California. For development of algorithms and technologies for MRI, CT, and hybrid X-ray/MRI imaging.

Leonard Pinchuk, co-founder, president, and chief executive officer, Innovia LLC and Related Companies, Miami, Florida. For development of biomedical polymeric materials for angioplasty balloons, drug eluting stents, and other devices.

Andrea Prosperetti, Charles A. Miller Jr. Professor of Mechanical Engineering, Johns Hopkins University, Baltimore, Maryland. For contributions to the fundamentals and applications of multiphase flows.

Kaushik Rajashekara, chief technologist, Electric Power and Control Systems, Rolls-Royce Corporation, Indianapolis, Indiana. For contributions to electric power conversion systems in transportation.

Nambirajan Seshadri, senior vice president and general manager, Mobile Wireless Group, and chief technology officer, Mobile Platforms and Wireless Connectivity, Broadcom Corporation, Irvine, California. For contributions to wireless communications theory and development of mass market wireless technology.

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Christine A. Shoemaker, Joseph P. Ripley Professor of Engineering, School of Civil and Environmental Engineering, Cornell University, Ithaca, New York. For development of decision-making optimization algorithms for environmental and water resources problems.

Amit Singhal, Google Fellow, Google Inc., Mountain View, California. For contributions to information retrieval and search.

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David A. Stahl, professor, Department of Civil and Environmental Engineering, University of Washington, Seattle. For application of molecular microbial ecology to environmental engineering.

Rogers H. Stolen, Distinguished Visiting Professor in Materials Science and Engineering and faculty member in the Center for Optical Materials Science and Engineering Technologies, Clemson University, Clemson, South Carolina. For contributions to fiber nonlinear optics and invention of polarization preserving fiber.

Samuel I. Stupp, director, Institute for Bionanotechnology in Medicine; and Board of Trustees Professor of Materials Science, Chemistry, and Medicine; Northwestern University, Evanston, Illinois. For advances in processes of self-assembled polymers for biomedical applications.

Gordana Vunjak-Novakovic, vice chair and professor of biomedical engineering and director of the Laboratory for Stem Cells and Tissue Engineering, Columbia University, New York City. For bioreactor systems and modeling approaches for tissue engineering and regenerative medicine.

Michael S. Waterman, University Professor, USC Associates Chair in Natural Sciences, and professor of biological sciences, computer science, and mathematics, College of Letters, Arts, and Sciences, University of Southern California, Los Angeles. For development of computational methods for DNA and protein sequence analyses.

K. Dane Wittrup, C.P. Dubbs Professor of Chemical Engineering and Biological Engineering, and associate director, Koch Institute for Integrative Cancer Research, Massachusetts Institute of Technology, Cambridge. For developments in protein engineering, protein expression, and quantitative pharmacology.

Steven J. Zinkle, UT-Battelle Corporate Fellow and director, Materials Science and Technology Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee. For advancing understanding of radiation damage in metallic and ceramic components.

New Foreign Associates

E. (Edward) John Hinch, professor of fluid mechanics, Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, University of Cambridge, Cambridge, United Kingdom. For contributions to the mechanics of fluids, suspensions, and polymeric liquids and to industrial processes.

Sue E. Ion, consultant and visiting professor, Imperial College-London, Leyland, United Kingdom. For contributions to nuclear fuel development.

Frank P. Kelly, professor of the mathematics of systems and master of Christ's College, University of Cambridge, Cambridge, United Kingdom. For contributions to the theory and optimization of communication networks.

Kinam Kim, president, Samsung Electronics Company, Yongin-si, Gyeonggi-do, Korea. For contributions to semiconductor technologies for DRAM and nonvolatile memories.

Chao-Han Liu, Distinguished Visiting Scholar, Academia Sinica, Taipei, Taiwan. For contributions to ionospheric research and international leadership in atmospheric remote sensing.

Gennady A. Mesyats, director, P.N. Lebedev Physical Institute and vice president, Russian Academy of Sciences, Moscow. For development and application of pulsed power technology.

Pradip, chief scientist and head of the Process Engineering Lab, Tata

Research Development and Design Centre, Pune, India. For contributions to processing of minerals and waste materials.

P. Rama Rao, chairman, International Advanced Research Centre for Powder Metallurgy and New Materials (ARCI), Hyderabad, Andhra Pradesh, India. For advancing the understanding of deformation and fracture of structural materials and development of materials research infrastructure for societal needs.

Willem P.C. Stemmer, chief executive officer, Amunix Inc., Mountain View, California. For co-invention of directed evolution and development of protein therapeutic platforms.

Andrés Weintraub, professor, Department of Industrial Engineering, University of Chile, Santiago. For deployment of innovative decision support systems for natural and human resources in South America.

NAE Newsmakers

John E. Bowers, director, Institute for Energy Efficiency, and professor, Department of Electrical and Computer Engineering, University of California, Santa Barbara, is the recipient of the **2012 John Tyndall Award.** Professor Bowers was selected for international leadership in the development of novel optoelectronic devices, including "groundbreaking research in hybrid-silicon lasers and photonic integrated circuits." This hybrid technology lowers the cost of photonic subsystems, making it practical to apply optical communication technology in areas where it has been prohibitively expensive. The Tyndall Award is presented by the Optical Society and the IEEE Photonics Society. Professor Bowers received the award in Los Angeles during the plenary session of the 2012 Optical Fiber Communication Conference and Exposition/National Fiber Optic Engineers, March 4–8.

Anil K. Chopra, Johnson Professor of Structural Engineering, University of California Berkeley, has been included in the list of **"20 people who have made the biggest difference in dam engineering over the last 10 years."** Individuals on the list are selected by the editorial team of *International Water Power and Dam Construction Magazine* and industry experts based on nominations from people around the world. Dr. Chopra was selected for "pioneering methods for earthquake response analysis of structural systems, including dynamic interaction with soils and fluids" and for "encouraging students to study very tough issues associated with concrete dams (gravity and arch) since the 1980s." Dr. Chopra is also a consultant on earthquake engineering to numerous government and private organizations.

