Fall 2017

OPEN SOURCE HARDWARE

The BRIDGE

LINKING ENGINEERING AND SOCIETY

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The
BRIDGE

NATIONAL ACADEMY OF ENGINEERING

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The Bridge publishes articles on engineering research, education, and practice; science and technology policy; and the interface between engineering and technology and society. The intent is to stimulate debate and dialogue both among members of the National Academy of Engineering (NAE) and in the broader community of policymakers, educators, business leaders, and other interested individuals. *The Bridge* relies on its editor in chief, NAE members, and staff to identify potential issue topics and guest editors. The quarterly journal has a distribution of about 7,000, including NAE members, members of Congress, libraries, universities, and interested individuals. Issues are available at www.nae.edu/Publications/Bridge.aspx.

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The

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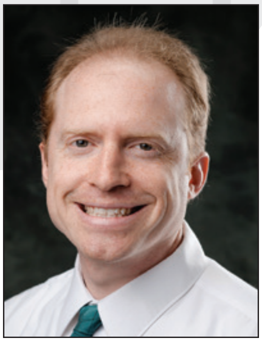
Editor's Note

Features

(continued on next page)

Editor's Note



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Introduction to Open Hardware in Science and Engineering

The articles in this issue look at how the development and use of free and open source hardware (FOSH or simply "open hardware") are changing the face of science, engineering, business, and law.

Free and open source software (FOSS) has proven very successful and now dominates the development of software on a global scale. It is available in source code (open source) and can be used, studied, copied, modified, and redistributed either without restriction or with restrictions only to ensure that further recipients have the same open source rights.

Similarly, FOSH provides the "code" for hardware—including the bill of materials, schematics, instructions, computer-aided designs, and other information needed to recreate a physical artifact. Use of FOSH can improve product innovation in a wide range of fields. In this issue authors from a variety of disciplines and work environments discuss how this open model of innovation will drive the future of engineering.

First, Alicia Gibb, founder and executive director of the Open Source Hardware Association (OSHWA) and director of the ATLAS[1] Blow Things Up (BTU) Lab at the University of Colorado Boulder, argues that hardware is the next step to open sourcing everything. She touches on intellectual property (IP) issues, cites the benefits of open source hardware, introduces and explains the role of OSHWA, and hints at the future of open hardware.

The open source paradigm is already making deep inroads in the hardware space in 3D printing. With the development of the open source RepRap project (a 3D printer that can print itself) the cost of 3D printers has dropped to a point where nearly anyone can afford one for rapid prototyping and small batch manufacturing.

Ben Malouf and Harris Kenny of Aleph Objects describe their company's approach to the use of open hardware in every aspect of their business to create the popular Lulzbot 3D printer. Their primary product is open—and consistently wins one of the top spots in *Make:* magazine's annual 3D printer shootout, ahead of proprietary 3D printers from much larger companies with far greater resources. Lulzbot printers, and those of many other manufacturers, are rapidly increasing in sales as the number of free and open source 3D printable designs erupts on the Web, making distributed manufacturing a reality.

In this context, law professor Lucas Osborn at the Campbell University School of Law takes us on a deep dive into how IP law will need to change in this new 3D printing era. After summarizing the basics of IP law and explaining why it was created, he discusses how it could both benefit and hinder 3D printing technology. His arguments will challenge readers independent of their views on patent law. For those with conventional IP leanings, he shows how IP law can hinder innovation. For those born in the Internet age, where sharing is second nature and little thought is given to licenses as long as the code is posted on Github, he offers some important lessons. He ends with a challenge for engineers to make more of an effort in helping form IP law that will benefit innovation.

If these lessons on IP and open hardware replication with 3D printers are turned to experimental research in science and engineering, there is an important opportunity to radically reduce the costs of experimental research while improving it. In the next article I argue that by harnessing a scalable open source method, federal funding is spent just once for the development of scientific equipment and then a return on this investment (ROI) is realized by digital replication of scientific devices for only the costs of materials. With numerous examples I show that the ROI climbs into the thousands of percent while accelerating any research that the open

[1] Founded in 1997 as the Alliance for Technology, Learning, and Society.

paradigm touches. To harness this opportunity, I propose four straightforward and negative-net-cost policies to support FOSH development and improve access to scientific tools in the United States. The policies will directly save millions in research and STEM education expenditures, while providing researchers and students access to better equipment, which will promote advances in technology and concomitant benefits for the American economy.

Thinking about the future and the changes needed to support this development in STEM education, AnnMarie Thomas and Deb Besser of St. Thomas School of Engineering consider how engineers and engineering educators can use maker methods to introduce students to engineering and build their technological literacy. They show that the maker movement is closely tied to open hardware and sharing as well as the traits of successful engineers. Makerspaces and fabrication (fab) labs (what Gibb calls hackerspaces) are physical hubs of the maker culture.

Although these trends are clearly important for the United States, this cultural change and open hardware ethos can have dramatic impacts in the developing world. Matthew Rogge, Melissa Menke, and William Hoyle of TechforTrade explain the potential for open source and 3D printing to produce many needed items in low-resource settings, where lack of infrastructure makes local production impractical and high tariffs, unreliable supply chains, and economic instability make importation costly. Saving 90 percent on medical or scientific tools is nice in my lab, for instance, but it literally saves lives in a developing world context.

The contributions conclude with an op-ed by Tom Callaway, a senior software engineer at Red Hat, Inc., an open source software company with revenue over $2 billion last year (up 15 percent year over year). What makes this business accomplishment so impressive is that all of the company's software products are available for free. Although old ways of thinking demand that companies secure a monopoly and certainly not give away "intellectual property" for free, Red Hat's success comes from offering its customers support, collaboration, control, and a high-quality product. Tom argues that the proven open source software mentality is porting to hardware, opening up incredible opportunities for humanity. He concludes, "open source and open innovation work…. They also empower society and make it possible to push the limits of what is possible. When the barriers to collaboration are lifted, people can accomplish incredible things."

As all of the articles show, open source tools in the hands of this and future generations of engineers will be incredible indeed.

Open source products benefit from community collaboration to constantly innovate, improve, and maintain competitiveness.

Hardware

The Next Step toward Open Source Everything

Alicia Gibb is founder and executive director of the Open Source Hardware Association and director of the ATLAS Blow Things Up Lab at the University of Colorado Boulder.

Alicia M. Gibb

Hardware is considered anything made of atoms instead of bits. Open source hardware (OSHW) is hardware of any type (e.g., electronics, mechanical parts, even clothing) whose source files are publicly available for anyone to use, remanufacture, redesign, and resell provided that the hardware remains open source and attribution is given.[1]

Introduction

Open source hardware involves sharing, transparency, and the acceptance of predecessors and successors to a creator's work, whether a company that might build something from the hardware or a project that might copy part or all of a hardware design.

Transparency in hardware is increasingly important as technologies become more sophisticated: as complexities are added, the particulars of the design are harder to discern. Open source hardware makes the source files readily accessible to anyone who wants to build the object. The files may include schematics, diagrams, code, and assembly instructions, depending on the type of hardware. A gear logo, shown in figure 1, may be applied to the hardware as long as the communal definition of OSHW (cited above) is followed and the source files are publicly posted without restriction. The gear

[1] As defined by the Open Source Hardware Community (https://www.oshwa.org/definition/).

FIGURE 1 The communal open source logo.

logo is communally owned and not trademarked, making it very open but difficult to defend if used incorrectly.

If the open source hardware definition sounds familiar, OSHW took many cues from open source software, although there are important differences. With hardware, sharing the source does not mean you get the product, although the 3D printing community is making strides to change this.

Software can generally be 100 percent open, but such openness is difficult with hardware because the creator may not have built all the parts used on the project or product. For example, on many OSHW devices the integrated circuit (IC) is not open source. But as long as a datasheet exists openly without a nondisclosure agreement and the OSHW designer does not control the intellectual property (IP) of the chip, the hardware can still be considered open source. Invention of desktop chip fabricators would give the IC market a push toward open source, similar to the way desktop 3D printers led to open source 3D printers and prints.

Open source hardware inventors often don't know the source of the raw materials used to build their components and printed circuit boards. Thus far, the OSHW community does not find the atomic layer of the source useful and is not required to post it.

Hardware and Intellectual Property Protection

Innovation currently has four IP options: trade secrets, patents, public domain, and open source hardware.

- With a trade secret, inventors keep their ideas under lock and key but do not get any protections if their secrets are published.
- Patents, which disclose how an invention works, must be publicly filed with a country's patent and trademark office. In exchange, a monopoly is granted for 20 years (USPTO 2015, chap. 2700).
- Public domain is truly open, with no restrictions and free for public use.
- Open source hardware lies between patents and public domain.

When patents were first created, they were meant to incentivize inventors (Newman 2013). But although they are a well-established tradition in the United States (more than 200 years; USPTO 2002), many people in the OSHW movement want a new option. They argue that the original design and incentives of the patent system no longer correlate with the contemporary patent system and in fact hurt innovation rather than promote it (Boldrin and Levine 2013; Gold et al. 2010).

But the patent application process has become a behemoth of litigation, paperwork, and high price points. For many small businesses the cost of applying for a patent is too high, and the cost of defending one is well out of reach. In addition, the paperwork to get a patent and the time it takes to get one hinder innovation—the process is too time consuming and the patent is out of date by the time it's awarded.

The patent system has also been criticized for its loose definition of "unique." As lawyer Tom Ewing pointed out in an interview on *This American Life*, "It took 121 years for us to get the first 1 million patents. Now it takes more or less six years to get another million patents" (Glass et al. 2013). Have humans really become 10 times more innovative since the last century, or has the patent system changed its standards?

Parallels are often drawn between the Industrial Revolution and the Internet Age, with both viewed as eras when inventors focused on shortening time and geographical distances. But it can be argued that there was more dramatic innovation during the Industrial Revolution than in the Internet Age (Gordon 2017). The USPTO awards many patents for things that aren't unique, making it difficult to measure innovation by the number of patents awarded.

The rise of OSHW occurred partially in response to frustrations with the current patent system. Today's inventors are looking for other incentives; some find motivation enough for sharing their hardware in the knowledge that they'll receive attribution. Just as sharing and personalization have taken a front seat on social media platforms, there is interest in extending the capacity for hardware entrepreneurship to reap the benefits of sharing by allowing for personalization (von Hippel 2006).

Benefits to Open Source Hardware

Open source products benefit from community collaboration, allowing for more refined iterative products and processes. Designers get the benefit of standing on the shoulders of those who came before without the fear of litigation when they borrow for OSHW. Businesses that follow open source principles are more likely to succeed because they have to listen to their customers to survive and compete instantly in the marketplace by responding to consumer interests (e.g., color, features, cost).

Entrepreneurs have many reasons to choose OSHW over patenting an innovation:

- If organizational support for a product or project disappears (e.g., a company goes out of business), the design files can still be used and produced by others, so the product can live on and continue to evolve.
- Open hardware makes the design easier to scrutinize, which generates feedback and helps make the hardware more robust and better engineered.
- Widespread review by an active and growing community makes it easy for new users to find troubleshooting advice.
- OSHW lowers barriers to entry while increasing competition for companies to continuously improve the quality and usability of their products.
- OSHW allows for product personalization, which can change the form and function of a product. For example, it's arguable that the Arduino team would never have come up with a microcontroller to be sewn into clothing, but Leah Buechley created a specialized type of Arduino by altering both the form and function to create the first sewable microcontroller, the Lilypad (Gibb 2010).

OSHW depends on derivative works (Gibb 2015), which can be altered in many ways or directly copied, as long as they are properly attributed. They may include changes that are not part of the physical piece, such as economic or geographic alterations that bring hardware to a new price point or a new part of the world.[2]

As the founding entrepreneur of an OSHW company, Nathan Seidle (2012) explained in a TEDxBoulder talk that OSHW makes products more innovative and helps his business stay on its toes. He observes that pioneering companies that focus on patents and litigation rather than allocating their funds to continued innovation may become "unfit" for competition and even risk bankruptcy. Conversely, using and building open source hardware yields "millions of dollars of economic value from a relatively simple scientific device being released under open licenses representing orders of magnitude increase in value from conventional proprietary development" (Pearce 2015, p. 1).

The OSHW Community

Industries and Products

First used in conjunction with ham radio, OSHW became popular in the electronics industry in the late 1990s (Mota 2013). It now spans industries and sectors from tractors and automotive design to ecology, disaster relief, and fashion, and involves people who identify with more than 45 job titles, from engineer to journalist (OSHWA 2013).

The first large-scale OSHW success was the Arduino open source electronics platform, produced by a team at Interaction Design Institute Ivrea and now a permanent OSHW feature (Gibb 2015). Its component-level modification, breakout boards, and electronic kits have become standard, and advances in open source tools include laser cutters, CNCs, and 3D printers.

OSHW spans industries and sectors from tractors and automotive design to ecology, disaster relief, and fashion.

Open source is proving to be a leading attribute of 3D printers, and the companies that design and sell them are excelling and growing faster than their closed counterparts (Kenny 2015).

Hackerspaces

Hackerspaces (also called makerspaces) are collectives where people experiment with art, technology, and science, generally using nontraditional methods for innovation and shared space, tools, and knowledge (Mota 2015). Many spaces offer classes and have open hack nights for the public to learn some tricks of many different trades. The maker market (where not all items are

[2] Derivatives aren't just for open source materials. In music, for example, covers and remixes have always proliferated regardless of IP protection, leading to the statement that "everything is a remix" (Ferguson 2012).

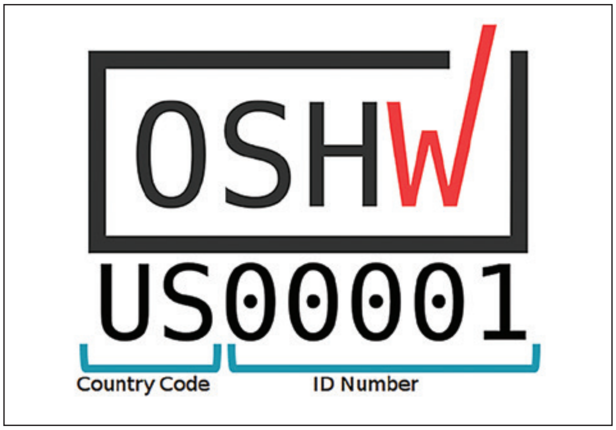

FIGURE 2 The Open Source Hardware Association (OSHWA) certification logo.

open source) is projected to be an $8.4 billion industry by 2020 (Bajarin 2014).

The OSHW movement, similar to the do-it-yourself (DIY) and maker movements, is not a new concept but rather a revitalization of historical methods that were displaced as modern manufacturing came to the fore (Sale 1995). Producing hardware cheaply and efficiently, modern manufacturing created a consumer culture rather than a DIY culture. That change, combined with fear of students getting hurt, led many schools to drop shop classes and other hands-on classroom experiences. In the past 10 years, though, the pendulum has begun to swing back in favor of creating and fixing things as shop classes pop up again and websites offer DIY instruction (Quinton 2013).

These trends promote the growth, both nationally and internationally, of the OSHW community. Data show OSHW projects in 79 countries (OSHWA 2012, 2013)—and this number may be an underestimate because the survey was in English.

The Open Source Hardware Association

In 2012 a newly formed 501(c)3 nonprofit association for OSHW took on the challenge of advocating, educating, and uniting stewardship of the OSHW movement. The Open Source Hardware Association (OSHWA; pronounced ah-shwa) aims to be the voice of the OSHW community, to ensure that technological knowledge is accessible to everyone, and to encourage the collaborative development of technology that serves education, environmental sustainability, and human welfare (oshwa.org/about).

OSHWA hosts and funds the annual Open Hardware Summit, seeks translations for the OSHW definition, and creates international branches. In 2016 it established OSHW certification and led a session at the White House.

Certification

OSHWA launched a certification program in October of 2016, in response to a request from both hobbyists and Fortune 500 companies.

Hardware certification is important because it is difficult to license hardware without a patent. But most OSHW companies and hobbyists do not want to go to the trouble and expense of getting a patent. As a solution, OSHWA produced a trademarked certification, with a logo (figure 2) for companies that wish to apply it. This solution doesn't protect the hardware or give the user the same protections as a patent, but it allows for some legal recourse if a company uses the trademarked OSHWA logo without adhering to the OSHW definition.

Within six months of the OSHW certification launch, companies and hobbyists in nine countries certified more than 100 projects or products.

Civic Engagement

In June 2016, as executive director of OSHWA, I was honored to lead a session on OSHW innovation for a "Maker to Manufacturer" event hosted by the White House Office of Science and Technology Policy.[3] Participants suggested the following ways to move open source innovation forward with OSHWA's help.

The OSHW community needs to better explain the value proposition of OSHW, by, for example, offering educational experiences for policymakers and illustrating the social change and rapid innovation associated with OSHW. It also needs to clarify how licensing technically works with OSHW, although the latter has been partially addressed through the certification program.

At the government level, (1) the OSHW community would like to be part of any process that might impose limits through regulations that affect IP and hardware. (2) The creation of scalable standards and taxonomies for OSHW would be beneficial. (3) Conversations should strategically begin in particular hardware fields best suited to introduce, educate, and advance with OSHW. (4) Tax incentives for OSHW inventors and entrepreneurs to share their source publicly for the good

[3] The session took place during the Maker to Manufacturing Stakeholder Engagement portion of the National Week of Making, June 17–23, 2016.

of rapid innovation, forgoing a monopoly, would be helpful. And (5) the USPTO needs to be more aware of open source prior art to help broaden the IP landscape.

From a university perspective, change must happen in tech transfer offices for innovation to move forward. Too often universities have IP constraints stemming from the Bayh-Dole Act, which prohibits follow-on inventions from taxpayer-funded research and can prohibit the inventor from continuing to innovate.

From an industry perspective, researched case studies on the business of open source would be helpful to companies looking to join the community, together with some education about how risk-averse IP practices such as patents have a trickle-down effect on innovation that can affect entire industries. Companies could benefit from an open toolbox of the first 1,000 common pieces needed for any project or a “simple things” database with the source for building blocks. In some industries sharing test results would be helpful to support the reproducibility of scientific studies.

Looking to the Future

In addition to the suggestions above, the following ideas can move open source hardware forward and make the OSHW movement stronger.[4]

A “Laundry Label” for Hardware

The laundry label concept, proposed by Tom Igoe and Catarina Mota (2013), is a labeling system to identify the specific attributes of each piece of hardware, similar to clothing labels that state the fabric content and provide instructions for washing. (It is also referred to as a nutrition label.)

This label is different from the OSHW logo or OSHW certification logo, both of which simply state that the hardware complies with the OSHW definition. The laundry/nutrition label might contain information such as which pieces and design files are open and which closed, which software includes libraries of the parts, which parts need to be verified again by a standards entity (e.g., the Federal Communications Commission) after alteration, and how to recycle the hardware. For resellers, the label might list the amenities associated with a product, such as whether it has a 3D design file.

Further Protections

The use of prior art allows OSHW to be recognized as open. But the US Patent and Trademark Office (USPTO) does not always find prior art when reviewing patent applications. One benefit of an OSHW repository or database is that the USPTO could check it against patent applications for prior art.

The USPTO needs to be more aware of open source prior art to help broaden the IP landscape.

OSHWA is the institution best situated to undertake the above-mentioned tasks, and many people are asking it to do just that. Although implementation may take a while, the best way for OSHWA to tackle this is to establish a way to easily identify which projects are open source through the OSHW certification program. One can imagine a future where the USPTO has a poster of the OSHW logo to compare with logos on source files in order to identify valid OSHW.

Conclusion

To continue to spread and improve, open source hardware needs all industries to participate, especially engineering. It is my hope that, next time you’re working on a hardware project, you’ll ask yourself if there is an open source version out there. Check the OSHW certification database (http://certificate.oshwa.org/certification-directory/) and start looking for the OSHW logo on items.

Together, we can create an open source world.

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[4] This section draws from Gibb (2015), pp. 281–282.

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Conventional wisdom says businesses have to keep secrets to stay competitive. But do they?

Freedom Reigns in Desktop 3D Printing

Ben Malouf and
Harris Kenny


Ben Malouf


Harris Kenny

Many companies obsess over patent monopolies. Established technology firms spend millions on infringement litigation, crushing would-be competitors before they can get traction. And startups generally begin spending money on patent attorneys before they even earn revenue.

But free software projects like GNU/Linux and Wikipedia and the RepRap[1] desktop 3D printer movement demonstrated a business opportunity in doing the opposite. In January 2011 Jeff Moe founded Aleph Objects, Inc. with the goal of building a *f*ree software, *l*ibre[2] innovation, and open source hardware (FLO) company that shares everything freely. From computer-aided design (CAD) files to assembly line layouts, the company would be built on an unconventional (for hardware) foundation of complete transparency.

By 2016 Aleph Objects was the fastest-growing privately held computer hardware company in the United States on the *Inc.* 5000 list.[3] It employs nearly 150 people in Loveland, Colorado, where its LulzBot 3D printers are

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[1] "RepRap" stands for *rep*licating *rap*id prototyper.

[2] The term "libre" has been adopted to convey the freedom (of access, use, and discovery) that comes with free and open-source materials, not only the lack of cost.

[3] Available at https://www.inc.com/profile/aleph-objects.

Ben Malouf is director of marketing and Harris Kenny is president, Aleph Objects, Inc.

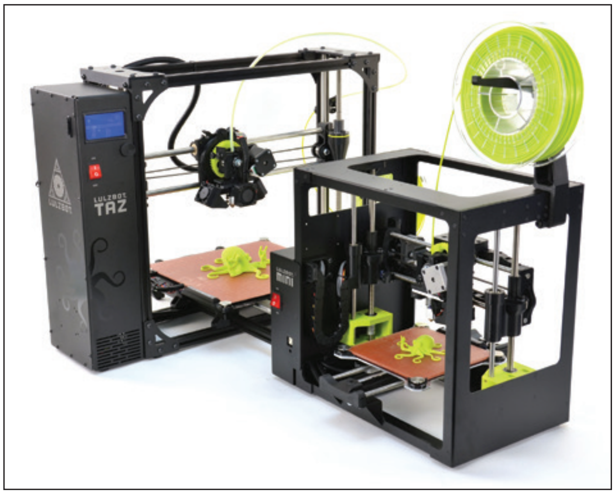

FIGURE 1 The LulzBot TAZ 6 (left) and LulzBot Mini Desktop (right) 3D printers. The 3D-printed bright green "rocktopuses" represent a mascot for the LulzBot brand. License: CC BY-SA 4.0 International by Aleph Objects, Inc.

designed, built, and delivered to market. The printers (figure 1) are known for their quality, ease of use, and reliability, and the company's market share continues to grow.

Much of the desktop 3D printing industry reflects FLO values, with companies leveraging collaborative communities to innovate and grow. The industry has experienced rapid innovation and development since free software and open source hardware became driving forces.

We review RepRap and the history of FLO in desktop 3D printing and how a collaborative spirit and respect for user freedom have fueled dramatic growth and built an active and devoted user community.

The RepRap Project

What Is 3D Printing?

3D printing is a method of creating an object with a computer-controlled machine via an additive process that draws on hardware, software, materials, and content. None of these four drivers can be extricated from the others, they are all interdependent. Therefore, progress in the development of 3D printing technology requires multidisciplinary contributions from numerous individuals, typically over an extended period of time.

Insights from widely varying industries, technologies, and products are all combined to advance 3D printing technology. RepRap was successful because, as a FLO project, it brought all four drivers together in collaboration.

RepRap Innovation and Evolution

The RepRap project was born in England at the University of Bath in 2005, brainchild of Adrian Bowyer, a senior lecturer in mechanical engineering.[4] The aim was to build an affordable, self-replicating, freely shared desktop 3D printer. Fundamental to the idea was that one RepRap could be used to 3D print the components to build another. In addition, the components could be given to someone else, who could do the same.

Philosophically, a big part of the idea behind RepRap was to democratize the tools of manufacturing, disrupting the concept of where *things* come from, changing the source from a factory overseas owned by a large corporation to a desktop machine in one's own home, office, classroom, or library. Further, entirely freeing the hardware component of the tool chain enabled greater versatility and much faster innovation.

In May 2008 the second RepRap 3D printer, itself printed by the first (figure 2), printed a part for a third "grandchild" machine. Thanks to the Internet, the RepRap project was almost instantly an international endeavor with teams and individuals around the world building their own 3D printers.

Also inherent in RepRap was the concept of evolution. As mechanical engineers, tinkerers, and hackers around the globe built their own printers they made improvements and shared them with the community. Some changes were iterative, a tweak here and there to make assembly easier; some were wholesale redesigns aimed at lowering cost, increasing performance, and simplifying assembly. Many early contributions focused on hardware as the starting point, identifying and implementing improvements to the functioning of the machine based on physics and mechanical engineering principles.

Hardware: Technology and Materials

RepRaps leverage fused-filament fabrication (FFF) 3D printing technology: a thermoplastic filament is forced through a heated nozzle (similar to the way a hot glue gun functions) and the melted plastic is applied in successive layers until an object is fully formed. Aside from their 3D-printed components, early RepRap 3D printers were largely composed of things like steel threaded rods, screws, nuts, washers, and plywood that could easily be sourced at hardware stores.

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[4] Information about RepRap history, hardware, and software is available at https://en.wikipedia.org/wiki/RepRap_project.

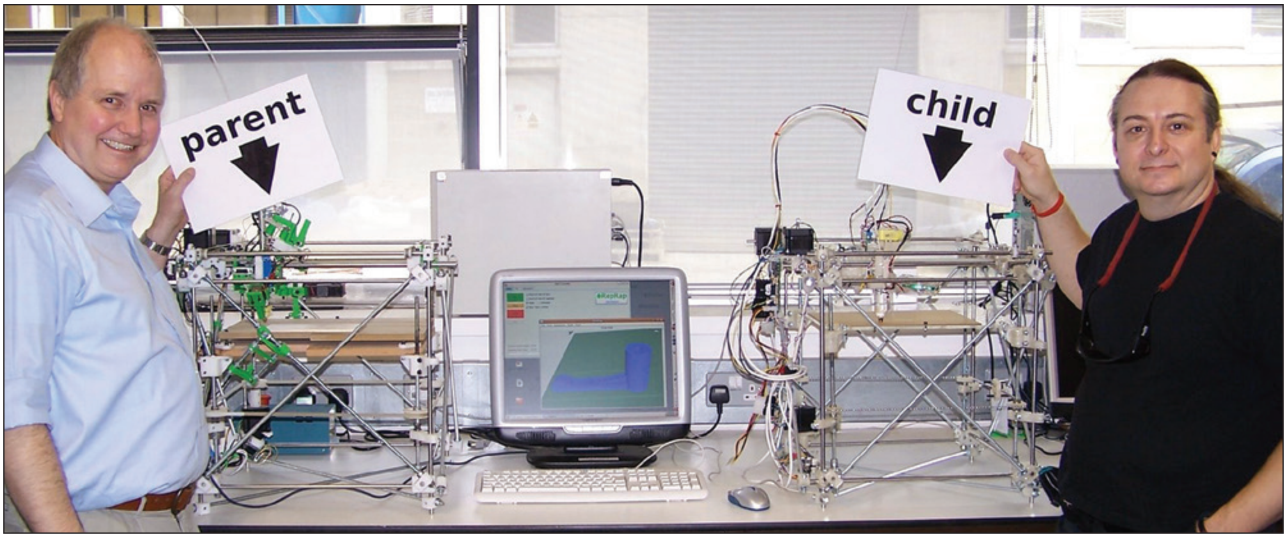

FIGURE 2 Adrian Bowyer (left) and Vik Olliver (right) with a "parent" RepRap machine, made on a conventional rapid prototyper, and the first complete working "child" RepRap machine, made by the RepRap on the left. The child machine made its first successful grandchild part a few minutes after it was assembled. License: CC BY-SA 4.0 International by RepRap.org.

RepRap electronics were controlled by open source hardware Arduino development boards running free software firmware. Other components, like stepper motors, belts, and hot end parts, were slightly more difficult to source but could be purchased online if not found locally. Thanks to shared bills of materials (BOMs), it was easy to find good sources of specialty components. And startups emerged to offer commonly needed RepRap parts, kits for building machines, and reels of plastic filament.

Early material development efforts focused on finding commonly available plastics that would be compatible with the hardware specifications being developed. Plastics common in early use included high-density polyethylene (HDPE), acrylonitrile butadiene styrene (ABS), and polylactic acid (PLA). Many other experimental materials were adopted and modified from other industries and applications, but ABS and PLA proved to be the most useful and easy to work with. As the project grew, materials science and filament extrusion companies developed to greatly expand the number of materials available for RepRap 3D printers.

Software

Of course, software was required to operate the machines. 3D CAD files had to be converted into tool paths that the 3D printer firmware could execute. G-code, a programming language in use since the 1950s and still common in computer numerical controlled (CNC) milling machines and laser cutters, was an obvious choice. In essence, it tells the 3D printer's tool head how to build the object—where to go and how fast to get there, with simple coordinates, layer by layer.

In line with the collaborative mentality of the RepRap project itself, developers began work on free software tools to run the printers. The first was developed by Bowyer and was simply called *RepRap Host*.

In 2009 a more accurate and full-featured application called *Skeinforge* was released by Enrique Perez. *Skeinforge* was the default slicer and printer host software for most early RepRap users, but it was both notoriously slow at processing files and complicated to configure. Eventually, *Slic3r/Pronterface* and *Cura*, also free software, made leaps in functionality and ease of use and became the standards in the RepRap community. They remain in active development, with numerous forked versions specific to different printer brands available. Other free software options (e.g., *OctoPrint* and *Matter Control*) have emerged, adding features such as wireless and network functionality.

3D Model Files

As the number of RepRap 3D printer owners grew exponentially, so did their demand for content—3D models—to print on their machines. Free software 3D modeling options (e.g., *Blender*, *FreeCAD*, and *OpenSCAD*) grew with the hardware community. Users flocked to these resources because of the free licensing, ubiquity of freely licensed tutorial content, no-cost availability, and continuing improvements in reliability and ease of use.

A 3D model created in native file formats needed to be exported in a standardized format that could be easily converted to G-code. The de facto standard became sharing the 3D model file in .stl or .obj format, simple mesh 3D model files, which the printer operator would then convert to G-code in their slicing software of choice.

The standardized and open file format enabled rapid proliferation of content across the Internet. One of the earliest and most successful websites to facilitate this sharing was Thingiverse; others are YouMagine, Pinshape, Yeggi, GitHub, and Repables.

Like the hardware and software, the model content was also generally freely licensed and shared, most commonly through Creative Commons Attribution (CC BY) and Creative Commons Attribution-Share-alike (CC BY-SA). An increasing number of public domain models are also being created as digital derivatives of sculptures, busts, vases, statues, and other antiquities and works of art.

Users need products that will ship immediately, work directly out of the box, and include access to technical support.

RepRap's Legacy

Fast forward to 2017. While desktop 3D printing has been largely commercialized, with hundreds of thousands of such printers sold annually, the legacy of RepRap is still evident in the roots of almost every machine on the market. 3D printer brands like LulzBot grew out of the RepRap movement and remain committed to their free software and open source hardware roots. In addition, supporting the original equipment manufacturers are numerous companies offering accessories, aftermarket parts, and an ever growing variety of filament materials.

The desktop 3D printing category simply never would have developed so quickly were it not for the collaborative community that formed around RepRap.

Selling Technological Freedom

Free Software: A Success Story

Red Hat, a software company based in Raleigh, North Carolina, shares all its code under free and open source licenses. It is a multibillion-dollar publicly traded company. How has it achieved so much success?

The company's founders recognized that the stability, flexibility, and security of free software GNU/Linux-based operating systems were extremely appealing to enterprise customers. What was not appealing was the prospect of building an IT team to deploy and support the software since there was no central organization developing, selling, and supporting it. Red Hat filled the niche, offering corporate customers a tested and supported version of a GNU/Linux operating system.

Red Hat has grown without compromising its commitment to FLO principles by being a service-based, highly customer-focused organization. Its customers appreciate its software and world-class support, and the community respects its contributions to free (and open source) projects.

Could the same model work with open source hardware?

Open Source Hardware: Improving on RepRap

When Jeff Moe founded Aleph Objects, he didn't set out to design and build 3D printers, he set out to build a successful open source hardware company, one that would make such hardware as influential as free software projects like GNU/Linux and Wikipedia.

By 2011 the RepRap community had designed, iterated, and heavily tested numerous designs. RepRap kits were available from a growing selection of sources online, but often with multiweek lead times, little to no assembly documentation, and generally limited technical support. The hobbyist RepRap community was growing and the printers were getting more sophisticated and capable, but businesses, educators, and other users needed a less time-consuming path to adoption, something that would ship immediately, that worked out of the box and included access to technical support.

Much as Red Hat had built a software company around making GNU/Linux easier for businesses to adopt, Aleph Objects would manufacture and sell assembled, calibrated, tested, and well-supported RepRap 3D printers. The bet was that customers who did not have the time or skill to build their own 3D printers from a kit, let alone calibrate and maintain them, would value the collaboratively engineered reliability and open source hardware versatility of RepRap 3D printers. To that end, the first LulzBot 3D printer, the Prusa v1.0 (figure 3), was developed.

As with Red Hat, foundational in the philosophy of Aleph Objects is a commitment to sharing all development under free and open source licenses. Hardware designs are not restricted by patent monopolies, or even kept secret. From day one, the public-facing development (devel) server has been automatically updated every half-hour with the latest working files from the Aleph Objects research and development (R&D) team, including not just CAD but BOMs, testing documentation, assembly instructions, and more. The greater 3D printing community is actively encouraged to learn from the files, build their own printers and components, and even sell clones if they are so inclined. Of course, all of this seems counterintuitive to anyone who has worked for a traditional hardware company, particularly in a global economy.

What is to stop another company from replicating the LulzBot machines and selling them at a discount? How does the company continue to succeed even as it seems to stack the deck against itself?

Going with the FLO

While it may look like a disadvantage from the outside, the FLO philosophy incorporates quality and a commitment to customer service. The philosophical reasons to share are easy to understand. Ownership of ideas has always been a troublesome concept, but even more so now, in the internet age, when information can blanket the world instantly.

Children are taught to share, but that ideal doesn't apply to adults in business. Conventional wisdom says the reason is that businesses have to keep secrets to stay competitive. But do they?