The Industrial Research Institute presented the **2011 IRI Medal** to **Uma Chowdhry,** senior vice president and chief science and technology officer at DuPont from 2006 until her retirement in 2010. She was honored for "championing innovations to advance environmentally sustainable solutions; building robust, multidisciplinary collaborations between R&D, marketing, and manufacturing to deliver competitively differentiated, customer-focused solutions worldwide; developing strategic partnerships with government, universities, and corporations to harness the creativity of the entire innovation ecosystem; championing the role of women in science and engineering; and mentoring science and engineering professionals."

Joseph DeSimone, Chancellor's Eminent Professor of Chemistry, University of North Carolina, and William R. Kenan Jr., Distinguished Professor of Chemical Engineering, North Carolina State University, will receive Sigma Xi's **2012 Walston Chubb Award for Innovation.** Dr. DeSimone has published more than 260 scientific articles, has been issued more than 115 patents in his name, and has another 120 patents pending. The Chubb Award, which has been given since 2006 to honor and promote creativity in science and engineering, includes a $4,000 honorarium and an invitation to deliver the Walston Chubb Award Lecture at Sigma Xi's annual meeting.

Solomon W. Golomb, Andrew and Erna Viterbi Professor of Communications and Distinguished University Professor, University of Southern California, has been selected as the recipient of Sigma Xi's **2012 William Procter Prize for Scientific Achievement.** Dr. Golomb is being honored for playing a key role in formulating the design of deep-space communications for lunar and planetary exploration, while he was assistant chief of the Telecommunications Research Section at the Jet Propulsion Laboratory. The Procter Prize has been presented annually since 1950.

John M. Kulicki, chairman and CEO of the bridge engineering firm Modjeski and Masters, is the recipient of the prestigious **J. Lloyd Kimbrough Award** "for significant achievements in bridge analysis and design." The award is presented by the American Institute of Steel Construction to honor pre-eminent engineers and architects who have made outstanding contributions to the structural steel industry through their design work. Dr. Kulicki will receive the award at the 2012 NASCC (North American Steel Construction Conference): The Steel Conference, which will be held in Dallas on April 18–21, 2012.

Louis J. Lanzerotti, Distinguished Research Professor of Physics, New Jersey Institute of Technology, was selected as the **2011 William Bowie Medalist** by the American Geophysical Union (AGU). Dr. Lanzerotti was honored for more than 40 years of contributions "to research on space plasmas and geophysics and engineering problems related to the impact of atmospheric and space processes on terrestrial and space technologies." The presentation was made at the Honors Ceremony at the 2011 AGU fall meeting in San Francisco on December 7, 2011. The Bowie Medal was established in 1939 in honor of William Bowie for his "spirit of helpfulness and friendliness in unselfish cooperative research."

Cleve B. Moler, chairman and Chief Scientist of The MathWorks, Inc., received the **IEEE Computer Society Sidney Fernbach Award**. Dr. Moler received a certificate and a $2,000 honorarium for "fundamental contributions to linear algebra, mathematical software, and enabling tools for computational science"— in November 2011 in Seattle at SC11, an international conference of high-performance computing, networking, storage, and analysis.

Shlomo P. Neuman, Regents' Professor, Department of Hydrology and Water Resources, University of Arizona, has been elected a "corresponding member" in the Class of Physical Sciences by the prestigious Bologna Academy of Sciences.

The Global Semiconductor Alliance (GSA) has announced that **Henry Samueli,** industry pioneer and co-founder and chief technology officer, Broadcom Corporation, is the winner of the **2011 Dr. Morris Chang Exemplary Leadership Award**. Dr. Samueli was presented with this lifetime achievement award during the GSA Awards Dinner Celebration on December 8, 2011.

The Association for Computing Machinery (ACM) and the IEEE Computer Society has awarded the **2011 Seymour Cray Computer Engineering Award** to **Charles L. Seitz**, researcher, writer, and consultant, and a founder of Myricom, Inc. The award is given in recognition of innovative contributions to high-performance computing systems that exemplify Seymour Cray's creative spirit. The winner receives a crystal memento, a certificate, and a $10,000 honorarium.

Changing the Conversation Is Now on *Facebook*

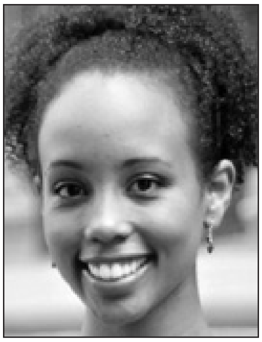
The 2008 report, *Changing the Conversation: Messages for Improving Public Understanding of Engineering*, presented a new positioning statement for engineering and some new, research-based messages and taglines. The new messages have been adopted by a number of engineering professional societies and a few schools of engineering, but by hardly any technology-focused companies.

To make the *Changing the Conversation* (CTC) report more widely available to the engineering community, NAE applied for and received support from NSF to create an online messaging "toolkit" (*www.engineereingmessages.org*), which was launched one year ago. The site provides background on the engineering messaging "problem" and tips for using messages, catalogs nearly 130 examples of messaging about engineering and case studies of successful messaging, and includes interactive features that enable members to share and discuss their work.

With support from the United Engineering Foundation (UEF), NAE recently launched a *Facebook* page (*www.facebook.com/engineersctc)* intended to build awareness and increase the adoption of CTC messages by new audiences, such as engineering administrators, faculty, and students; leaders in professional engineering societies; and leaders and mid-level managers in technology-intensive industries, particularly those responsible for communication, marketing, and hiring. The UEF-funded project will also promote the CTC messages and website through *Twitter* and *LinkedIn* and will monitor and interact with relevant blogs.