Scenario 1: The Monopoly Approach

Company A is founded around an idea for a widget. The novelty of the widget is considered a revelation, the reason Company A will succeed. Intuitively, it does not do Company A any good if Company B and Company C start making the same widget. Whether they came up with the idea on their own or copied it from Company A is immaterial.

Company A focuses on "protecting" the idea for its widget with a patent monopoly. Law firms and government programs exist to help companies do just that, so why would they question it?

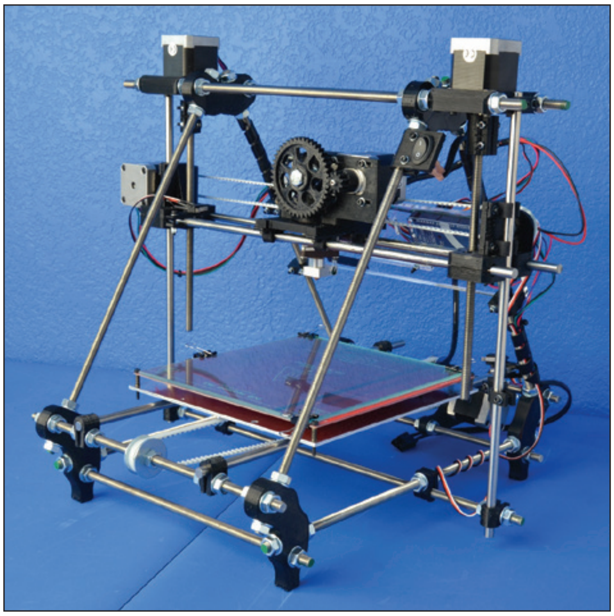

FIGURE 3 The LulzBot Prusa v1.0 (ca. 2011), Aleph Object's first commercially available RepRap 3D printer. License: CC BY-SA 4.0 International by Aleph Objects, Inc.

Several years later, Company A has cornered the widget market, selling 10,000 per month despite an unreasonably high price. The company makes minor improvements to its widget, adding and patenting little features and accessories here and there to boost revenue, but because it has a monopoly, there is little incentive to spend on R&D. Those funds are better allocated to marketing and lawyers.

Company B was sued by Company A for infringement and forced into bankruptcy. Company C never started up at all, never hired a staff, and never contributed to widget innovation.

Scenario 2: The Open Source Approach

In a collaborative, FLO-based scenario, Company A starts up around an idea for a widget, but does not keep it secret. It shares everything about it with the public, and before it has even started making the widgets, an online community has sprung up and is helping implement improvements to the design. From that community, Companies B and C have also started up, making their own (also shared) versions of the widgets. None of the companies can compete by simply having a widget. All three must focus on making the *best* widget for the best price, taking care of their customers, and getting improved versions of the widget to market faster. The rate of innovation and improvement is dramatically increased, customers are happier, and monopolies are avoided.

Real-Life Scenarios

Perhaps the examples above oversimplify things, but the business argument against patent monopolies and for collaborative innovation is not just a thought exercise. Companies like Tesla Motors have taken steps to disarm their patent monopolies, acknowledging the value in having innovative competitors and recognizing how their patent monopolies prevented good ideas from emerging.

> *With open source product development, the rate of innovation and improvement increases, and customers are happier.*

In desktop 3D printing, manufacturers favoring proprietary designs and restrictive print material choices have struggled to gain traction and/or maintain relevance, while more open companies have grown steadily, leveraging community participation and evangelism to improve products and build their brands.

Specific Commitments to Openness

Aleph Objects is committed to sharing and publishing all its development under free licenses that allow others to learn from and utilize the company's work in their own, and it puts a priority on maintaining the infrastructure to make this possible.

Public Access Servers

Here are the four primary public access servers maintained by Aleph Objects and what can be found there:

- download.lulzbot.com: complete source files for every LulzBot product released by Aleph Objects, minus development files that did not end up in the final product, managed with an Apache Webserver
- devel.alephobjects.com: work-in-progress source files, automatically updated every half-hour with working files from the LulzBot R&D team, managed with an Apache Webserver
- code.alephobjects.com: work-in-progress source code in development, managed with *Phabricator* (version control software)
- ohai.lulzbot.com: assembly and maintenance instructions, for both internal and customer-facing processes, managed with a custom Django web application (OHAI stands for open hardware assembly instructions).

By integrating the public servers into internal processes, Aleph Objects adheres to a "release early, release often" philosophy. Making R&D information available as it is created allows outside developers and potential customers to give feedback before prototypes are even built, let alone final products ship. This level of transparency has engendered a great deal of trust from the 3D printing community, whose core is still largely composed of former RepRap developers and operators who value control over the technology they use.

Internal Consistency

Further enhancing Aleph Objects' reputation in the FLO community, the company "eats its own dog food," so to speak. The entire company runs on free and open source software (all workstations run the Debian GNU/Linux operating system) and leans heavily on programs such as *Odoo*, *Drupal*, *FreeCAD*, *Blender*, *Libre Office*, *NextCloud*, *OpenProject*, and *Phabricator*.

The company benefits in numerous ways, including access to and control over its systems, input into the features and offerings of the tools it uses, rapid scalability of its infrastructure, and avoidance of licensing and support fees associated with proprietary software. LulzBot customers benefit by not having to pay for expensive proprietary software to make use of shared source files from the company.

Open Source Certification

Two independent organizations have built programs to certify open source hardware, the Free Software Foundation and the Open Source Hardware Association. The former has a program for certifying hardware products called Respects Your Freedom,[5] and the latter governs the Open Source Hardware certification program (http://certificate.oshwa.org/). Both programs serve to quell the

[5] Information about the certification program and a list of certified products are available at www.fsf.org/resources/hw/endorsement/respects-your-freedom.

growing practice of "open washing," or using the term "open source" in marketing materials to earn a nod from the community while not actually adhering to any open source principles or practices. At the time of this writing, LulzBot 3D printers are the only FFF 3D printers to have either certification, and the only 3D printer of any kind to have both.

Mass Replication

Finally, Aleph Objects still adheres to the RepRap ideal of using 3D printers to make more 3D printers. At the heart of the company's manufacturing facility is the Cluster: more than 150 LulzBot 3D printers operating 24/7 to print components used to build more 3D printers. The Cluster is an unparalleled test environment for design changes and new products. It can quickly accumulate thousands of hours of test data, driving a better customer experience when new products are released.

To date, Aleph Objects has printed nearly 2 million printer components. The Cluster has also enabled the company to scale as demand has increased by simply adding more printers. Further, LulzBot users can 3D print their own replacement parts or design their own modifications.

The Open Future

Aleph Objects' R&D team is working on development of its next-generation LulzBot 3D printer, code-named "Athena." Like other LulzBot 3D printers, its development is shared publicly on the devel server.

Athena represents a departure from some of the early RepRap hardware and software, demonstrating some exciting leaps forward. It will feature all-new electronics with a control board running embedded GNU/Linux, and state-of-the-art, nearly silent motor controllers. The tool head will have on-board logic and a kinematic semipermanent electromagnet coupling that enables the printer to exchange tool heads during a print. The machine is slated for release in 2018.

Conclusion

Desktop 3D printing started as a free software and open source hardware project, and with those roots FLO principles have remained a driving force in the industry. Recently, IC3D, a maker of premium 3D printing filaments, released the world's first open source hardware–certified filament.[6] While 3D printers, 3D printing software, and 3D model content have been freely licensed for years, this is the first time a filament manufacturer has made such efforts. The move opens up a whole new category of technology to the community and serves as another example of FLO's expanding role in the industry.

Desktop 3D printing started as a free software and open source hardware project, and FLO principles remain a driving force in the industry.

The desktop 3D printing space has changed radically since the early days of RepRap, with many once-dominant manufacturers losing ground and former upstarts claiming their market share. The latter succeed by partnering with the community and sharing progress and lessons learned.

Looking ahead, effective companies must continue to focus on their users and to maintain a rapid pace of innovation. Thanks to the pioneering collaborative efforts of RepRap designers, free software developers, materials scientists, and content contributors, FLO—free software, libre innovation, and open source hardware—development continues to drive innovation in the 3D printing industry.

[6] Open Source ABS 3D Printing Filament (Rev 0), available at Github.com.

3D printing is revolutionizing innovation and may require adaptation of intellectual property protections.

Reevaluating Intellectual Property Law in a 3D Printing Era

Lucas S. Osborn

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How will three-dimensional (3D) printing technology (also known as additive manufacturing) challenge presumptions in intellectual property law? The technology democratizes design, distribution, and manufacturing such that these activities are accessible to even moderately skilled individuals.

Millions of makers will thus, knowingly or not, interact with intellectual property law as they go about creating, tweaking, and sharing designs (Gibb 2014). For example, an open design heat exchanger may unwittingly infringe another's patent. Moreover, goods that have an aesthetic element to them may infringe another's copyright, trade dress (e.g., a product's packaging or design), or design patent. Importantly, individuals or companies can be guilty of infringement *regardless of whether* they intended to infringe or even knew about the intellectual property right involved.

Brief Introduction to Intellectual Property Rights

Intellectual property (IP) law includes copyrights, patents, trademarks, industrial designs (design patents), and trade secrets. In this article I review basics of the law that are most relevant.

Copyrights

While most laypeople may be familiar with copyrights, which protect creative expression such as literature, drawings, music, movies, and sculptures, they often do not realize how easy it is to obtain copyright protection for a work. The work need only meet the following criteria:

1. not be copied from something else,
2. be fixed in some tangible medium (e.g., written on paper, stored on a disk), and
3. contain a modicum of creativity.

Copyright protection *automatically* attaches to work that meets these three criteria (although there are benefits to obtaining a federal copyright registration, which can often be done for about $100). Thus, a 3D-printed sculpture (which is creative), as well as the STL (stereolithography) file of it, receives automatic protection.[1]

Purely utilitarian objects, such as a basic shovel, are not copyrightable. But what about the STL file that will print the shovel? Intuition might suggest that if the shovel is not protected, the STL file ought not to be either. But the law is not that clear.

Of particular relevance to 3D printing, the copyright statute specifically identifies "technical drawings," like traditional blueprints, as copyrightable. Is an STL file sufficiently like a blueprint to also enjoy protection? This is unsettled, and depends in part on how courts will interpret copyright law's requirement for a "modicum of creativity."

Traditional blueprints have creative components that many STL files will not, such as the choice of perspectives to display and which parts to label (recall that only a "modicum" of creativity is required). Most STL files include only the information required to manufacture an item; if that item is purely utilitarian, then arguably there was no creativity (in the copyright sense) in making the file. Such questions are yet to be answered.

Importantly, a person does not need to be aware that something is protected by copyright to be liable as an infringer. Ignorance is not bliss. At the same time, for copyright infringement the accused must actually copy the protected work. This could be as simple as making a copy of the file on one's computer.

Patents

Patents protect utilitarian inventions such as new mechanical or electrical devices, processes, and chemicals. Compared to copyrights, obtaining a patent is much more difficult. The invention must be, among other things, (1) new, (2) not obvious, and (3) useful. Furthermore, rights attach only once a patent is issued, and patents take years to procure and cost thousands of dollars. If someone owns a patent, she can prevent others from making, using, selling, and offering to sell the invention.

But a patent only specifically protects "claims," a term of art that refers to the enumerated sentences at the end of a patent. For example, the background portion of a patent may discuss the history and state of the art of heat exchanger technology, but claim number 1 may specify a "shell and tube heat exchanger where the outer layer of the tube is lined with alloy X." Such a claim would generally only be infringed by a similar heat exchanger with a tube lined with alloy X.

Focusing on claim language is important for 3D printing. If someone owns a patent that claims a physical heat exchanger, for example, that patent will not directly protect against someone who merely makes and sells a 3D printable *file* of the heat exchanger. Someone with the file must physically print the heat exchanger (or otherwise sell, use, etc. the physical item) for there to be direct infringement.[2]

Purely utilitarian objects, like a shovel, are not copyrightable. But what about the STL file that prints the shovel? The law is not clear.

Liability in patent law is even stricter than in copyright. As with copyright, an infringer need not be aware of the patent. But unlike copyright, in patent law an infringer does not even need to copy someone else's work to be liable.

Trademarks and Other Protections

Other IP law will be highly relevant to the 3D printing industry. Trademarks, for example, protect product

[1] In this article I refer to any 3D printing file generically as an STL file.

[2] A patent owner may be able to stop someone from distributing the file based on an "indirect infringement" theory, but this article does not delve that deeply into patent doctrine.

brand names and logos. Trademark law also covers "trade dress" rights when, for example, a product's design is so distinctive that it indicates to consumers that the product comes from a particular source.

Design patent rights (generally referred to as "industrial design rights" outside the United States) protect ornamental or aesthetic aspects of a utilitarian article, such as the pleasantly shaped contours of a smart phone.

Finally, trade secrets protect virtually any information or technology that gains some value from not generally being known. They may be alloy compositions or complex manufacturing specifications. One of the most well known and most valuable trade secrets is the Coca-Cola recipe.

The Incentive Theory of Patents and Copyrights

Although each area of IP law will be important to 3D printing technology, this article focuses on patent rights and their relevance to open source hardware designers.

Proponents of the patent system justify it in large part as an incentive to invent. The idea is that only the first innovator must sink large amounts of capital into researching and developing an innovation. Follow-on competitors can charge a lower price for the product while the first innovator loses in the marketplace because it cannot charge a price high enough to recoup its R&D costs.

Patents can discourage follow-on research by preventing others from using and improving on a patented technology.

The patent system purports to provide innovators with the incentive to invent (and to disclose and commercialize those inventions) by granting a 20-year exclusive right to "make, use, sell, and offer to sell" the innovation. The copyright system is organized around a similar rationale: People won't write as many books or make as many movies if these works can be copied with impunity and sold at a cheaper price.

Unfortunately, the patent system imposes certain costs on society. First, by giving an exclusive right to its owner to make, use, sell, and offer to sell the invention, a patent allows the owner to sell the invention at an inflated price, assuming there are no reasonable substitutes. The higher price creates a deadweight loss because some purchasers, who would have bought the product at a lower price, are priced out of the market for the item (Merges and Nelson 1990).

Second, the patent system imposes a societal cost by impeding follow-on technology. Inventions are cumulative: inventors build on them to create new ones (Scotchmer 1991). Patents can discourage follow-on research by preventing others from using and improving on a patented technology. In this way, longer patent terms can slow the rate of cumulative research advances.

The *theory* of the benefits and costs of the patent system is well known. Ideally, a patent system appropriately balances the costs and benefits of patents to maximize the benefits to society. But the *actual* costs and benefits of the patent system are not well known. Because the system is so complex, scholars have noted for decades that it is not possible to know for certain whether the current patent system is a net benefit or not (Merges 2011).

How IP Law Can Help 3D Printing Technology

Even without fully knowing the costs and benefits of IP law, one can catalogue some ways the law might help 3D printing technology and open source design.

Advantages

Patent law might provide the incentive needed to research and develop a new 3D printer or printing material. In addition, if IP rights protect certain computer-aided design (CAD) or STL files, such rights incentivize creation of those files and the objects they will manufacture.

Beyond the traditional "incentive" benefits, however, IP law is key to open source initiatives. Open source software, for example, relies on copyright law to prevent downstream users from "enclosing" a software product (i.e., selling it as a non–open source proprietary product): if downstream users violate the terms of the free open source license by enclosing a product, they become copyright infringers.

Without copyright law, an original open source provider would have little control over downstream users. Although the original provider would have a breach of contract claim if someone to whom he *directly* licensed breached the license agreement, the claim would not necessarily reach users further down the chain if there is no privity (i.e., contractual connection) between them and the original licensor (Osborn 2017). Copyright infringement claims, however, do not require privity. The ability to control multiple generations of downstream users is a key distinction between open source software and public domain software.

As with software, open source hardware designers who want to control multiple generations of downstream users (e.g., to prevent them from enclosing aspects of the design) need help from IP law. Designers can rely on patent law, or in some cases copyright law, to prevent downstream users from enclosing certain designs.

Challenges

One drawback to using patent law is that patents are difficult to obtain. An inexpensive patent may cost $8,000 and take three years to procure. By then, the open source community may have moved on from a given design.

Patents are expensive and time consuming to obtain in part because patent law is complex. Not only must the inventor create something that meets the criteria enumerated above, in the patent application she must describe how to make and use the invention and draft "claims" that specify what she wants to protect. Claim drafting is a highly nuanced undertaking that professional patent attorneys or patent agents typically perform (with accompanying costs).

Copyrights, on the other hand, are comparatively cheaper and easier. As indicated above, copyright protection automatically conveys for creations in a "tangible medium of expression," such as writing. Federal registration for a copyright can cost less than $100, and laypeople can generally file for the registration without attorney assistance.

Copyrights may be of limited value to makers of hardware, however, because they do not protect utilitarian objects, only creative expression. As mentioned in the introduction, hardware designers may still benefit from copyright protection for an STL file because the threshold for what counts as "creative" expression is extremely low: simple prose, simple pictures, and simple software code can suffice.

The copyright statute's applicability to technical drawings has particular salience to open source design. If an STL file of a useful object can constitute a "technical drawing," it may receive copyright protection, but only if the technical drawing contains a modicum of creativity (Osborn 2014). But this is an unsettled question in the law: Does a CAD or STL file of a heat exchanger contain copyrightable creativity (Osborn 2017)? Even if copyright law protected a file, it would prevent only slavish copying of the file. It would not prevent someone from independently creating her own design file of a heat exchanger.

The ability to control multiple generations of downstream users is a key distinction between open source and public domain software.

Given the importance of IP law to open source licensing, open hardware designers should become familiar with it.

How IP Law Can Hinder 3D Printing Technology

Intellectual property law can slow 3D printing technology development if it overprotects rights holders. Overprotection implies that the costs (deadweight loss from higher prices and slower follow-on innovation) outweigh the benefits (incentives to create, invent, and commercialize).

Too Much Incentive?

If patents are stronger than needed to incentivize innovation, society may needlessly endure some of patents' negative effects. Thus, policymakers must understand that 3D printing technology significantly reduces the cost of innovation (Osborn et al. 2016).

- Building and modifying prototypes is markedly easier and less expensive.
- The technology also allows multiple designers to collaborate remotely to improve a product iteratively.
- Once a product is finalized, 3D printing technology lowers the costs of distribution by allowing users to share the design files instantaneously over the Internet.
- The technology revolutionizes manufacturing by allowing users to "print" items remotely.

People therefore need less monetary incentive to engage in these activities. In these ways 3D printing challenges the fundamental cost-benefit analysis undergirding the current US intellectual property system. Moreover, people invent and create for nonmonetary reasons too—just consider the open source hardware movement. People may innovate because they love the innovation process, or for professional or community recognition, or to improve the world (Raustiala and Sprigman 2012).

As the need for monetary innovation incentives shrinks, nonmonetary incentives provide proportionally more of the incentive to create. If the cost to invent or create is near zero, then the standard incentive-based IP theory largely disappears; there are no "sunk costs" that need to be recouped, and nonmonetary incentives might supply sufficient fodder for creation (Lemley 2015).

Reevaluating Intellectual Property Law

In such a world, lawmakers will need to reevaluate IP law. Some will suggest abolishing patents and copyrights, at least in certain technology sectors (such as 3D-printable goods). But that might be overly hasty, because 3D printing technology also makes copying cheaper and easier. This has at least two effects.

> *Without IP protection, copiers will not need to attribute anything to the inventor.*

First, even innovators who experience relatively modest costs to create are vulnerable to being undercut by copiers. With 3D printing technology, copying another's design files can be costless and instantaneous. Thus, IP law may remain salient simply from a cost perspective.

Second, copying can dampen even nonmonetary incentives. For example, someone who creates a new product may want some sort of recognition for the accomplishment and/or may want to control how it is used and distributed. But without IP law of some sort (or perhaps contractual protections), free riders will not need to attribute anything to the first creator. Person A may do all the work, but person B may get all the credit.

Thus, even with mature 3D printing technology, society will likely benefit from some form of IP or other legal protection, though perhaps the term of protection could be shorter. Even before 3D printing fully matures, however, policymakers should analyze IP laws and consider rebalancing them in the face of this technology.

Mechanisms for Rebalancing IP Rights

One way lawmakers can rebalance the strength of IP rights is by shortening the term of protection (Osborn et al. 2016). Today most copyrights last for the life of the author plus another 70 years, and patents last 20 years from the date they are filed. One can reasonably argue that lawmakers should shorten these periods given the decreased costs of innovation for 3D-printable products. Policymakers will debate how much to shorten them, and there is certainly no magic number. I suggest that lawmakers shorten the term enough to enable measurement of the change's impact; for example, taking at least 5 years off the 20-year patent term.

Changing the terms of patents and copyrights would, however, weaken those IP rights across all technology sectors, not only for 3D-printable products. Alternatively, lawmakers may want to weaken patents only in certain technology sectors. For example, commentators tend to agree that the software industry has much less need for patent protection than does the pharmaceutical industry (e.g., Kesan and Gallo 2009). Pharmaceutical companies might spend more than $1 billion to develop a single successful blockbuster drug (with many failed drugs along the way), whereas software companies (where technological failure rates are much lower) might spend several orders of magnitude less to develop a successful program. Moreover, software enjoys separate copyright protection against slavish copying.

Lawmakers thus might lower patent strength in specific industries where 3D printing (or other technological improvements) has lowered the costs of research and development. And rather than simply shortening the patent term for "sectors affected by 3D printing" (a vague and changing category), lawmakers could use patent law doctrine selectively for goods affected by 3D printing.

Although technical patent doctrine is beyond the scope of this article, a simple example can suffice. One way to infringe a patent is to "make" the patented thing without permission. Currently, patent law doctrine does not clearly state whether an STL file that will print a utilitarian device (1) is itself eligible for patenting (as opposed to patenting the physical device, which patent law clearly allows) or (2) will infringe a patent directed to the physical device (Holbrook and Osborn 2015).

Lawmakers and courts could interpret these doctrinal questions in such a way as to weaken patents by declaring that STL files (1) are not patentable and (2) will not infringe a patent directed to a physical device. The net effect of these rules would be to weaken (dramatically) patent protection for items that can be 3D printed because a patent holder would only have a direct infringement claim against a person who physically printed the STL file (i.e., who "made" the physical object). But because discovering who prints an object in the privacy of their home or small business could be extremely difficult, the patent holder would effectively have a very weak patent.

Conclusion

Laws are formulated based on input from various interested constituencies. If parties with interests at stake do not fully participate in the political process, the law may not reflect their views and society might be worse off. It is thus incumbent on those scientists and engineers who truly understand 3D printing technology to consider what sort of IP rules would best incentivize innovation and to advocate for such rules.

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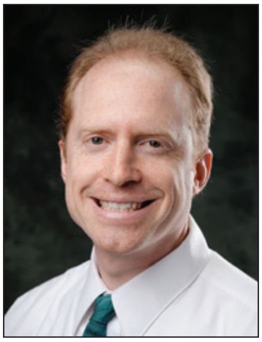
Free and open source hardware can reduce research and education costs, increase access, and enhance scientific and technological progress.

Impacts of Open Source Hardware in Science and Engineering

Joshua M. Pearce



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There is an opportunity to radically reduce the costs of experimental research while improving it by supporting the development of free and open source hardware (FOSH) for science and engineering. By harnessing a scalable open source method, federal funding is spent just once for the development of scientific equipment and then a return on this investment is realized by direct digital replication of scientific devices for only the costs of materials.

FOSH for science and engineering has been growing at a rapid pace and already supports many fields. Scaled peer production and digital replication reduce traditional costs by 90–99 percent, making scientific equipment much more accessible not only for research but also for preparation of the next generation of scientists and engineers as research-grade tools are available for science, technology, engineering, and math (STEM) education.

I propose four straightforward and negative-net-cost policies to support FOSH development and improve access to scientific tools in the United States. The policies will directly save millions in research and STEM education expenditures, while providing researchers and students access to better equipment, which will promote advances in technology and concomitant benefits for the US economy.

The Problem of High-Cost Proprietary Scientific Equipment

Scientists all over the world have limited access to the best scientific tools largely because of the inflated prices of proprietary scientific equipment for experimental research (Pearce 2014). This slows the rate of scientific development in every field. Even American scientists, who have dominated research expenditures for decades and have the most well-equipped research labs in the world (NSB 2012), rarely have access to a complete collection of the best tools to do their work.

In addition, the high costs of scientific instruments often limit access to exciting and engaging labs in both K–12 and university education (Gutnicki 2010) as there is simply not enough lab-grade equipment available at reasonable prices for everyone to use. This weakens recruitment into STEM fields and results in a drain on scientific talent for the future.

Historically, the scientific community had to choose one of two suboptimal paths to participate in state-of-the-art experimental research: (1) purchase high-cost proprietary tools or (2) develop equipment largely from scratch in their own labs, which can have an enormous time investment penalty resulting in high personnel costs.

The high cost of modern scientific tools thus excludes many potential scientists from participating in the scientific endeavor and slows technical progress in all laboratories.

Solution: Free and Open Source Hardware for Science and Engineering

A new option is emerging: low-cost, often highly sophisticated and customized scientific equipment is being developed as free and open source hardware, similar to free and open source software (FOSS) (Fisher and Gould 2012; Pearce 2012).

FOSS is computer software that is available in source code form and can be used, studied, copied, modified, and redistributed either without restriction or with restrictions only to ensure that further recipients have the same rights under which it was obtained: free, or libre.[1] Under similar rights, FOSH provides the "code" for hardware—including the bill of materials, schematics, instructions, computer-aided designs (CAD), and other information needed to recreate a physical artifact—and enables improved product innovation in a wide range of fields (Fisher and Gould 2012; Hienerth et al. 2014; Pearce 2014).

FOSH in the Laboratory

The open source paradigm combines three-dimensional (3D) printing with open source microcontrollers running on FOSS (Pearce 2012, 2014), and hundreds of scientific tools have already been developed to allow free access to plans (Pearce 2014). For example, in DNA nanotechnology labs, gel scanners, horizontal electrophoresis gel molds, and homogenizers for generating DNA-coated particles can all be fabricated using an open source approach for up to 90 percent less than commercially offered tools (Damase et al. 2015). Similarly, there is a long list of open source money-saving tools for biology labs—microscopes, centrifuges, hot plates, magnetic stirrers, waveform generators, EEGs, and Skinner boxes, to name a few (Baden et al. 2015).

The high cost of modern scientific tools slows technical progress in all laboratories.

Scientists and research engineers design, share, and build on one another's work to develop scientific tools (Harnett 2011). For example, open source microcontrollers like the Arduino are being used for a variety of chemical educational tools, from simple colorimeters and pH meters to automated titrators, data loggers, and generic control devices for automated assays (Urban 2014). An open source Python framework has been developed for the Arduino that offers even more flexibility for applications, such as high-voltage power supplies, pressure and mass flow controllers, syringe pumps, multiposition valves, and data recording systems (Koenka et al. 2014).

Open source microcontrollers can also be used for more sophisticated and targeted applications like the electrochemical pretreatment of boron-doped diamond electrodes (Rosa et al. 2017) and radial stretching systems with force sensors (Schausberger et al. 2015), saving hundreds of dollars, and a robot-assisted mass spectrometry assay platform (Chiu and Urban 2015) and automated

[1] The term "libre" has been adopted to convey the freedom (of access, use, and discovery) that comes with free and open source materials, not only the lack of cost.

peptide synthesizer (Gali 2017), saving over $25,000. Other groups are developing open source electronics to provide Big Data–like Internet of Things (IoT) meter devices for smart and energy-efficient buildings (Pocero et al. 2017) and sensor and computational platforms for smart cities (Jiang and Claudel 2017).

Open source electronics also drive open source 3D printers like the *rep*licating *rap*id prototyper (RepRap) (Anzalone et al. 2015; Jones et al. 2011), which can be used to manufacture high-quality scientific tools. Even complex manufacturing designs are free, and it is just as easy to replicate an $850 magnetic test tube rack as it is to make an inexpensive rack. Researchers at the University of Washington became frustrated with the exorbitant prices for commercial magnet racks and designed an open sourced 3D-printable tube magnet rack.[2] As the magnets are available for about $6 each it is possible to economically justify the purchase of a $500 RepRap 3D printer (Wittbrodt et al. 2013) for a lab to download, print, and avoid the cost of a single commercial magnetic rack.

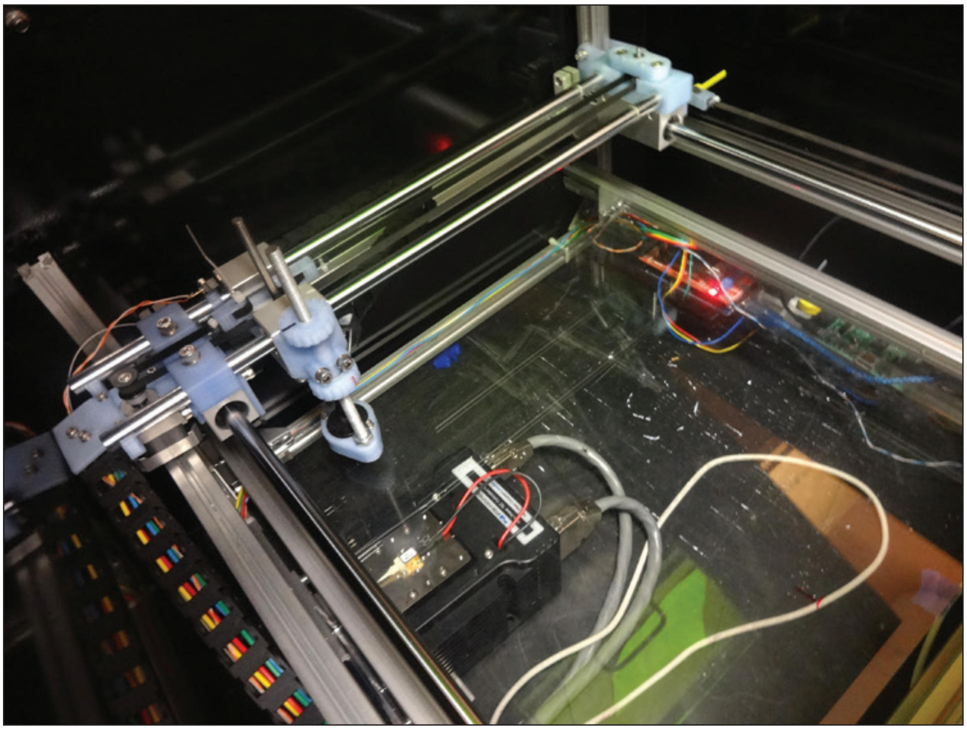

FIGURE 1 An open source polymer laser welding system composed of 3D-printed parts and controlled with open source electronics (Laureto et al. 2017). This system is used to make novel heat exchangers with additive manufacturing of polymer sheets.

The 3D printer can then be used to make a long list of progressively more sophisticated and costly tools (Baden et al. 2015; Pearce 2014). And sharing digital designs and 3D printers can be used to attempt new experiments with, for example, chemical reactionware (Kitson et al. 2013; Symes et al. 2012), or polymer laser–welded heat exchangers (Arie et al. 2017), which are fabricated with an open source system shown in figure 1.

The most powerful and expensive open source scientific equipment combines 3D printing and open source electronics. For example, several approaches have been shown to decrease costs for microfluidics platforms, saving researchers $2,000 or more (Pearce et al. 2016; Tothill et al. 2017). A single automated device such as a filter wheel changer can be built in a day for $50, replacing inferior commercial tools that cost $2,500 and have long lead times (Pearce 2012).

Not only has a 3D-printable open source optics library been developed (Zhang et al. 2013) and expanded (Gopalakrishnan and Gühr 2015; Salazar-Serrano et al. 2017), but scientists are pushing ever more complex tools such as an automated 3D microscope, saving several thousand to over $10,000 (Wijnen et al. 2016a).

Open source 3D printers driven by open source electronics can even become scientific tools themselves, as when they are used to make thin silica gel layers in planar chromatography (Fichou and Morlock 2017). This is particularly easy if they are controlled with Franklin, an open source 3D motion control software suite (Wijnen et al. 2016b) that has been used to control an automated mapping four-point probe (Chandra et al. 2017) and a 3D scientific platform (figure 2; Zhang et al. 2016), which can be used for laboratory auto-stirring and measuring as well as automated fluid handling and even shaking and mixing, taking the place

[2] Acadey 96 well plate/0.2 mL strip tube magnet rack (www.thingiverse.com/thing:79430).

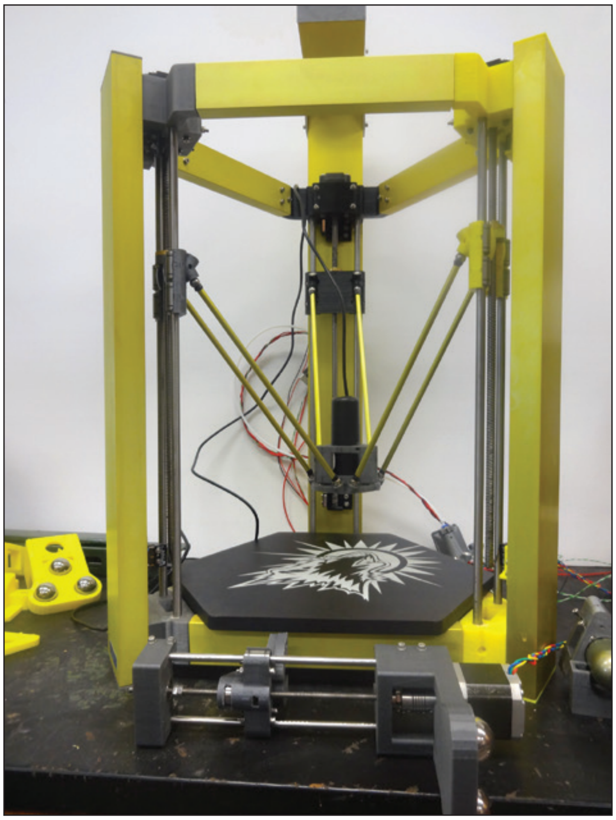

FIGURE 2 Open source 3D platform for low-cost scientific instrument ecosystem. Mounted on the end effector is a USB microscope (Wijnen et al. 2016). In the background is a standard fused filament print head (grey), which was used to print out the syringe pump used for fluid handling (foreground) as well as the various scientific and engineering tools shown on the left in yellow plastic (e.g., pcb mill, glass stir rod holder). Details are available in Zhang et al. (2016).

of dedicated open source tools like the simple mixer shown in figure 3 (Dhankani and Pearce 2017).