New Mirzayan Science and Technology Policy Graduate Fellows

Kristen Coakley



Mahlet Mesfin

Kristen Coakley received her Ph.D. in biomedical sciences from the University of California, San Francisco. She also holds a bachelor's degree in biological sciences from Mount Holyoke College. As a research technician and Ph.D. candidate, her interests were focused on the development and function of the adaptive immune system, including mechanisms underlying autoimmunity and lymphomagenesis.

While pursuing her Ph.D., Kristen designed and taught science lessons for grades 1–6 in the San Francisco Unified School District (SFUSD). She also volunteered on weekends as a docent at the California Academy of Sciences, with a focus on the Philippine coral reef and American swamp exhibits. Through her experiences as a volunteer, she discovered a love of conveying the implications of scientific research to the general public and an interest in making science education more effective.

At NAE, Kristen is working on the Integrated STEM Project. When she is not working, she loves to shop at farmers' markets and cook the tasty ingredients she finds there.

Mahlet Mesfin recently completed her Ph.D. in bioengineering at the University of Pennsylvania. Her dissertation topic was characterizing signaling pathways triggered in neurons after traumatic brain injury. Prior to attending Penn, she had earned a B.S.E. in chemical engineering and M.S.E. in biomedical engineering from the University of Michigan. In her 10 years of academic training and internships, she has conducted biomedical research on a wide range of subjects, including tissue engineering, lab-on-chip microdevices, and neurobiology.

At Penn, Mahlet chaired the Black Graduate and Professional Student Assembly and co-founded the Penn Graduate Women in Science and Engineering Program with five other students. Through her work on diversity with these groups, she not only discovered a love for policy and advocacy, but also developed skills for addressing change on a university-wide level She hopes her Mirzayan Fellowship will provide hands-on experience that merges her scientific interests with a deeper understanding of policy at the federal level.

During her internship, Mahlet is working with the NAE Program on Diversity in the Engineering Workforce and the Committee on Women in Science, Engineering, and Mathematics, a program of the Public and Government Affairs Division of the National Research Council.

Mahlet enjoys spending time with friends and family, trying out new restaurants, and traveling. She also plans to run her first half-marathon in 2012.

The Asad, Taj, and Jamal Madni Matching Gift Challenges

Jamal Madni, Taj Madni, Charles M. Vest, and Asad M. Madni

This year, Dr. **Asad M. Madni**, a member of the class of 2011, his wife Taj, and his son Jamal are generously sponsoring two $50,000 matching gift challenges to encourage giving by NAE members elected from 2009 to 2012 and by fellow members of Section 7. Dr. Madni approached NAE about sponsoring a challenge during the 2011 Annual Meeting.

The goal of *The Asad, Taj, and Jamal Madni Challenge for Newer Members* is to encourage recently elected NAE members to become active contributors. The Madnis' challenge will match, in full, any gift made in 2012 by members of the class of 2009, 2010, 2011, or 2012. *The Asad, Taj, and Jamal Madni Section 7 Challenge* is focused on increasing the proportion of contributions by members of Section 7. This challenge grant will match any individual's gift that is larger than that member's 2011 donation. Both challenges were inspired by one of NAE's goals for its 50th anniversary—to achieve a 50 percent participation rate by NAE membership.

Dr. Madni expressed his hopes for NAE in the following moving words:

> I am inspired by the brilliant minds at the National Academy of Engineering who provide their expertise to globally improve the quality of life and in addressing issues that are vital to our nation's future in order to maintain our global technical and economic leadership. These challenges are intended to encourage contributions to the NAE Independent Fund in order to assure the independence of our voice on national policy and to initiate projects that are vital to our nation's future.
>
> — Asad M. Madni,
> NAE Class of 2011

For more information on participating in the *Asad, Taj, and Jamal Madni Challenges*, or to learn more about NAE's goals for its 50th anniversary, please contact Radka Nebesky, NAE senior director of development, at 202-224-3417 or *rnebesky@nae.edu*, or visit *www.nae.edu/giving*.

A Message from NAE Vice President Maxine L. Savitz

Maxine L. Savitz

I am happy to report that 2011 was a successful fundraising year for NAE. Thanks to the extraordinary generosity and support of more than 650 members, we raised almost $3.4 million in new cash and pledges, 30 percent of NAE's annual budget. We thank you for your confidence that we will use these contributions to continue to serve the engineering community, students, policy makers, and the public.

More than one-third of the private money we received in 2011, slightly more than $1.2 million, was donated to the NAE Independent Fund. This vital, unrestricted money not only provides core support, but also enables us to initiate important new projects that lack federal funding, as well as to expand the scope and impact of current programs.

Perhaps one of the best examples of the exceptional potential of flexible funds was the development of the Grand Challenges for Engineering. This initiative, which began as an idea to inspire student and public engagement with engineering, has since taken on a life of its own. Several universities have organized curricula around the Grand Challenges and have established the Grand Challenges Scholars Program. Seven Grand Challenges Summits have been held in the United States, organized by Duke, USC, Olin College, and others, and the first Global Grand Challenges Summit will be held in 2013 in cooperation with the Royal Academy of Engineering and the Chinese Academy of Engineering. The 14 Grand Challenges were selected by an NAE-appointed committee under the sponsorship of NSF, but continued engagement in the project was made possible by unrestricted donations provided by NAE members.

50th Anniversary

In December 2014, NAE will celebrate 50 years since its founding as a parallel organization of outstanding engineers under the NAS charter. We can look back on past accomplishments spearheaded by NAE members, including influential projects and studies, such as *Rising Above the Gathering Storm*, *America's Energy Future*, and the recent report on the *Deepwater Horizon*. But we can also look ahead to finding new ways of addressing the changing needs of a rapidly changing society.

With an eye to the future of NAE, we have launched a 50th anniversary fundraising activity: Celebrating 50 Years of Engineering Leadership and Service. We hope to engage members who have never given to NAE, as well as to inspire our loyal donors to consider making additional commitments to help us reach some very ambitious goals:

- increasing membership in our lifetime giving societies—the Einstein, Heritage, and Golden Bridge societies
- initiating crucial new projects supported by Leadership Gifts
- promoting friendly competition among sections to increase the percentage of members who give to NAE

Nobody understands better than our members the crucial role of engineering and technological innovation in driving the U.S. economy, national security, and quality of life. If our efforts are successful, we will reach our 50th anniversary with enough resources in hand to help the engineering community address the Grand Challenges facing us today, turn complex technological questions into opportunities for innovation and improvement, and maintain NAE's position as a national voice for engineering. Please visit *www.nae.edu/giving* for more details.

Outstanding Contributions

All contributions are greatly appreciated, and all of them make a difference in the work of NAE. Before I close, however, I want to highlight some of the most remarkable gifts we received in 2011:

- **Ross ('02)** and **Stephanie Corotis** established a $100,000 charitable gift annuity to benefit NAE.
- The estate of **Lee L. Davenport ('73)** established a bequest of $50,000 to support joint work with IOM to improve the efficiency of the U.S. health care system.
- **Irwin ('82)** and **Joan Jacobs** sponsored two matching gift challenges, their third and fourth such challenges in the past three years. This year's challenges for

the Class of 2011 and the Classes of 2009 and 2010 helped raise almost $150,000 for the NAE Independent Fund.

- **Lockheed Martin** donated $500,000 to support the Global Grand Challenges Summit; $250,000 to *EngineerGirl!*; and $100,000 to support the National Engineering Forum.
- **Asad ('11), Taj,** and **Jamal Madni** have committed $100,000 to sponsor two matching gift challenges in 2012, one for new members and one for Section 7 members.
- **Robin ('07)** and **Rose McGuire** contributed $100,000 to encourage Native American students to pursue careers in engineering.
- **Gordon ('76)** and **Betty Moore** donated $100,000 to NAE's unrestricted Independent Fund.
- **Northrop Grumman** donated $100,000 to encourage diversity in the science and engineering workforce.
- **The O'Donnell Foundation** invested $500,000 in Frontiers of Engineering Education (FOEE), a program that promotes effective, innovative engineering education.

Gifts made regularly each year to NAE also demonstrate genuine commitment to our mission and goals. As a longtime donor who understands that every donation to NAE is a choice to support an organization whose work matters greatly, I thank the following members who have contributed to NAE for 15 or more consecutive years:

Clarence R. Allen ('76)
Charles A. Amann ('89)
John C. Angus ('95)
Wm. Howard Arnold ('74)
Harold Brown ('67)
Jack E. Buffington ('96)
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Andrew J. Viterbi ('78)
Irving T. Waaland ('91)
Johannes ('76) and **Julia** ('88) **Weertman**
Wm. A. Wulf ('93)

Be on the lookout in 2012 for opportunities to participate in activities leading up to NAE's 50th anniversary celebration. We will be discussing plans for this milestone at regional meetings and throughout the year and will provide more information in our spring and fall appeals. Remember, too, that we are always available to discuss your ideas for celebrating NAE.

On behalf of the NAE Council, our president **Chuck Vest**, and myself, thank you very much for your contributions in 2011. Our supporting members, friends, partner corporations, foundations, government sponsors, and other organizations make all the difference in our ability to positively impact our world and to continue advocating for engineering. I am grateful for your contributions, and I look forward to your continued involvement in 2012.

Maxine

Maxine Savitz

National Academy of Engineering 2011 Donor Recognition

INDIVIDUALS

Lifetime Giving Societies

The National Academy of Engineering gratefully acknowledges the following members and friends who have made generous charitable lifetime contributions. Their collective, private philanthropy enhances the impact of NAE as a national voice for engineering.

Einstein Society

In recognition of members and friends who have made lifetime contributions of $100,000 or more to the National Academies as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation. Names in bold are NAE members.

$1,000,000 or more

Bruce and Betty Alberts
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Fritz J.* and Delores H.* Russ
Jillian Sackler
Raymond and Beverly Sackler
Bernard G.* and Rhoda Sarnat
Leonard D. Schaeffer
Sara Lee and Axel Schupf

$500,000 to $999,999

Anonymous
Rose-Marie and Jack R. Anderson
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Kenneth E. Behring
James McConnell Clark
Richard Evans*
Harvey V. Fineberg and Mary E. Wilson
Eugene Garfield
William T. Golden*
Joan and **Irwin Mark Jacobs**
Thomas V. Jones
Cindy and **Jeong Kim**
Ralph* and Claire* **Landau**
William W. Lang
Richard and Ronay Menschel
Ruben F.* and Donna **Mettler**
Dane and Mary Louise **Miller**
Shela and **Kumar Patel**
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William J. Rutter
John and Janet **Swanson**
Roy and Diana Vagelos
Alan M. Voorhees*

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John Abelson
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Penny and Bill George
Jerome H.* and Barbara N. Grossman
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Simon Ramo
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Stephen and Anne Ryan
Henry and Susan **Samueli**
Melvin I. Simon
Ted Turner
Leslie L. Vadasz
Charles M. and Rebecca M. **Vest**

*Deceased
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$100,000 to $249,999

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Peter and Vivian **Teets**
Andrew and Erna **Viterbi**
John C. Whitehead
Wm. A. Wulf
Alejandro Zaffaroni
Janet and Jerry Zucker

Golden Bridge Society

In recognition of National Academy of Engineering members and friends who have made lifetime contributions of $20,000 to $99,999 to the Academies as personal gifts or as gifts facilitated by the donor through a donor-advised fund, matching gift program, or family foundation.

$50,000 to $99,999

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Friend

Kristine L. Bueche

Heritage Society

In recognition of Academies members and friends who have thoughtfully planned gifts today that will provide for the future by including the Academies in their wills or by other deferred gifts. Names in bold are NAE members.