FOSH in the Classroom

FOSH methods offer the potential to radically reduce the costs of not only doing science but also training future scientists (Pearce 2013). For example, open source electronics can aid in chemical education (Urban 2014), and FOSH can be used to help teach young students programming skills (Hill and Ciccarelli 2013), reduce costs in physics education (Zhang et al. 2013), and teach mechatronics (Kentzer et al. 2011).

An entire university classroom of physics optics setups can be printed in-house for $500 using a selection of predesigned components from the open source optics library on an open source 3D printer, replacing $15,000 of commercial equipment (Zhang et al. 2013). This

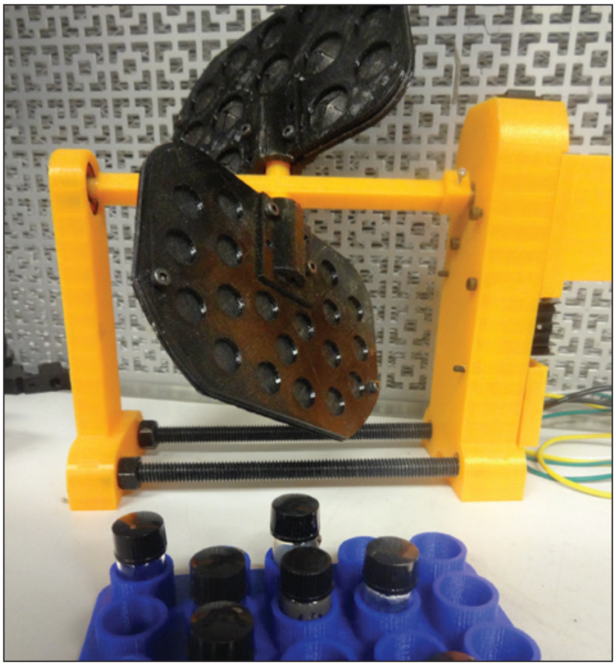

FIGURE 3 An open source 3D-printed sample holder and laboratory sample rotator mixer and shaker controlled with an open source Adafruit pro trinket microcontroller (Dhankani and Pearce 2017).

would save over $66 million if scaled only to the basic physics labs in US degree-granting institutions, and over $500 million if scaled to all US public and private secondary schools.[3]

Scaling and Returns on Investment in FOSH

Clearly there is an enormous return on investment (ROI) possible for funders of scientific research and for STEM education by investing in the development of FOSH for all the sciences, basic and applied (Pearce 2016).

To fully take advantage of the scalability of FOSH for the benefit of both areas, the United States must implement policies that allow knowledge to scale horizontally. Such scaling will be accomplished by federal funding spent only once for the development of scientific equipment, followed by an immediate ROI through the digital replication of devices for no more than the costs of materials. In this way research-grade scientific instruments will be much more accessible at every level of the educational system and a greater percentage of America's scientists will be able to participate in experimental science.

[3] US Department of Education, National Center for Education Statistics, Digest of Education Statistics (http://nces.ed.gov/programs/digest/2013menu_tables.asp).

The ROI thus goes beyond simply funding laboratories themselves. Improvements in science lead to improvements in technology, which can in turn enhance virtually every aspect of the economy (Salter and Martin 2001). Historically the ROI were on the order of 20–70 percent (Salter and Martin 2001), but a study of the ROI for funders on the design of an open source syringe pump (Wijnen et al. 2014) found that it was as much as 1,000 percent after only a few months (Pearce 2016).

Federal funding for scientific hardware should be directed to FOSH projects via a purchasing preference.

Four Policies to Accelerate FOSH Development

To foster double- and triple-digit returns on investment, four policies are needed to support scientific FOSH development in the United States:

1. Form a task force of the National Academies of Sciences and Engineering (NAS and NAE) to identify the best opportunities to realize strategic national goals and a high ROI for the creation of open source scientific hardware. The country's largest current expenditures on equipment should be determined along with likely future expenditures. This goes beyond cataloguing the largest single-point expenditures to tools used across many disciplines and found in labs throughout the country. The value, V_{USA}, can be maximized by

$$V_{USA} = \sum_{i=1}^{N_{USA}} c_j \times n_j$$

where N_{USA} is the total number of labs in the United States, c_j is the cost per unit of j instrument, and n_j is the number of j instruments in i lab.

The resulting list of high-ROI equipment can then be compared against the existing (and rapidly growing) list of libre hardware to determine the primary targets for policy 2 (below). Beyond the highest national value equipment, the task force could also rank all science-based purchases from internationally sourced suppliers by value (following the equation above), so that equivalent (or superior) open source devices could be identified as either existing or needing to be developed for policy 2. Such information could assist national goals such as improving balance of trade and reshoring manufacturing in the United States (see policy 4).

2. Earmark federal funding for the development of FOSH scientific equipment identified from policy 1. This can be accomplished with a combination of traditional calls for proposals for academic grants and programs like the Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) programs. National contests like the XPRIZE or "first to make" can promote progress toward specific technical goals by offering "bounties." All federal funding for scientific hardware should be directed to FOSH projects via a purchasing preference. Last, because of the high ROI of such projects, funding for FOSH scientific equipment design should be prioritized over current offerings for hardware purchase.

As with proprietary tools, all FOSH scientific designs should be vetted, tested, and validated. This work needs to be funded with high priority. This step will largely eliminate the technical risks for labs to adopt the use of the hardware, while at the same time ensuring that scientific equipment no longer becomes obsolete, as proprietary systems do when a company loses key personnel, discontinues a product line, or goes out of business.

3. Create a national free online database of tested, vetted, and validated FOSH, with the bill of materials, digital designs, instructions for assembly and operation, and source code for all software and firmware. Efforts on this front have been started at the University of California, Berkeley's Tekla Labs, which created a library of open source documents for the construction of more than 150 quality pieces of lab equipment. Similarly, the NIH 3D Print Exchange in the custom labware category has begun doing this on the national level (https://3dprint.nih.gov/) (Coakley et al. 2014; Coakley and Hurt 2016).

To be included in the database FOSH tools must undergo peer review. To this end scientific publishers are providing venues for scientists and engineers to publish their validated studies of scientific FOSH with new journals such as *HardwareX* (Elsevier) and the *Journal of Open Hardware* (Ubiquity) as well as open access journals that support open hardware such as *PLoS One* and more conventional specialty journals and instrumentation journals (e.g., *Journal of Laboratory Automation*). Papers that do not disclose the source of the hardware should be discouraged as largely unhelpful to the scientific enterprise.

4. To provide incentives for US entrepreneurs to scale production of manufactured components that are not easily digitally distributed (e.g., microcontrollers, sensors, actuators—often called "vitamins" as they are necessary to make a piece of FOSH equipment), enact purchasing policy preferences at all levels of government for validated FOSH (policies 2 and 3) for government labs and all government-funded projects. As the United States has some of the world's leading open source firms (e.g., Red Hat is a $1 billion/year FOSS company, and FOSH companies like Sparkfun Electronics and Adafruit Industries produce millions of dollars of revenue a year), a preferential purchasing policy would also support "Made in the USA"–related employment. Last, to bring traditionally closed source companies to the open source way, consider tax benefits to save companies development money (e.g., an enhanced tax deduction for FOSH release of valuable hardware determined by policy 1).

Conclusions

It is well established that knowledge sharing via networked science has incredible power and scales well (Lang 2011; Salter and Martin 2001; Woelfle et al. 2011). "Crowd science" (Young 2010), "citizen science" (Wiggins and Crowston 2011), "networked science" (Nielsen 2011), and "massively collaborative science" (Franzoni and Sauermann 2014) will all benefit from low-cost scientific hardware, enabling practitioners and collaborators to go far beyond what is possible with software and computer simulation alone.

Latterly scaled peer production and replication of free and open source scientific hardware generally provide savings of 90–99 percent of the traditional costs, making scientific equipment much more accessible for both research and STEM education. To accelerate the development and use of FOSH for science, this paper suggests four negative-net-cost federal policies:

1. formation of an NAS/NAE task force to identify opportunities to realize strategic national goals and a high return on investment for creation of FOSH scientific tools,
2. a shift in federal funding from proprietary equipment to the development of scientific FOSH,
3. creation of a free online catalogue of validated scientific FOSH with vetted peer-reviewed designs, and
4. purchasing policy preferences for FOSH for all government-funded projects as well as tax incentives for businesses to adopt FOSH protocols.

Given the incredible ROI of the open source paradigm (a minimum of 100 percent ROI), the policies can be implemented at no net cost.

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Engineers and engineering educators can use maker methods to introduce students to engineering and build their technological literacy.

The Maker Movement and Engineering

AnnMarie Thomas and
Deb Besser

AnnMarie Thomas

Deb Besser

With calls for increased preK–12 education in science, technology, engineering, and math (STEM) (NAE/NRC 2009) and discussions of the need for more hands-on and design experiences in college-level engineering curriculum (Prince 2004), the growth of the maker movement offers promise and opportunity. And in the context of open source hardware, we note particularly the importance of sharing and collaboration among makers. From the beginning, open source hardware and online project instruction websites and forums have been critical components of the maker movement (Gibb 2014).

The past decade has seen dramatic growth both in the number of makerspaces, Maker Faires, and other maker gatherings (Dougherty 2016) and in the presence of maker curriculum in schools and libraries around the United States and the world. We believe it is important for engineers and engineering educators to learn about this trend and consider using maker methods to introduce students to engineering and build their technological literacy.

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A Brief History of the Maker Movement

What is "making"? And how does the growth of the maker movement create opportunities for engineering and engineering education?

Definition of Terms

Before addressing the connections between the maker movement and engineering, we define some of the terminology. Humans have always been makers of things, from food to shelter. The drive to make is essential to the species' survival. What the current maker movement has created is a sense of identity and community.

A maker can be defined as someone who makes something. The simplicity of that statement probably contributed to the growth of this movement. Defining disciplines is generally not a simple task (as evidenced in a paper on how faculty members define engineering; Pawley 2009), and this is particularly true in the maker movement, where there is no authoritative body determining what is or is not "making," and who is or is not a maker.

Makers self-identify and can use the designation with no application process, degree, certification, or other formalities. The term "making" has grown to encompass a broad swath of disciplines and activities, from robotics to cosplay to the use of toothpicks to create cityscapes. The inclusive nature of the term means that there are innumerable opportunities for inter-/cross-/antidisciplinary work.

Make: Magazine and Maker Faires

The modern maker movement can be traced to *Make:* magazine, first published in 2005. It features profiles of artists and engineers, step-by-step instructions for projects, and reviews of maker and do-it-yourself books and products. As readership of the magazine grew, founder Dale Dougherty and his team decided to try an in-person maker gathering (Bilton 2010):

> Maker Faire started from the ideas in the magazine. We were covering lots of interesting people and I thought it would be interesting to bring them all together in one place. They did such different things, but they had a lot in common.

The first Maker Faire was held at the San Mateo fairgrounds in April 2006, with over 300 makers and 20,000 attendees. Ten years later there were 191 Maker Faires, totaling over 1.4 million attendees.[1] In 2014 the White House held a Maker Faire on its grounds, complete with a mobile fab lab (fabrication laboratory), an electric giraffe, and a family showing their pancake printer.

The Maker Faires and *Make:* magazine are just two manifestations of the current awareness and celebration of making.

Making in K–12 Education

Learners in makerspaces actively engage in higher-order analysis, synthesis, and evaluation as they create and redesign (Bonwell and Eison 1991). And there is evidence that active learning improves student attitudes, increases retention, and attracts underrepresented students (Freeman et al. 2014; Prince 2004). Making as a formally recognized component of K–12 education is a growing area of research (e.g., Halverson and Sheridan 2014; Wohlwend and Peppler 2015).

Humans have always been makers of things, from food to shelter. The drive to make is essential to the species' survival.

Resources

As with other aspects of the maker movement, there is no single prescribed way to implement making in K–12 settings. Instead, grassroots networks share best practices, curriculum, and discipline integration strategies.

The Maker Education Initiative (MakerEd.org) is a nonprofit organization whose mission is to "[provide] educators and institutions with the training, resources, and community of support they need to create engaging, inclusive, and motivating learning experiences through maker-centered education." It has taken a leading role in gathering maker educators and resources through digital and in-person events and resource libraries.

In addition, books such as *Design, Make, Play: Growing the Next Generation of STEM Innovators* (Honey and Kanter 2013), *Invent to Learn: Making, Tinkering, and Engineering in the Classroom* (Martinez and Stager 2013), and *Makeology: Makers as Learners* (Peppler et al. 2016)

[1] http://makerfaire.com/media-center/#fast-facts

show the breadth and depth of creativity in maker programs and makerspaces.

Makerspaces and Fab Labs

A common starting point for incorporating making in a community, school, or other venue is the creation of a dedicated space, often called a makerspace, to encourage making activities.[2] These open places for experimentation and creation with tools and technology can be seen as an extension of the fab lab concept and network. The "fab lab" concept was introduced in the early 2000s by Neil Gershenfeld (2005), and there are now hundreds of fab labs worldwide.[3]

Makerspaces can encompass everything from a full fab lab to a corner of a classroom with tape and scissors.

While every fab lab could be considered a makerspace, the reverse is not necessarily true. Fab labs that are part of the Fab Lab Network (usfln.org/) subscribe to a core set of materials and a knowledge-sharing community (http://fab.cba.mit.edu/). Makerspaces encompass everything from a full fab lab to a corner of a classroom with tape and scissors.

Shared Attributes of Makers and Engineers

After attending a Maker Faire, one of us (Thomas) realized that many of the attributes of makers are useful to develop in engineering students. This led to a project of interviews with dozens of makers about their childhoods. The interviewees included National Academy of Engineering members such as Woodie Flowers and David Kelley, technology business owners including Lenore Edman and Nathan Seidle, and educators like Jane Werner and Kipp Bradford. Most of them grew up well before "maker" became a common term and long before *Make:* magazine and Maker Faires. Despite pronounced differences in where and how they grew up, common themes emerged in nearly every interview. Below are the shared characteristics that we propose constitute a "maker mindset" (Thomas 2014, p. 5):

- Makers are curious. They are explorers. They pursue projects that they personally find interesting.
- Makers are playful. They often work on projects that show a sense of whimsy.
- Makers are willing to take risks. They aren't afraid to try things that haven't been done before.
- Makers take on responsibility. They enjoy doing projects that can help others.
- Makers are persistent. They don't give up easily.
- Makers are resourceful. They look for materials and inspiration in unlikely places.
- Makers share—their knowledge, their tools, and their support.
- Makers are optimistic. They believe that they can make a difference in the world.

Perhaps unsurprisingly, these traits have much in common with the values, attitudes, and thinking skills identified as "engineering habits of mind": systems thinking, creativity, optimism, collaboration, communication, and attention to ethical considerations (NAE/NRC 2009, p. 152). And research reveals common education pathways among makers and engineers (Foster et al. 2014; Jordan and Lande 2013; Lande et al. 2013)—many self-identified makers have some formal education in engineering.

The maker traits are also echoed in a popular book on broader habits of mind, with the subtitle "16 Essential Characteristics for Success" (Costa and Kallick 2008, p. xxi), that describes a disposition open to critical and creative problem solving and calls for "responding with wonderment and awe," "taking responsible risks," and "finding humor."

Engineering Education and the Maker Movement

Makerspaces are now a common feature of college campuses (Barrett et al. 2015), and in 2016 the *International Journal of Academic Makerspaces and Making* was launched as a peer-reviewed outlet "to enable the sharing of best practices in academic making." In addition,

[2] The *Makerspace Playbook* (2013) walks through the steps to set up a makerspace, considering place selection, tools and materials, safety, projects, and a number of other aspects. It is available at https://makered.org/wp-content/uploads/2014/09/Makerspace-Playbook-Feb-2013.pdf.

[3] Information is available from the Fab Foundation (www.fabfoundation.org/).

engineering colleges and universities have begun to ask students about their involvement in the maker movement. For example, MIT's undergraduate application offers the "Maker Portfolio" option, described as "an opportunity for students to showcase their projects that require creative insight, technical skill, and a 'hands-on' approach to learning by doing."[4]

What can the fields of engineering and engineering education learn from the maker movement? Much of what is emerging about the role of making in education, particularly engineering education, confirms prior findings on student learning.

Often when education designers refer to Bloom's taxonomy, there is a tendency to focus on the cognitive domain (Bloom et al. 1956). But the taxonomy also includes the psychomotor and affective branches of learning. When people are actively creating with technology they are naturally engaging these two domains. The affective includes motivation, attitude, enthusiasm, values, and appreciation, and these self-directed attributes are essential for curious creating, risk taking, and playful making.

Challenges

The maker movement is not, unfortunately, immune from the diversity challenges seen in the STEM subjects and in engineering in particular. But a growing body of work is looking at how some maker projects and activities may be effective in getting more women interested in STEM. For example, e-textiles (a common staple of Maker Faires and programs) are broadening participation of women in electronics (Buechley et al. 2013). And diverse communities are being supported in computer programming by the Scratch language, which has become an integral element of many youth maker programs (Resnick et al. 2009; Roque et al. 2016). Research is being conducted on new ways to assess and describe the learning that takes place in maker settings (Petrich et al. 2013).[5]

A 2012 study commissioned by Maker Media and Intel surveyed 789 Maker Faire exhibitors, *Make:* magazine subscribers, and *Make:* newsletter subscribers about their attitudes, behaviors, and demographics. Given a list of 28 categories and asked which words "describe [them] as a maker," "engineer" was the third most common selection (after "hobbyist" and "tinkerer"). Still, only 23 percent of the respondents chose it (Dougherty 2012), suggesting that, while related, makers and engineers do not see these fields as comparable. There is much to be celebrated and learned from both cultures and communities.