Andreas and Juana **Acrivos**
Gene and Marian **Amdahl**
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Charles Yanofsky
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Calendar of Meetings and Events

March 1–31	Election of NAE officers and councillors
March 22	NAE Regional Meeting University of California Santa Barbara, California
March 29–31	German-America Frontiers of Engineering Symposium Potsdam, Germany
April 2	Deadline for nominations for 2012–2013 NAE awards
April 18	NAE Regional Meeting University of Maryland College Park, Maryland
April 25–26	Meeting of the Committee on Integrated STEM Education
April 28–29	USA Science & Engineering Festival Walter E. Washington Convention Center, Washington, D.C.
May 10–11	NAE Council meeting
May 16	NAE Regional Meeting Cornell University Ithaca, New York
May 23	NAE Regional Meeting Jet Propulsion Laboratory Pasadena, California

All meetings are held in National Academies facilities in Washington, D.C., unless otherwise noted.

In Memoriam

ERSEL A. EVANS, 89, retired vice president and laboratory technical director, Westinghouse Hanford Company, died on November 9, 2011. Dr. Evans was elected to NAE in 1975 “for leadership and contributions in the development and application of fuels and materials engineering for advanced nuclear systems.”

ADEL F. SAROFIM, 77, Presidential Professor, Department of Chemical Engineering and Institute for Clean and Secure Energy, University of Utah, died on December 4, 2011. Dr. Sarofim was elected to NAE in 2003 “for advancing our understanding of the mechanisms and modeling of processes that control radiation in and pollutant emissions from combustors.”

HAROLD S. MICKLEY, 93, retired vice chairman, Stauffer Chemical Company, died on December 3, 2011. Dr. Mickley was elected to NAE in 1978 “for research on transpired turbulent boundary layers, and leadership in the industrial development of oxyhydrochlorination processes.”

NAE Annual Meeting, September 30–October 1, 2012

The 2012 NAE Annual Meeting, on September 30–October 1, 2012, will be held at the National Academies building and the Keck Center of the National Academies in Washington, D.C. Orientation for the Class of 2012 will be held on September 29, the day before the meeting. On the evening of the 29th, new members and foreign associates will attend a black tie dinner in their honor hosted by the NAE Council. The induction ceremony will be held at noon on Sunday, September 30. An awards program will follow in the afternoon.

Events for Monday morning, October 1, will include the Business Session for members and foreign associates and the annual NAE Forum. In the afternoon, section meetings will be held at the National Academies Building and the Keck Center. The concluding event that evening will be an optional dinner dance at the JW Marriott.

The flyer for the 2012 Annual Meeting and online registration form will be available on the NAE website in mid-June. The flyer will also provide information about the spouses’ program on Monday, October 1.

Publications of Interest

The following reports have been published recently by the National Academy of Engineering or the National Research Council. Unless otherwise noted, all publications are for sale (prepaid) from the National Academies Press (NAP), 500 Fifth Street, N.W., Keck 360, Washington, DC 20001. For more information or to place an order, contact NAP online at *http://www.nap.edu* or by phone at (800) 624-6242. *(Note: Prices quoted are subject to change without notice. Online orders receive a 10 percent discount when you sign up for a MyNAP account. Please add $5.00 for shipping and handling for the first book and $1.00 for each additional book. Add applicable sales tax or GST if you live in CA, CT, DC, FL, MD, NC, NY, VA, WI, or Canada.)*

A Review of the U.S. Global Change Research Program's Strategic Plan. In 2011, a new National Research Council committee was formed to advise the U.S. Global Change Research Program (USGCRP), which was established in 1990 to coordinate the efforts of numerous federal agencies and departments working on issues related to climate change. The committee's first major task was to review the USGCRP draft Strategic Plan 2012–2021 ("the Plan"). This report includes numerous suggestions for improving the Plan, ranging from relatively small edits to basic questions about the scope, goals, and capacity of the program to meet its goals. The key issues include identifying initial steps to enlarge the scope of the program, as proposed in the Plan; developing critical science capacity that is now lacking; linking new knowledge to practical applications; and establishing an overall governance structure to enable the program to move in new directions.

NAE members on the study committee were **Warren M. Washington** (chair), senior scientist, National Center for Atmospheric Research, and **Robert E. Dickinson**, professor, Department of Geological Sciences, University of Texas, Austin. Paper, $35.00.

National Water Resources Challenges Facing the U.S. Army Corps of Engineers. The U.S. Army Corps of Engineers (USACE) is responsible for the construction, operations, and maintenance of much of the nation's water resources infrastructure (e.g., flood-control levees, multipurpose dams, locks, navigation channels, port and harbor facilities, and beach-protection infrastructure); regulating the dredging and filling of wetlands subject to federal jurisdictions; reducing flood damage and supporting commercial navigation; and, since 1996, restoring ecosystems. The National Research Council Committee on U.S. Army Corps of Engineers on Water Resources Science, Engineering, and Planning was formed, at the request of USACE, to provide independent advice on strategic and planning issues. In this report, based on initial investigations and discussions with USACE leadership, the committee surveys key challenges, defines the limits of what USACE can be expected to accomplish today, and describes future prospects for the agency. The report, which includes several findings, but no recommendations, is a foundational resource for USACE, Congress, federal agencies, and project co-sponsors, among others.

NAE members on the study committee were **David A. Dzombak** (chair), Walter J. Blenko Sr. University Professor of Environmental Engineering, Carnegie Mellon University; **Gregory B. Baecher**, Glenn L. Martin Institute Professor of Engineering, University of Maryland; and **Robert A. Dalrymple**, Willard and Lillian Hackerman Professor of Civil Engineering, Johns Hopkins University. Paper, $27.00.

Recapturing a Future for Space Exploration: Life and Physical Sciences Research for a New Era. During its more than 50-year history, NASA's success in human space exploration has depended on its ability to address a wide range of biomedical, engineering, physical science, and related obstacles—an achievement made possible by committed support for research in life and physical sciences for human space exploration and by its human space exploration infrastructures for scientific discovery. Despite budgetary challenges and changes in direction, some progress has been made. However, research in the life and physical sciences has been scaled back for a decade, leaving NASA poorly positioned either to take advantage of the fully equipped and staffed ISS laboratory or to pursue research to support further human space exploration. Nevertheless, the Committee for the Decadal Survey on Biological and Physical Sciences in Space, which authored this report, believes that a focused science and engineering program can be successful. The goal of this report is to propose a strategy and develop a forward-looking research portfolio that will recapture the excitement of human spaceflight and lead to a U.S. space program that benefits the nation, excites the public, and returns the United States to the forefront of space exploration for the global good.

NAE member **Vijay K. Dhir**, Distinguished Professor and dean, Henry Samueli School of Engineering and Applied Science, University of California, Los Angeles, was a member of the study committee. Paper, $85.75.

Renewable Fuels Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy. The United States has a long history of investigating biofuels and is on a course to substantially increase their use. This report provides an evaluation of the economic and environmental consequences of increasing biofuels production as a result of the Renewable Fuels Standard, as amended by EISA (RFS2). The evaluation includes descriptions of biofuels produced in 2010 and those projected to be produced and consumed by 2022, reviews of model projections and other estimates of relative impacts on land prices, and a discussion of the potential environmental harm and benefits of biofuels production and the barriers to achieving the RFS2 consumption mandate. The recommendations of the study committee will be important for policy makers, investors, the transportation sector, and everyone concerned about the environment, the economy, and energy security.

NAE member **Jerald L. Schnoor**, Allen S. Henry Chair in Engineering and co-director, Department of Civil and Environmental Engineering, University of Iowa, was a member of the study committee. Paper, $68.00.

U.S. and International Perspectives on Global Science Policy and Science Diplomacy: Report of a Workshop. Based on many areas of common interest among peoples from diverse cultures, advancing science and engineering has increasingly become a global enterprise. The National Academies held a workshop in Washington, DC, in February 2011, to assess effective ways to meet international challenges through sound science policy and science diplomacy. To ensure that the workshop would have an international perspective on these issues, participants included representatives of Bangladesh, Brazil, Egypt, Germany, Jamaica, Kazakhstan, Malaysia, Morocco, Rwanda, South Africa, and Syria, as well as two recently named U.S. science envoys, Rita Colwell and Gebisa Ejeta. This report summarizes issues addressed during the workshop, including the characteristics of science, such as its common language and methods; the open, self-correcting nature of research; the universality of important questions; and respect for evidence. Many workshop participants noted that advancing global science and science diplomacy (what some prefer to call “global science cooperation”) are distinct, but complementary activities. Whether it is called cooperation or diplomacy, there are many historical examples of the importance of international scientific cooperation in building positive governmental relationships and dealing with sensitive and urgent problems.

NAE member **C.D. (Dan) Mote Jr.**, Regents Professor and Glenn L. Martin Institute Professor of Engineering, University of Maryland, College Park, was a member of the workshop committee. Paper, $34.00.

Vision and Voyages for Planetary Science in the Decade 2013–2022. This report provides a survey of the current state of knowledge of the solar system and recommends flagship missions in planetary science for 2013–2022 that could provide a steady stream of discoveries about the solar system and identifies research priorities selected through a rigorous review based on the results of studies by five expert panels. The authoring committee concludes that NASA’s highest priority major mission should be the Mars Astrobiology Explorer Cacher (MAX-C), a mission to Mars that could not only help determine whether the planet ever supported life, but could also help answer questions about its geologic and climatic history. Other major projects should include (1) a mission to Jupiter’s icy moon, Europa, and its subsurface ocean, and (2) the Uranus Orbiter and Probe mission to investigate that planet’s interior structure, atmosphere, and composition. For medium-size missions, the committee recommends that NASA select two new missions to be included in its New Frontiers Program, which consists of frequent, mid-size spacecraft missions to explore the solar system. The committee also cautions that, if NASA cannot conduct these flagship projects within budget, it should focus on smaller, less expensive missions first.

NAE member **A. Thomas Young**, retired executive vice president, Lockheed Martin Corporation, was a member of the study committee. Paper, $55.00.

Achieving High-Performance Federal Facilities: Strategies and Approaches for Transformational Change: A Workshop Report. Buildings account for 40 percent of primary energy use in the United States, 12 percent of water consumption, and 60 percent of all non-industrial waste. In addition, the production and delivery of electricity from power plants for use in buildings account for 40 percent of U.S. greenhouse gas emissions. The federal government manages approximately 429,000 buildings of many types with a total square footage of 3.34 billion square feet worldwide, of which about 80 percent is owned space. More than 30 departments and agencies are responsible for managing these buildings, and each agency's portfolio of facilities is determined by its mission and programs. In 2010, the General Services Administration Office of Federal High-Performance Green Buildings asked the National Academies to appoint an ad hoc committee of experts to conduct a public workshop and prepare a report that identifies strategies and approaches for achieving a variety of objectives associated with high-performance, green, federal buildings. To avoid repeating information that is already available in other reports, papers, books, and databases, the committee decided to focus on how current initiatives and available resources could promote sustainability as the preferred choice at all levels of decision making. The hope is that the resulting report will be of value to federal agencies with different kinds of missions, facilities, and operating procedures.

NAE members on the study committee were **David J. Nash** (chair), chairman and CEO, Dave Nash & Associates International LLC, and **Arthur H. Rosenfeld**, Lawrence Berkeley National Laboratory (Emeritus). Paper, $38.00.