Future

The maker movement has displayed rapid growth in the United States and globally. Making and engineering are complementary. As engineering education at all levels embraces making, it presents opportunities to introduce a new audience to technology, engineering design, and collaborative problem solving.

Making provides a new lens through which content and activity traditionally thought of as engineering (such as circuit design, machining, and computer programming) can be seen in a new light. Rather than restricting such activities to engineering classes and careers, through making they are accessible in community centers, fab labs, libraries, and K–12 classrooms—and they invite fun, creativity, and collaboration.

People who actively create with technology naturally engage the psychomotor and affective branches of learning.

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[5] See also the Maker Ed Open Portfolios Project, Research Brief Series (http://makered.org/opp/research-briefs/).

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With lower costs and fewer barriers to entry, 3D printing can create opportunities for small businesses to enter markets.

3D Printing for Low-Resource Settings

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3D printing has the potential to produce many needed items in low-resource settings, where lack of infrastructure and weak manufacturing capacity make local production impractical, and high tariffs, unreliable supply chains, and economic instability make importation costly. With lower costs and fewer barriers to entry, 3D printing can create opportunities for small businesses to enter markets producing and selling 3D products.

The ability of 3D printing to align local production with global information sharing can be transformational. 3D printers are engines for innovation and can help local designers work together to create solutions to problems faced by their communities. Further, the use of open source designs can create scale in a way that is fast and free.

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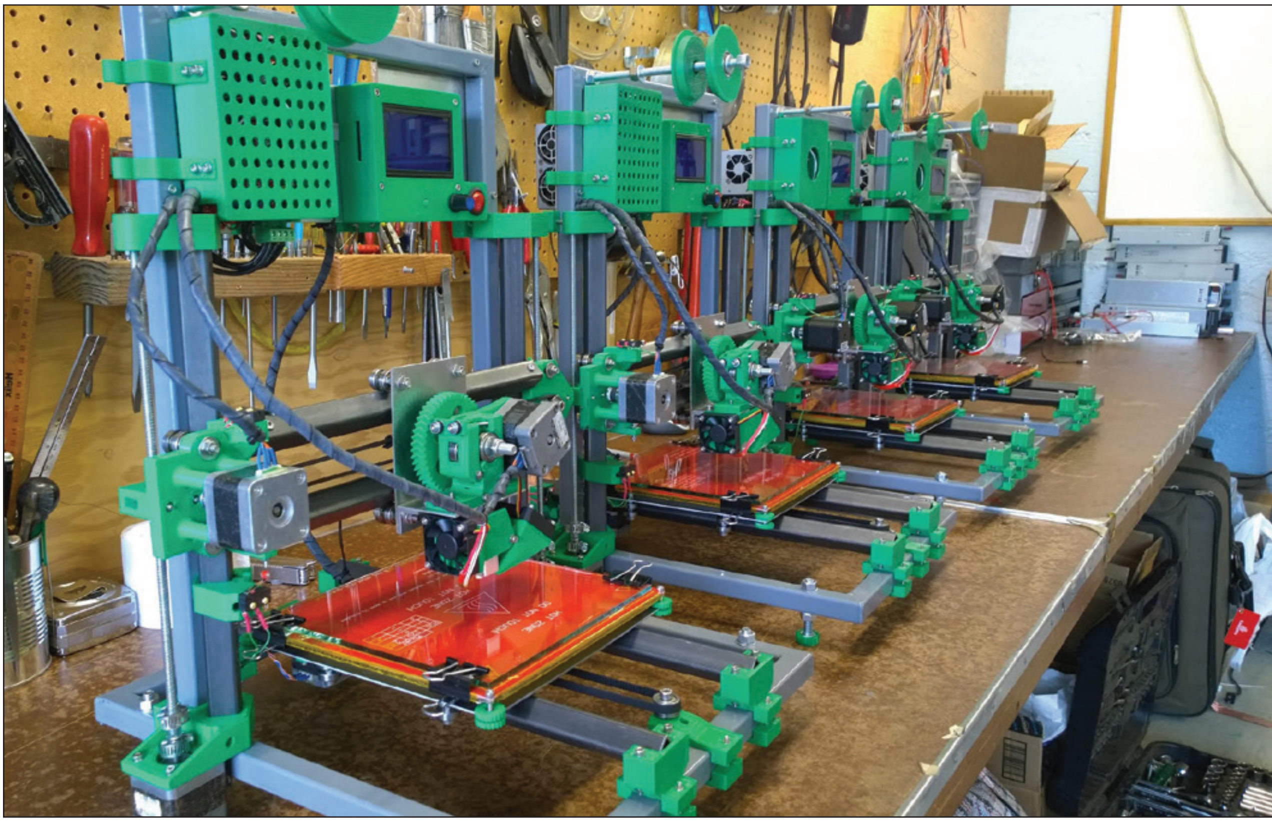

FIGURE 1 Test batch of TechforTrade Retr3D printers.

We review the work of TechforTrade—a UK charity focused on bridging the divide between emerging technology, international trade, and economic development—in its use of 3D printing for development. We also summarize key areas that must be addressed to advance this potential (Birtchnell and Hoyle 2014).

Affordable 3D Printing: The Retr3D Printer

TechforTrade developed the Retr3D printer with the goal of designing an open source 3D printer that is low cost and can be locally manufactured with a minimal number of imported parts (figure 1). To achieve this goal, parts typically found in 3D printer designs—such as linear bearings, smooth steel rods, and specialty aluminum extrusions—have been removed from the Retr3D design. Instead, locally available deep groove ball bearings and square steel tubing are used.

In many developing countries, machines introduced as part of a project are later abandoned after breakdowns occur. The causal factors for their abandonment can be complex, but local ownership and support can help prevent the same fate for 3D printers. Local manufacture is an important step in ensuring that machines stay in operation. Building locally ensures that there is a location in country where replacement parts can be obtained as well as someone with the necessary skills to make repairs. And open source design means that anyone with a Retr3D printer has access to the information needed to keep it running.

Global Configurability

The Retr3D printer design is parametric and can be configured using global variables and equations to accommodate the variation in raw materials between different locations. For example, the square tubing used for the printer's frame and linear motion system vary in dimension by as much as 3 mm from country to country, so making tight-fitting sockets to fit the tubing requires slightly different 3D-printed parts for each location.

It was particularly important to be able to use components reclaimed from discarded electronics, such as motors, power supplies, and fans, when available. Modern computer-aided design (CAD) software with parametric capabilities can easily handle such jobs: adjusting parameters from one country to the next, or even from one printer to another, is just a matter of inputting the dimensions.

Field-Tested Durability

The current version of the Retr3D printer is robust. Testing of initial Retr3D designs and other RepRap printers showed that many were sensitive to transport on rough roads. Loss of calibration and damage were common.

By adopting a design with a stiff welded steel frame, the Retr3D printer has proven to be much more durable. Furthermore, the construction of the printer frames can be easily outsourced to local welding shops.

Open Source Electronics

Use of open source electronics has helped to reduce the printer's cost and improve its maintainability. RAMPS 1.4 electronics are commonly used with RepRap-style printers, and their popularity has helped to make them both low cost and widely available.

The electronics on a Retr3D printer can be entirely replaced for \$31 and, thanks to the modular design of RAMPS, if there is damage to only one component it can be easily changed for between \$2.50 and \$12.00. With proprietary 3D printers, replacement parts generally cost far more—if they are even available.

Local Filament Production

Nearly all low-cost open source 3D printers that are robust and easy to use are fused-filament fabrication (FFF) machines, which use 3 mm or 1.75 mm diameter plastic filament as their raw material. Filament is typically produced on an industrial scale and needs to be imported in developing countries where the market is quite small. This importation can be costly and time consuming and can lead to unpredictability in the production of 3D-printed goods.

TechforTrade has been developing a low-cost, small-scale means for producing 3D printer filament from postconsumer polyethylene terephthalate (PET) bottle flake. PET plastic works well with FFF printers and waste PET is readily available in nearly any location on the planet. Not only does this help to reduce the challenges of import duties and unpredictable supply chains, but it also allows for value to be added locally to the waste plastic.

Postconsumer PET has proven significantly more difficult to process into filament than other plastics readily available in the waste stream—because of its high melt temperature, low melt viscosity, hygroscopicity, susceptibility to hydrolysis, and crystallization behavior—and designing a low-cost solution has been challenging. TechforTrade explored the use of high-density polyethylene (HDPE) and acrylonitrile butadiene styrene (ABS). HDPE is easy to obtain and producing filament with it is relatively easy, but it tends to shrink as it cools, making it difficult to use for printing. ABS is also fairly easy to recycle into filament and prints quite well, but it was eliminated because many products made from ABS, such as electronics enclosures, contain brominated flame retardants, which can be toxic and pose significant health risks (Sepúlveda et al. 2010).

Many of the technical challenges of PET plastic have been overcome, and its availability and superior printability make it a worthwhile polymer to pursue.

With proprietary 3D printers, replacement parts generally cost far more— if they are even available.

Small-Scale Recycling in Developing Countries

Many rural communities in the developing and developed world alike lack access to recycling facilities. Without local means for size reduction or compaction, it is frequently too costly to transport high-volume, low-mass plastic bottles to a centralized processing center. But with relatively low capital requirements, a small-scale recycling system utilizing 3D printing may be a viable means for small communities to handle plastic waste while also gaining access to needed items.

Challenges

In many developing countries, the recycling system is largely informal. Vast numbers of waste collectors work in difficult and sometimes dangerous conditions to make small amounts of money. In Tanzania, for example, waste collectors make around \$2 a day selling their plastic at \$0.15/kg to groups that shred it and then export it to other countries where the actual recycling and bulk of the value addition are done.

Furthermore, capital investments are generally high, requiring expensive equipment and lots of space in centralized locations. As with many commodities, the route to profitability is through the processing of large volumes.

In addition, local recycling systems are vulnerable to international economic forces. In late 2015 a recycling group that worked with TechforTrade in Tanzania was forced to close its doors because of the effects of plummeting oil prices earlier that year. And the only recycling facility in east Africa with hot wash capabilities closed for similar reasons. While this was certainly difficult for investors and those in higher-level operations, it was surely much harder on the waste collectors.

Opportunities for Value Capture

Developing small-scale equipment for the production of recycled 3D printer filament keeps the value addition steps within the country and enables recycling on a minimum viable scale. Reducing the necessary capital investment makes it possible for those at the bottom of the pyramid to participate in and benefit from the value addition process.

Following the value chain from waste PET to 3D-printed products reveals the opportunities gained through access to the equipment required at each step.

- Collected plastic bottles are valued at about $0.15/kg.
- Converted to clean flake, the value rises to $0.70/kg.
- Recycled PET 3D printer filament typically sells for around $30/kg.[1]
- The value of a printed part made from the filament may reach $600/kg.

Of course the final price depends greatly on the printed product. The value presented here was determined from average low product prices and masses of 3D-printed products (reviewed in Wittbrodt et al. 2013).

Adding value locally increases a country's GDP and reduces reliance on foreign imports. And such small-scale recycling endeavors are likely less vulnerable to swings in the global recycling market.

Because of the high volumes traditionally used in the plastics industry, small quantities of virgin plastic resin pellets can be much more difficult and expensive to obtain than plastic flake. So even if the price of virgin resin crashes, most likely it will still be easier and cheaper to locally produce filament from flake.

[1] Information from www.bpetfilament.com.

Finally, the price of 3D-printed products from recycled PET is much less tied to the price of oil. Even large swings in the value of plastic scrap would represent only minute changes in the value of the final printed product.

Machines for Capturing Value

There have been many technical challenges to overcome in producing PET filament of sufficient quality directly from flake on small-scale low-cost equipment. TechforTrade is developing a bottle washing and delabeling station, a chopper for producing flake, and a filament extruder (figure 2), all of which are open source, with a total materials cost for the whole system of less than $2,000.

The Thunderhead filament extruder can produce 5–10 kg of filament a day and is sufficient to supply 20–40 3D printers for full-time production. In terms of value, based on the sale price of $30/kg for 100 percent recycled PET filament, the extruder is capable of producing $150–300 worth of filament per day. Development is ongoing, but initial prints are promising (figure 3).

In time, as greater numbers of small-scale filament producers are established, they may be able to aggregate their excess product and sell it on the international market under the Ethical Filament mark.[2]

3D-Printed Products with Social Benefit

Expensive items are often imported to developing countries and incur high duties, making them even more costly. Furthermore, foreign sales support can be expensive and time consuming.

Fortunately, a vast number of open source 3D-printable designs are available for download from sites such as Appropedia, GrabCAD, and Thingiverse. TechforTrade focuses on items that are high value added, otherwise difficult to obtain, and have the potential for social benefit.

The Open Flexure Microscope

The open flexure microscope, designed by Richard Bowman and first used to examine water quality in India under the NGO Waterscope, replaces a high-value product that would normally be imported (Sharkey et al. 2016). It uses a USB webcam or a Raspberry Pi camera and a monolithic 3D-printed body to display the magnified sample onto a laptop or Raspberry Pi screen with a resolution of around 2 μm. TechforTrade has made the microscope in Tanzania and Kenya and sees it

[2] See "Setting the standard for ethically produced 3D printer filament from recycled waste materials" (http://ef.techfortrade.org).

FIGURE 2 Thunderhead filament extruder prototype at STICLab in Dar es Salaam, Tanzania.

FIGURE 3 Keychain printed with recycled polyethylene terephthalate (PET) filament made with the Thunderhead filament extruder and printed using a Retr3D printer.

as an excellent product for demonstrating the potential impact of open source design combined with distributed manufacturing via 3D printing (figure 4).

Use in the Field, Lab, and Classroom

TechforTrade has been examining herd health, human health, and educational uses of the open flexure microscope in East Africa. The ability to quickly download and print our first microscope allowed us to get out into the field and talk with potential customers, with a minimal investment of time and money.

The microscope was tested in a veterinary science lab in Nairobi, where technicians anecdotally preferred the product but needed a carrying case and higher resolution. Changes were made in coordination with Bowman, after which our team in Kenya returned to the veterinary technicians to begin work on a sales and distribution agreement.

The microscope was also tested at a local health clinic, where technicians used it to correctly identify pathogens. The clinic director cited the capability of capturing digital images as a valuable feature, as it allowed for quality assurance by routinely reviewing a random sampling of slides; without digital imagery, such reviews are not possible because the sample is destroyed after the test is performed.

FIGURE 4 Open flexure microscope (left) made in Nairobi using Retr3D printers. Microscope view is projected on the laptop screen.

TechforTrade also spoke with five schools in Tanzania and six in Kenya about the feasibility of introducing the microscopes in the classroom. STICLab and AB3D have sold a few microscopes to parents and are starting to test them in schools. Early feedback indicated a need to bundle the microscope with educational materials to make learning easier. Digital Blacksmiths Nairobi has started to bundle the educational microscope with slides and activities.

Bowman's group has continued development of the microscope, adding a low-cost motorized stage and focus (Sharkey et al. 2016). These developments open up a range of possibilities such as automated sample scanning, remote control, and even the potential use of artificial intelligence to assist with diagnoses.

Other Products for Research, Education, and Health

Low-cost 3D printers can print a wide variety of items that have great potential for impact. For the laboratory, open source syringe pumps (Wijnen et al. 2014), centrifuges (Pearce 2012), and micromanipulators (Baden et al. 2015) are available.

Printable items for education include molecular model building kits (betawolf 2014), manipulatives for understanding mathematical relationships (Mshscott 2014), and fossils (AfricanFossils.org). In health and medicine, applicable products include eyeglass frames (Vivenda 2015), prosthetics (EnablingtheFuture.org), and orthotics (dsnettleton 2013).

Millions of open source designs are available but lack instructions for use, promotional materials, packaging, or other features needed to quickly move into sales. Such challenges are being addressed by a supportive new network whose goal is to help make promising designs into products ready for sale and then share the products through the network.

Developing Globally, Implementing Locally: The Digital Blacksmiths Network

TechforTrade is building the global Digital Blacksmiths Network (currently piloted in Africa) with the goal of helping to coordinate open source product development and ensure that network member businesses have access to the technology, training, and support they need to bring 3D-printed products to the local marketplace.

Standardization and Support

The network will run like a franchise that gives each member a high degree of freedom in designing business and product lines while standardizing quality, business systems, supply chains, and support. The network is in pilot phase, with three early-stage businesses and a central organizing body working on further product development and support.

Businesses that sell 3D-printed items require much more than a working design in order to take a new product to market. Items must have the polish of a professional product: packaging, marketing materials, instructions, assembly guides, aftersales service, quality standards, vendors of nonprinted parts, regulatory approvals, and the like. Frequently, however, open source designs lack these "extras."

Creating a consumer-ready product is no small task.

Innovation and Knowledge Transfer

Another goal with the Digital Blacksmiths Network is to reduce the distance between where needs are and where solutions are developed. Local implementation does not necessarily mean producing exact copies of the standard design used in the network. Many items require some modification for the local context in which they will be used.