Policy Options for Reducing Energy Use and Greenhouse Gas Emissions from U.S. Transportation: Special Report 307. This report focuses on how policies pertaining to (1) cars and light trucks, (2) medium and heavy trucks, and (3) commercial airliners could lead to major changes in trends in transportation energy use and emissions. These three modes of transportation, the largest users of energy, account for the vast majority of passenger and freight trips. According to the committee that produced this report, reducing petroleum use over the next half-century will require not only tougher fuel economy standards, but also measures that pique the interest of consumers and suppliers in vehicle fuel economy, alternative fuels, and a more efficient transportation system. Major policy options addressed in this report—fuel taxes, vehicle-efficiency standards, fuel standards, infrastructure investments, and coordinated transportation and land-use planning—have the potential to bring about large reductions in energy use and emissions over time, although each of them also presents challenges in terms of the scope and timing of results. The committee suggests that combining transportation policy options could achieve large-scale, timely reductions. In addition, because transportation accounts for most of the petroleum used in the United States, reducing energy consumption in this sector can also bring down the costs of securing world oil supplies. In addition, the transportation sector, which produces one-quarter to one-third of U.S. carbon dioxide (CO_2) emissions, can make an enormous difference in helping to stabilize atmospheric concentrations of CO_2 and other greenhouse gases by the middle of this century.

NAE members on the study committee were **John M. Samuels Jr.**, president, Revenue Variable Engineering LLC, and **Kathleen C. Taylor**, retired director, Materials and Processes Laboratory, General Motors Corporation. Free PDF.

Global Change and Extreme Hydrology: Testing Conventional Wisdom. A major challenge for the climate and hydrologic science communities is determining the real-world nature of changes in climate and hydrology and apparent anomalies in reconciling their extreme manifestations. The National Research Council Committee on Hydrologic Science held a workshop on January 5–6, 2010, to examine how climate warming translates into hydrologic extremes, such as floods and droughts. The workshop brought together three groups of experts—atmospheric scientists and hydrologists, whose focus is on the scientific underpinnings and empirical evidence linking climate variability and hydrologic extremes, and water managers, that is, decision makers charged with designing and operating water systems that must be resilient in the face of a changing climate and hydrologic extremes. This summary of the workshop proceedings provides (1) an overview of current science in terms of climate change and extreme hydrologic events and (2) a discussion of the "conventional wisdom" that climate change will "accelerate" the hydrologic cycle and evaporation and generate more precipitation, because a warmer atmosphere will be able to retain more water vapor. Descriptions of changes in frequency and severity of extremes, the difficulties of modeling these changes, and the problems of communicating the results to water resources practitioners are also included.

NAE members on the study committee were **Dennis P. Lettenmaier**, Robert and Irene Sylvester Professor of Civil and Environmental Engineering, University of Washington, Wilson Ceramic Laboratory; and **Daniel P. Loucks**, professor, School of Civil and Environmental Engineering, Cornell University. Paper, $27.00.

Limiting Future Collision Risk to Spacecraft: An Assessment of NASA's Meteoroid and Orbital Debris Programs. The amount of debris orbiting Earth (aka space junk), which has been accumulating for decades, could damage or even destroy satellites and spacecraft. Over the past 50 years, various National Aeronautics and Space Administration (NASA) communities have significantly improved meteoroid and orbital debris (MMOD) programs. Satellites have been redesigned to protect critical components from damage by moving them from exterior surfaces to interior structures. Orbits are monitored and adjusted to minimize the risk of collision. MMOD shielding on the International Space Station protects critical components and astronauts from the impacts of small, untracked debris and meteoroids. This report provides a review of NASA's efforts to understand the MMOD environment, determines what NASA is and is not doing to mitigate the risks, and recommends improvements. Although the report committee identifies many positive aspects of NASA's MMOD programs (e.g., responsible use of resources), it also recommends that the agency develop a formal strategic plan as a basis for prioritizing the allocation of funds and efforts. Other recommendations include improving long-term modeling and measurements, updating debris environmental models regularly, and taking other steps to improve the characterization of the long-term evolution of the debris environment.

NAE members on the study committee were **George J. Gleghorn** (vice chair), retired vice president and chief engineer, TRW Space and Technology Group, and **Kyle T. Alfriend**, TEES Distinguished Research Chair and professor of aerospace engineering, Texas A&M University. Paper, $45.00.

Preparing for the High Frontier: The Role and Training of NASA Astronauts in the Post-Space Shuttle Era. The National Aeronautics and Space Administration's (NASA) retirement of the Space Shuttle and changing involvement in International Space Station operations will necessitate changes in the role and requirements of NASA's Astronaut Corps. At NASA's request, a National Research Council committee addresses three main questions in this report: (1) what the role and size of the Johnson Space Center Flight Crew Operations Directorate should be; (2) what the requirements of astronaut training facilities will be; (3) and if the Astronaut Corps' fleet of training aircraft is a cost-effective way to prepare astronauts for NASA's spaceflight program. This report presents an assessment of the issues raised by these questions, but does not explicitly address the future of human spaceflight.

NAE members on the study committee were **Bonnie J. Dunbar**, Dunbar International LLC, and **Henry McDonald**, Sim Center, University of Tennessee at Chattanooga. Paper, $37.00.

Future Science Opportunities in Antarctica and the Southern Ocean. Antarctica and the surrounding Southern Ocean, one of the world's last frontiers, covers nearly 14 million square kilometers (approximately 1.4 times the size of the United States). Establishing and maintaining infrastructure to ensure sufficient heat, light, transportation, and drinking water, and at the same time minimize pollution and ensure the safety of researchers requires substantial resources. The committee of experts that conducted this study suggests actions the United States might take to support the success of the next generation of Antarctic and Southern Ocean scientists. The committee highlights two areas of research, studies related to global change and studies related to fundamental discoveries. In addition, the committee identifies key questions that will drive research in the coming decades and highlights opportunities for sustaining and improving U.S. research efforts in the region.