With the rapid prototyping capabilities of 3D printing and the use of participatory design techniques, which are becoming more prevalent in many aspects of consumer product development, novel designs can be quickly and cheaply market tested. For example, STICLab, a Digital Blacksmith business working with TechforTrade in Tanzania, modified the design of the Retr3D printer so that it includes an enclosure. This was in response to customer requests for printers that have dust protection and barriers between the user and the printer's moving parts. Now their designs are being included as an option for other groups.

When items that are under development require expert knowledge that an individual site may not have, other members of the Digital Blacksmiths Network can provide technical assistance, knowing that their efforts will be rewarded as their access to fully developed products grows. As a side benefit, experts from around the world who would like to contribute their knowledge but don't have an easy outlet (they can't just fly off to Tanzania for a month) can make significant contributions by consulting from afar on aspects such as design, legal concerns, and marketing strategy. This also enables the transfer of knowledge and skills through participation in the network.

With a catalogue of fully developed products, network members will not need to invest large amounts of time and money into developing their products from scratch. Rather, they can use their time to produce a wider range of products and thus access markets that might be too small to sustain a business on their own. Conversely, groups working in international development might use the network to quickly deploy new technologies.

Gaining Access to Risky Markets with Leapfrog Technology

The cell phone has become the classic example of a leapfrog technology that has had tremendous impact on the developing world. 3D printing technology is similar in its potential to be a leapfrog technology in the manufacturing sector in developing areas.

A 3D-printed microscope was tested at a local health clinic, where technicians used it to correctly identify pathogens.

Cell phones are used in many ways that address the needs of the poor around the world. Entrepreneurs and rural farmers have access to banking services and payment methods that are cost effective for them even at small scale (Kikulwe et al. 2014; Suri and Jack 2016). Small-scale growers and agricultural traders use mobile devices to track produce prices and transactions, helping to even the playing field and encourage collaboration rather than competition between producers and middlemen.[3] Many of the characteristics that have made cell phones so successful in developing countries—versatility, low cost, ease of use, portability, and connectivity—also apply to 3D printing.

[3] See "Trade Transparency: Open Book Trading" (http://tt.techfortrade.org/en/).

Just as cell phones ended the isolation of rural communities in terms of information, 3D printers may play a part in reducing material poverty in rural areas, where access to physical products is both limited by remoteness and costly in terms of last-mile delivery.

Versatility of 3D Printers

Like cell phones, 3D printers are extremely versatile. Without any change in setup, they can produce a vast array of items.

They are low cost, especially when compared to traditional mass manufacturing equipment. They are also lightweight and portable, making them easy to transport and set up in rural locations.

The goal is not to replace mass manufacture, but to fill in where mass manufacture is unable to deliver.

While 3D printers are not capable of high production rates, this isn't much of an issue for small-scale production of high-value items. The goal is not to replace mass manufacture, but to fill in where it is unable to deliver. And there is the potential for scaling up: when a shop's printing capacity is not sufficient to meet demand, additional printers can be added. Finally, because 3D printers are automated, one person can operate a number of machines.

Minimal Power and Skill Requirements

Low-cost 3D printers such as the Retr3D have low power requirements, around 130 W at 12 V DC, and so naturally work well with solar installations.

Minimal prerequisite skills and literacy have contributed to the success of the cell phone. Similarly, 3D printers require surprisingly little skill to set up, operate, and maintain when compared with traditional manufacturing equipment. The same process and setup are used regardless of the part being printed. This feature enables different groups to easily replicate a part developed elsewhere. All that is needed is access to the digital files.

Low-Risk Product Testing

The versatility of 3D printers makes them suitable tools for accessing small niche markets that would be very risky endeavors using other methods. Once a 3D printing shop is set up, new products can be tested almost on a whim. A catalogue of developed products will enable network entrepreneurs to quickly test their local markets and identify which combination of goods will yield a sustainable income.

There is no need to rely solely on one product or to carry large inventories, both of which can be quite financially risky. This is an important benefit in areas where resources are limited.

Legal Challenges

A number of challenges must be overcome for 3D printing to become a successful means for distributed manufacturing in developing countries. In addition to technical and financial challenges (from part availability to electronics repair, reliance on imports, and access to expert knowledge), there are issues concerning product liability, regulation, safety certification, and fair use. Obtaining needed legal advice and ensuring that a product is in compliance can be daunting, time consuming, and expensive.

In areas where regulation exists but is difficult to enforce, consumers may be exposed to dangerous products and designers' intellectual property rights may be infringed.

With increased abilities come more responsibilities and legal assistance will surely be needed.

Conclusion

Distributed manufacturing of open source hardware via low-cost 3D printing may open the door for many small-scale entrepreneurs, which in turn could play an important role in providing their communities with access to needed items while converting waste to value through recycling.

The use of automation and artificial intelligence in manufacturing is accelerating and there are concerns that low-wage earners in developing countries may be most vulnerable to job loss (UNCTAD 2016). With open source 3D printing technology, developing countries can foster the skills needed to be competitive in an increasingly technical world and at the same time steer design and manufacture toward products that are locally relevant.

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Op-ed

To the Moon and Beyond: Open Source and Open Innovation

Tom Callaway is a senior software engineer, Red Hat, Inc.

I was born in 1980, which means I am a member of the last generation that can remember a time before the Internet was a ubiquitous part of life in America. I recall my first computer fondly, the IBM XT, and typing in BASIC programs that my father photocopied for me, but what really stuck with me was how incredible it was to connect my modem to a bulletin board system (BBS) and leave messages for other people.

Today, America is always-on, real-time, and live-streamed. This is the practical reality that my children were born into. The world is heading toward a future society of a single digital civilization. In fact, as William Gibson so aptly said, "The future is already here—it's just not very evenly distributed."

Yet technology is still produced in much the same way as in 1980. I'm not referring to methods or transistor count, but to the belief that a small subset of people are better at producing technology in isolation than anyone else. It may have been possible to argue this case back then, when a day's research at the largest nearby library counted as due diligence, but today it is simply no longer true. No matter how smart the people are in any given company, the resulting technology is not as innovative as it would be if built in a collaborative fashion.

There is historical evidence to back this assertion. A core reason for the success of the Apollo program was the more than 400,000 engineers, scientists, and technicians working for more than 20,000 companies and universities who contributed to an effort that NASA could not have succeeded at alone and definitely not in the time available. The expertise, skills, and resources of a single individual, company, or community simply are not sufficient. In order to innovate competitively, you must collaborate with others and leverage their expertise, skills, and resources. This approach is now known as open innovation.

The Internet makes this sort of collaboration possible in a way that previously required a presidential mandate. Need expertise in power management, fire suppression, underwater optics, or hit-box algorithms? It's a few clicks away.

I've worked for Red Hat (the world's largest and most successful open source software company) for 16 years, which is not long in academic epochs but in the IT industry is practically forever. Red Hat has made its business model entirely on the value proposition that software can be produced better and faster by applying the concepts of open innovation.

Red Hat customers are not locked into a software but instead work with us to solve their IT problems. As CEO Jim Whitehurst said, "it's a neat trick to sell $2 billion of something that's technically free." Red Hat is proof that open innovation works as well today as it did in 1969.

The web pages you view are hosted by open source–powered servers, sent across open source–powered networking equipment to your open source–powered tablet or smartphone. Your car, DVR, and home security system use an ever increasing number of open source software solutions, not just because they are free but because they are good and, more importantly, they can be made better by anyone.

All of this logic applies to hardware. Hardware produced in an open source model results in faster innovation and higher-quality results. When a solution is developed for a problem, others are not forced by restrictive patents and licensing to reinvent that solution but can simply use it and tackle new problems.

The open source hardware movement is already starting to be realized. In *Make:* magazine's 3D Printer Buyer's Guide, three of the five "Best Overall" 3D printers are open source hardware (Prusa i3 MK2, Lulzbot TAZ, SeeMeCNC Rostock MAX). The Arduino is one of the most common microcontroller boards on the planet and it is completely open source hardware.

At Red Hat we know open source and open innovation work—we have built our business around these concepts. They also empower society and make it possible to push the limits of what is possible. When the barriers to collaboration are lifted, people can accomplish incredible things.

An Interview with . . .

Actor Masi Oka

Actor Masi Oka.

RON LATANISION (RML): Masi, you are the first actor who has spoken with us, and we're delighted. I'm curious about how you got into acting, given that Brown University is your alma mater and you have a degree in computer science and mathematics. Is that correct?

MASI OKA: Yes. I also studied a lot of art and music. A good thing about Brown is there's no core curriculum; that allowed me to take chances in a liberal education and also avoid classes that I didn't want to take, like history and English. I took all science classes, language classes, and art.

I think that started with my experience in high school. I was a big math and science geek at an all boys' school (it went coed my last year). I was in the chess club, math club, and computer club—everything that was very popular back in my high school days.

My friends were going to MIT, and to me at that time, they kind of talked the same, laughed the same, and thought the same. I wanted to change who I was. I saw undergrad education as not only an academic education but also a social education.

I was a high school kid—I wanted to be a little popular, I wanted to be with girls and such. But the biggest thing is that I didn't want to be stereotyped. Going to college meant I had a blank canvas to start with, and I realized I wanted to challenge myself and show the world that a human being has both a left side and a right side of the brain. That's why I went to Brown.

I did take theater classes when I was a kid, but my biggest fear at the time was, ironically, to be myself, to be confident in who I was and to be human. When I got to college I thought, 'Nobody's judging me, nobody knows who I was, so I want to do something completely opposite, something out of my comfort zone' and that was theater arts. I fell in love with it—it opened up my worldviews and perspective. But I never thought of it as a profession because how many Asian actors are there and how successful are they? Fortunately there are more opportunities now, but at that time there weren't many, and I didn't want to put financial burden on my single mother by being a struggling artist.

CAMERON FLETCHER (CHF): So you went into acting as a personal challenge for your own growth?

MR. OKA: Yes. I would say that was a good 90 percent of it. And I would say 10 percent is because I wanted to attract girls. [Laughter]

RML: In "Hawaii Five-O" you played the role of a medical examiner, Dr. Max Bergman. Did the cast look at you and say, "Boy, this guy is a real geek," or did they say, "This guy has a lot of interesting things on his plate"? How did you interact with the cast?

MR. OKA: Well, we're all actors. People play geeks who aren't necessarily geeks, and vice versa. That's our job. In a TV show, because typically it's a long-running endeavor, actors tend to play an exaggerated version of an aspect of who they are, and writers tend to write for the actor, so the role and the actor start to meld in a way as the seasons go on.

RML: I did a little reading before this conversation, and I understand you grew into the role of medical examiner after only one or two appearances during one of the earlier seasons—and you just left the show within the last few weeks.

CHF: Have you gotten fan mail about your decision to leave?

MR. OKA: Yes, we got a pretty big response, at least on the social network. I was surprised.

But the nice thing was that it was an amicable parting, and because of that the character got a really nice send-off. It's very rare you get a loving send-off and a tribute—you typically just get killed off.

CHF: Apart from your departure from this show, what do you hear from people who see you in action on the screen?

MR. OKA: It's a big spectrum. Especially for a lot of Asian-American actors, we are kind of role models because there are very few of us. So, in many ways, we have a responsibility to the next generation of kids wanting to grow up in the arts, especially for the Asian community.

I tend to play a comedic character in all the drama, so people are very happy—'you always bring us laughter.' The last episode, though, I brought them to tears. When I was playing Hiro Nakamura [on the TV series "Heroes" and "Heroes Reborn"], people told me my character was very optimistic and hopeful. I've even had people tell me that it saved their lives. It was very memorable to have two fans come up and tell me they were contemplating suicide and then they saw the show and my character, Hiro, inspired them to be more positive.

CHF: That's quite an impact.

RML: Yes, that's very powerful. And it is a good indication of the cultural impact of the kinds of things that not only actors but, particularly from our point of view, actors who have a technology orientation can do.

I'm curious, have you met other actors who also have a background in science or engineering or technology in a broad sense?

MR. OKA: There are actors that you probably don't know who have similar backgrounds. I haven't really spoken with anyone who has a huge background in these areas.

There are people now who are big fans of the geek-type culture. Back in the day, it wasn't that popular. Now it's more mainstream that people are proud to be geeks. I always say that to be a geek is to be human, because it means you are passionate about something, and I would rather be passionate about something than nothing, like a robot.

Nowadays, being an entrepreneur, being an IT guy is fashionable and they're respected, whereas the media portrayal of engineers and technologists when I grew up wasn't as favorable.

To be a geek is to be human, because it means that you are passionate about something.

RML: That's an interesting comment. We interviewed Tom Scholz,[1] the founder and lead of the rock band Boston—his background is in engineering, and his understanding of acoustics enters into his music. Is the same true in your case? Does technology play a role in your acting?

MR. OKA: Absolutely. I always talk about STEAM (science, technology, engineering, art, and mathematics) and education—the idea of bringing folks together. In many senses, everybody is an artist, everybody is an engineer. People can be social engineers, dream engineers, artistic engineers. It's the way you think.

When it comes to storytelling, comedies especially are very technical. There's a science behind comedy with formulas and rules. Not everybody has a sense of humor, but if you follow the formula you can typically have a higher rate of making people laugh than if you aren't aware of that formula. Same thing with music. Music is very technical.

For me, it's all about how you think. College teaches you how to problem solve, and your major is the language you use to solve it. It's all about critical thinking. Creative thinking is part of critical thinking, and critical thinking is also creative thinking. I don't think it's easy or fair to draw a line between them, because they go hand in hand.

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[1] The interview was published in the spring 2016 issue of *The Bridge*, available at https://www.nae.edu/Publications/Bridge/151971/152046.aspx.

Actually, I think the best artists are great engineers, and the best engineers are great artists. There's an old joke that the best mathematicians are the laziest because they find creative ways to solve a difficult problem in the most efficient way.

It's about thinking outside the box versus thinking more logically. I produce a lot and what's really important for me as a producer is flexibility of thought. To be stuck in one way of thinking, whether it's the left or right side of the brain, I think limits you as a person. We're human beings, and I think the left side and right side need to live in harmony.

We always talk about thinking outside the box for engineers, but for artists I say it's important to find a way to create a box, to define the problem so that they can solve it and be more creative by focusing their energy.

For me, it's been a mission since growing up to not be stereotyped, to be told you can only do this, to be labeled. That's how society does it. But every engineer has an artist in them and every artist has an engineer in them as well.

I think the best artists are great engineers, and the best engineers are great artists.

CHF: You mentioned that you're producing a lot. I understand you're producing a movie called "Death Note," and I guess you also produce in your other life as the owner of a company that creates digital games. Tell us about your producing.

MR. OKA: I work on movies, television, games. I invest in startups and advise them. I connect Japan and Hollywood, Hollywood and games, all with technology. It's about trying to bridge two worlds. That has always been kind of my motto.

What's fun about producing is you get to be in the whole process, from zero to finish, and that's exciting for me. As an actor, it's great to be able to create a character, but once you finish shooting, it's in the hands of the editor. And you don't create the character; the writer does, and then the actor brings it to life. The actor's only a part of the process.

What I love about producing is that there's really no single definition of what it involves. A producer could be a filmmaker, a financier, someone who knows people. The idea of being able to be part of a creative collaborative process from the ground up is what's really enticing for me. That's what I love about producing.

CHF: You mentioned your interest in creating a relationship between Japan and Hollywood. How are you going about that, and what does that relationship look like?

MR. OKA: I'm an advisor to six major corporations in Japan and the Japanese government. The way people think is different in the US and Japan. Japan has a village mentality; everything is done with a handshake—there are contracts but most of it is goodwill. In the United States, we need everything upfront in contracts. So the business culture and mentality are very different.

Creatively, you want to protect the properties that are developed in Japan; at the same time, you need to explain to the Japan side that certain things need to be changed for localization. So it's about having that understanding and being able to see a project from both perspectives and, also, as a fan and a producer, to determine how to make the best of everything.

A lot of the Japanese folks don't speak English, and a lot of times in meetings they want to be polite and not say anything. But after the meeting they'll call me and say, "We actually have some concerns." Most of the time I'm there to be able to think from both perspectives, to bridge the business and communication and creative gaps between the two sides.

Thanks to my success in the industry, I've been able to gain the confidence and the trust of a lot of the Japanese creators. They see me as an ally. And that's the biggest thing I can offer, communicating what the Japanese folks are thinking. I was born in Japan and moved to America when I was 6, so I think like an American but my heart is Japanese. Because of that, I know the subtle nuances of the culture in Japan and how to work with them.

At the same time, Japan doesn't see me as a full Japanese, and Americans don't see me as a full American, so I'm in that no man's land. But, because of that, I can do a lot of interesting things and break the mold.

CHF: You are uniquely qualified. I was interested—you are fluent in Japanese, I gather, but since you came to this country at age 6 you would have assimilated pretty quickly. Were you speaking and writing Japanese at home with your mother?

MR. OKA: Yes. My Mom spoke Japanese a lot and she forced me on Saturdays to go to Japanese school, which crams basically a week's worth of government-approved Japanese curriculum—language, math, science, and history—into one day. I hated it because I didn't get to watch Saturday morning cartoons or play soccer or team sports. Of course, these days I'm very thankful and grateful to my Mom; because of that I have an identity and, of course, a job right now.