NAE member **Thomas F. Budinger**, professor of the Graduate School, University of California, Berkeley, E. O. Lawrence Berkeley National Laboratory, was a member of the study committee. Paper, $50.00.

Sharing the Adventure with the Public—The Value of Excitement: Summary of a Workshop. On November 8–10, 2010, the National Research Council Space Studies Board (SSB) held a public workshop on how the National Aeronautics and Space Administration (NASA) and associated science and exploration communities can communicate the exciting prospects of major NASA activities and programs to the public. Over a period of two years, the workshop planning committee, in conjunction with SSB, developed five "Grand Questions" in space science and exploration around which the event was organized. This volume includes summaries of the workshop presentations and discussions.

NAE member **A. Thomas Young**, retired executive vice president, Lockheed Martin Corporation, was a member of the workshop planning committee. Paper, $49.00.

Proliferation Risk in Nuclear Fuel Cycles: Workshop Summary. In 2011, the U.S. Department of Energy asked the National Academies to convene a public workshop to address the capability of current and potential methodologies for assessing the risk of proliferation in states that host nuclear facilities and how these methodologies can be used by decision makers. The major subjects of the workshop were nonproliferation and new technologies, separate policy and technical cultures, the value of proliferation-resistance analysis, and the usefulness of social science approaches. This volume includes a summary of workshop presentations and discussions prepared by a designated rapporteur.

NAE member **C. Paul Robinson**, President Emeritus, Sandia National Laboratories, chaired the workshop planning committee. Paper, $36.00.

Continuing Assistance to the National Institutes of Health on Preparation of Additional Risk Assessments for the Boston University NEIDL, Phase 3. In 2003, the Boston University Medical Center was awarded a $128 million grant from the National Institutes of Health to build one of two National Emerging Infectious Diseases Laboratories (NEIDLs), maximum-containment laboratories for research on pathogens. The purpose of NEIDLs is to support the National Institute of Allergy and Infectious Diseases biodefense research agenda by conducting research on new approaches to treating, preventing, and diagnosing bacterial and viral diseases. The facility will include a biosafety level 4 (BSL-4) containment laboratory housed in a 192,000 square foot building, located in Boston's South End, an environmental justice community. Although the BSL-4 laboratory will occupy only 13 percent of the total space, it has been the source of virtually all community concerns about the project. Numerous public meetings have been held about plans for the facility, and three legal actions challenging the project have been initiated. This volume, the fifth in a series, provides information about additional studies that might be needed to assess the risks associated with the siting and operation of the building. It also includes comments and questions on a penultimate (90-percent complete) draft of the revised risk assessment, which according to the authoring committee, is much improved over past documents. Nevertheless, the committee recommends improvements before the final public version is published.

NAE member **John F. Ahearne**, Executive Director Emeritus, Sigma Xi, The Scientific Research Society, chaired the study committee. Free PDF.

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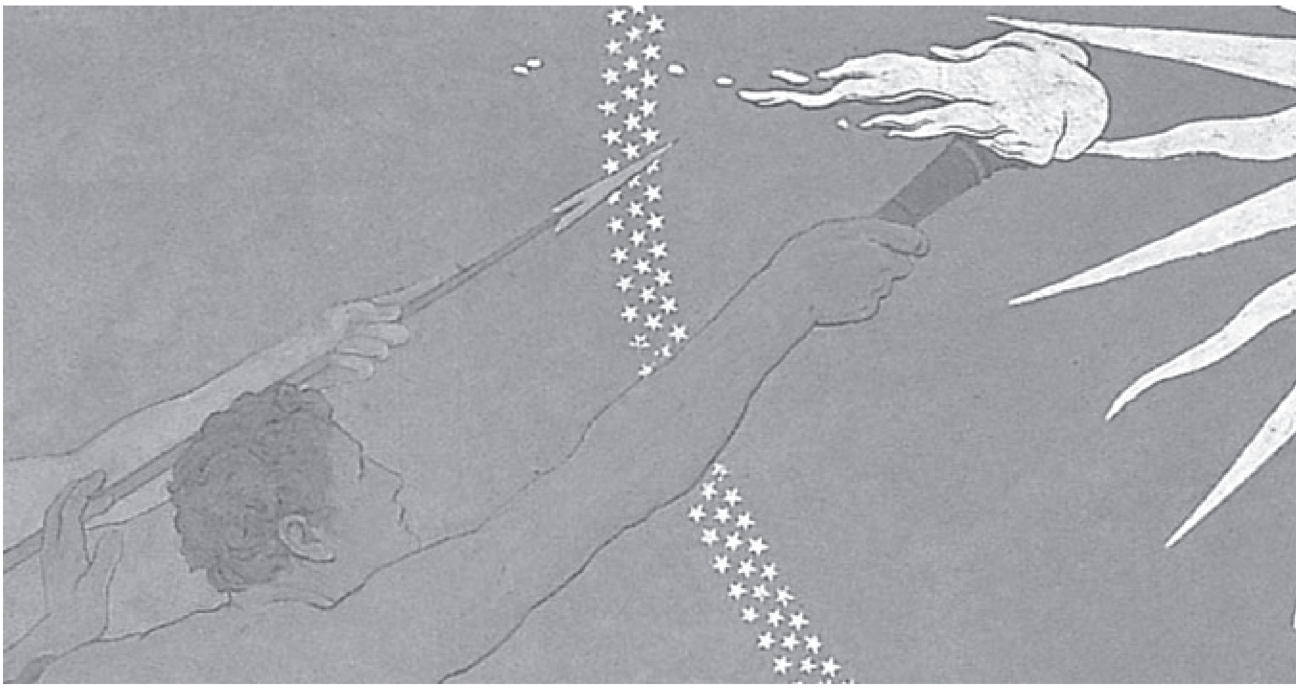

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