RML: Let me turn in a slightly different direction. A couple of times during our conversation kids and education have come up, and I'm aware that you have a long association with George Lucas, who's very interested in education through his foundation. Do you folks collaborate in any way in terms of K–12 or education in any form?

MR. OKA: Most of my stuff has been through the Japanese government, charities like Save the Music Foundation, working with the STEAM projects, but I haven't talked to George. I saw him twice at a party but that's about it.

RML: I've spent a lot of time in education myself, and I know that people are very much aware of George Lucas and the foundation and his program—it's called Edutopia. They have done quite a lot of really good stuff. He's very committed, it seems, to education, particularly at the K–12 level.

MR. OKA: That's interesting. I might reach out to George Lucas' folks and see if I can be involved.

RML: I think it would be of interest. I have another follow-up question. You mentioned a few minutes ago that you see technology in comedy, you described it in a formulaic sense. Could you give an example? How does that work?

MR. OKA: There are definitely things you think about. We talk about the rule of three, for instance: you set something up, you repeat it, and the third time you change it. It's a rhythmic thing. And we talk about repetition—the more you repeat something the funnier, but the more distance there is, the bigger the payoff.

Comedy can also involve derailment of thought. The audience might be thinking one thing, and all of a sudden a surprise happens and people laugh at that.

Another rule in comedy is 'heavy on the light and light on the heavy'—like taking the smallest thing, "Oh my God, I found a penny, this is the luckiest day of my life!" versus "Yeah, I won the lottery yesterday; no big deal; it's only $8 billion." That's heavy on the light, light on the heavy.

These formulas are the technology, in a sense, behind comedy. Of course, nothing *always* works because everybody has a different sense of humor, but the rhythm of the human body, anatomy, responds in certain ways to comedy.

CHF: Clearly rhythm is important to you because you mentioned music and the engineering involved in music, and I understand you play the piano and also do some beat-boxing and singing.

MR. OKA: Yes, I think rhythm is important—the rhythm of life, having a flow to your rhythm and momentum. The other thing is knowing your inner rhythm. It's good to be aware of that because sometimes you have to break it.

I see every day as a new start. I believe in trying to finish things you begin, but I always want to be open to new discoveries, and that's why I treat every day as a new start. If I'm only doing the same things over and over again in a constant rhythm or a loop, then I feel like I'm not experiencing or discovering new things and I'm closing myself off to new discoveries. So I always try to be aware. Doing something over and over again is great for some folks, but for me, I like to go on an adventure when I can.

I always want to be open to new discoveries, and that's why I treat every day as a new start.

When I find myself doing the same thing, the same routine, it's good to recognize that. Then I think, 'Let me try something different just to see, to expand my worldviews and enrich myself as a person. Who knows? I might like it, I might not. I might agree with it or I might disagree with it, but at least I might be exposed to something new.' That's what I'm talking about, to try and break the rhythm at times.

You can't constantly do it—it would be erratic. I'm just saying it's good to be aware, because life is short and I think it's important to experience it to the fullest. You can always choose to be safe.

FIGURE 1 Logo of Masi Oka's company Möbius.

I teach a "Yes, and…" workshop, which comes from my improvisation background. I teach it to a lot of Japanese folks as well as kids, adults, corporations—anywhere. I always tell participants they can say "no" whenever they want. When you say "yes" it can be very scary, but to say "no" closes the door to a lot of things and puts you in a safe spot.

I'm not saying that no is bad, but when you have an opportunity and the privilege to say "yes, and…," I say go for it. I always want to try to take that risk because you never know what you can learn. When you're just saying no, all those doors are shut.

CHF: I was interested to hear you mention a loop a moment ago, and your digital game company is called Möbius, like the strip. How did you come up with the name for your company?

MR. OKA: My production company is called Möbius Productions as well, so everything is under the Möbius banner. First of all, because I come from a mathematics background, yes, the Möbius strip is a mathematical entity, so that's part of my brand. Also, I like the fact that it has a twist, a surprise. I like the fact that it's one-sided: I'm not trying to be a two-sided business, I want to be transparent. I like the fact that it's infinite, that it's constantly going. And it's an acronym for Masi Oka Business in the United States. So this stands for a lot of things that I believe in and it's a good representation of my company and who I am.

RML: I'd like to hear about the game company. Where are you headed with that?

MR. OKA: The idea was to create some intellectual property because it's just so hard to get a movie made. Sometimes it takes 10 years ("Death Note" was 10 years in the making). Sometimes negotiations can be long. It's very erratic and a lot of things are not in your control. I thought the games industry was much easier—it's very naïve of me to think that way, but I knew it was faster.

I started with the mobile field, but success was based on more than the quality of the game and its mechanics; it's also about the business model. We went to what we were more comfortable with and knowledgeable in, which was the console side.

We're developing a game called "Outer Wilds," which I like to describe as "Myst" (an adventure puzzle PC game) meets "Groundhog Day" in space.

RML: That's an interesting description. Tell us more.

MR. OKA: One of our employees, Alex Beachum, was a USC grad and it was his master's thesis—it won the Independent Games Festival's grand prize 2 years ago, I believe. We thought, 'Our mobile games are not doing too well, why don't we do something that everyone already knows about?' Alex had this great vision and we decided to go with that. We're still developing it and hope to deliver it soon.

CHF: I listened to the 4-minute audio of "Timber Hearth" for "Outer Wilds." It was captivating, I would even say mesmerizing.

MR. OKA: Great, thank you. It's a very explorational game and a lot of detail has gone into it. My team has done a great job with it.

RML: What is your role in the company?

MR. OKA: Because my acting and producing and other endeavors take a lot of time, I'm kind of like a CEO but I'm mostly the financier and handle legal stuff. I leave all the creative stuff to my team. I'm there to give input and to approve things, and I'm there when we're brainstorming on new ideas, but most of the time I can't be there day to day so I trust my team and have them working as a family there.

CHF: I understand you're also doing things with virtual reality. What are you doing with that?

MR. OKA: Yes, I think there's a new forefront of VR. The first wave came and it was a bit lackluster. There's no killer content yet that defines VR. People are still trying to find what it is on the game side and on the entertainment side, because VR kind of lies in the middle. Is it interactive entertainment or a passive game?

I'm investing in a couple of VR companies. There's also a VR company called Limitless that's a bunch of

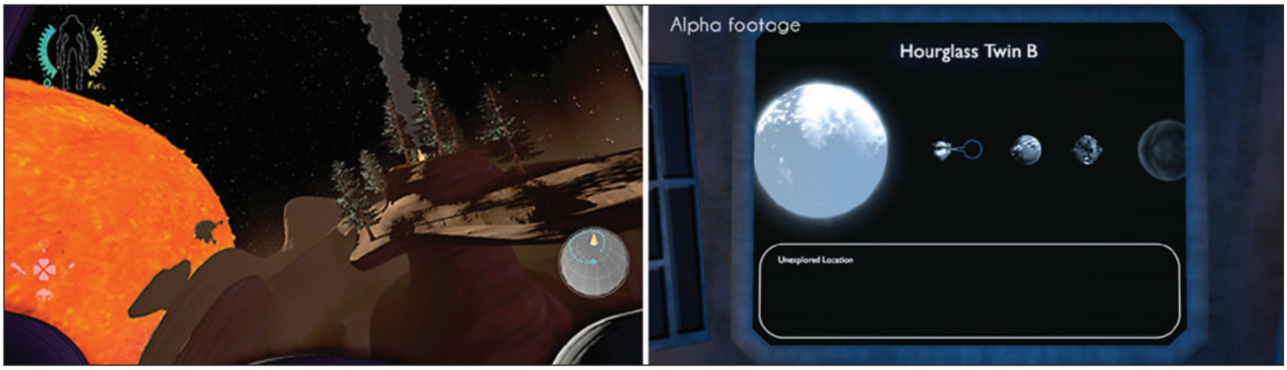

FIGURE 2 Screen shots from the Möbius video game "Outer Wilds."

Bungie and Pixar guys doing a game concept of mine, because Möbius doesn't do VR games.

RML: *The Bridge* reaches a fairly broad audience, not only NAE members but members of Congress and deans of engineering and other subscribers. Is there any message you would like to send that audience from the perspective of someone who is a trained technologist and, at the other end of the spectrum, someone very much engaged in affecting the culture of the country?

MR. OKA: I would just like to say, please enjoy life and be open-minded to experiences. It's important to have a goal but I think being close-minded robs a lot of the joy in life. I know a lot of engineers like to calculate things and make sure everything is in line. There's nothing wrong with being safe, but I'm asking you to consider being open minded, go into the unknown and take calculated risks sometimes.

We're building the future. I like to say that the winners create history but the challengers create the future. I'd like everyone to challenge themselves and go on discoveries and explore life. Try new things. You never know what discoveries are there. Explore life.

CHF: Thinking along those lines, you clearly are actively pursuing a number of different interests. Where do you see yourself in 5 or 10 years?

MR. OKA: Hopefully I'll be doing what I'm doing on a bigger scale, whether directing something or creating my own game or launching a new startup—or maybe working with the White House and the Japanese government to try to bring them together. And advising a lot of companies. I can see that.

I can also see myself being at a school and teaching. So I don't know.

Where would I like to be? I'd like to be with my family and have a happy life and be enjoying what I do both personally and careerwise.

RML: I think it would be really interesting for kids to hear from you. Do you have any interaction with young people in your off-time, whenever that may be?

MR. OKA: Yes. As I said, I teach the "Yes, and…" workshop, and I do that at high schools in the US and Japan. I would like to do more, I just don't know how. There's also a timing issue because, being an actor, you're a slave to production, so your schedule is not as flexible. Fortunately, I'm off a show right now, but who knows what's going to happen in the future.

RML: Interesting. Masi, we appreciate your time and I know you have a full schedule.

CHF: Thank you so much, Masi. What a pleasure.

MR. OKA: Thank you very much. Really appreciate it.

NAE News and Notes

NAE Newsmakers

Robert D. Allen, senior manager, Chemistry and Advanced Materials Research, IBM Almaden Research Center, received the Virginia Tech **2017 Graduate School Distinguished Alumni Achievement Award** at the VT commencement ceremony on May 11.

Three NAE members were honored as **Outstanding Faculty** during the 2017 Celebration of Faculty Excellence on May 2 at North Carolina State University (NCSU): **B. Jayant Baliga**, director, Power Semiconductor Research Center; **Jagdish Narayan**, John C.C. Fan Foundation Distinguished Chair Professor, Materials Science and Engineering; and **Frances S. Ligler**, Senior Scientist Emerita, Naval Research Laboratory, and Lampe Distinguished Professor of Biomedical Engineering, Joint Department of Biomedical Engineering, UNC–Chapel Hill and NCSU. The annual event honors faculty who have won prestigious state, national, and international awards and created new knowledge and advances in their disciplines.

William J. Chancellor, professor emeritus, University of California, Davis, was honored with the **UC Davis Medal**, the highest honor the university presents to an individual. Dr. Chancellor died February 16, 2017; the medal was accepted on his behalf by Nongkarn Chancellor, his wife of 56 years, at the College of Engineering's commencement ceremony on June 16.

The IEEE Computer Society's **2017 Harry H. Goode Award** was presented June 14 to **K. Mani Chandy**, Emeritus Simon Ramo Professor, Computing and Mathematical Sciences, California Institute of Technology, and Jayadev Misra, professor, Department of Computer Science, University of Texas at Austin. They received the award for "seminal contributions to distributed and parallel programming, including the development of the UNITY formalism."

Thomas V. Falkie, retired chair and CEO, Berwind Natural Resources Corporation, is a **2017 inductee into the National Mining Hall of Fame**. He was cited for his accomplishments in industry, academia, government, and professional societies that demonstrate a pattern of integrity and sustained excellence. The induction banquet was held September 23 in Denver.

Robert E. Fischell, chair and CEO, Fischell Biomedical LLC, is the recipient of the **2017 MDEA Lifetime Achievement Award**, which recognizes industry pioneers and both their crucial role in medical device innovation and significant influence on the medical technology industry. Dr. Fischell was recognized at a ceremony in New York on June 13.

Naomi J. Halas, Stanley C. Moore Professor, Department of Electrical and Computer Engineering, Rice University, has won a **2017 Weizmann Women and Science Award** from the Weizmann Institute in Rehovot, Israel. The biennial award, established in 1994, honors internationally renowned women scientists who have made significant contributions both in their field and to the larger scientific community. Dr. Halas was recognized as a plasmonics pioneer who has "profoundly influenced modern optics."

Nick Holonyak Jr., John Bardeen Chair Emeritus Professor of Electrical and Computer Engineering and Physics, University of Illinois, was honored by the Optical Society with the **2017 Benjamin Franklin Medal in Electrical Engineering**. Dr. Holonyak developed the first visible (red) laser and LED used in displays and lighting. His achievements have led to reduced energy consumption worldwide and contributed to the realization of optical data communications as the backbone of the Internet.

Kathleen Howell, Hsu Lo Distinguished Professor of Aeronautics and Astronautics and associate dean, College of Engineering, Purdue University, has been **elected to the American Academy of Arts and Sciences**. The new class of 228 members will be inducted at a ceremony on October 7 in Cambridge, Massachusetts.

Asad M. Madni, retired president, COO, and CTO of BEI Technologies Inc., and independent consultant, has been elected a **fellow of the Royal Aeronautical Society** (FRAeS). Established in 1866, the society has been at the forefront of developments in aerospace, seeking to promote the highest professional standards and provide a central forum for sharing knowledge. Dr. Madni has also been awarded the **Mahatma Gandhi Pravasi Samman Gold Medal** by the government of India and the NRI Welfare Society. The medal is awarded to people of Indian origin for outstanding contributions in their field in the country of their residence and in the service of the wider global community. The award ceremony will be held September 25 in the House of Lords, London.

Sanjit K. Mitra, Research Professor of Electrical Engineering, University of California, Santa Barbara, and Stephen and Etta Vara Professor Emeritus, University of Southern California, was honored at the 50th IEEE International Symposium on Circuits & Systems, held in Baltimore May 28–31. Two special sessions, entitled "50 Years of Circuits, Systems & Signals: A Session in Honor of Prof. Sanjit K. Mitra (Parts I and II)," featured eight papers by authors from Brazil, India, Italy, Singapore, and the United States.

Robert M. Nerem, Institute Professor and Parker H. Petit Professor Emeritus, Institute for Bioengineering and Bioscience, Georgia Institute of Technology, has been honored by the American Society of Mechanical Engineers, which established the **Robert M. Nerem Education and Mentorship Medal** to recognize him for his role in influencing engineering careers in the growing field of bioengineering. The new Nerem Medal, granted through ASME's bioengineering division, was launched at the Summer Biomechanics, Bioengineering, and Biotransport Conference, June 21–24, in Tucson.

Arun N. Netravali, managing partner, OmniCapital LLC, and president emeritus, Bell Laboratories, has been awarded the **2017 Marconi Prize** for his pioneering work in video compression that resulted in an array of video services (HDTV, digital TV, and video streaming, among others). Dr. Netravali will receive the award October 3 at a ceremony in Summit, New Jersey.

At its annual meeting in San Francisco in November 2016, the American Institute of Chemical Engineers initiated the annual **John M. Prausnitz AIChE Lectureship** to honor **John Prausnitz**, professor of the graduate school, Department of Chemical and Biomolecular Engineering, University of California, Berkeley, for his pathbreaking contributions to molecular thermodynamics for chemical process design.

Kenneth L. Reifsnider, Presidential Distinguished Professor of Mechanical and Aerospace Engineering and director, Institute for Predictive Methodology, University of Texas at Arlington, has been honored with a **Lifetime Achievement Award** by the International Conference on Computational and Experimental Engineering and Sciences. ICCES specifically recognized his pioneering contributions to science and applications of composite materials. Dr. Reifsnider received his award at the organization's conference in Madeira, Portugal, in June.

Rebecca R. Richards-Kortum, Malcolm Gillis University Professor, Department of Bioengineering, Rice University, has been elected a **member of the American Philosophical Society**, the oldest learned society in the United States.

William B. Russel, retired Arthur W. Marks '19 Professor, Department of Chemical and Biological Engineering, Princeton University, has been awarded the **Distinguished Alumni Award** by Rice University.

Larry L. Smarr, director, Calit2, University of California, San Diego, is the recipient of the **William "Brit" Kirwan Mentorship Award**. The award is presented annually to a member of the Internet2 community who embodies the spirit of Brit Kirwan's role as a mentor to countless professionals in the research and education community.

Sebastian B. Thrun, CEO, Udacity Inc., has been chosen to receive the **AAAI/EAAI 2017 Outstanding Educator Award**, established in 2016 to recognize a person (or group of people) who has (have) made major contributions to artificial intelligence (AI) education that provide long-lasting benefits to the AI community. He received the award for his pioneering efforts in the creation of high-quality, widely available, and affordable online courses, including seminal AI courses, and for demonstrating the excitement of AI research in self-driving cars and navigation.

Moshe Y. Vardi, George Distinguished Service Professor in Computational Engineering, Rice University, has received the **2017 ACM Presidential Award**. The citation lauded Dr. Vardi as "a true visionary whose outstanding leadership over the last decade has cemented the reputation of ACM's flagship publication—*Communications of the ACM*—as the premier chronicler of computing technologies by opening its pages to leading voices from multiple disciplines, extending its reach with new digital and mobile platforms and making it a monthly must-read for a global audience." The award was presented in June at ACM's banquet in San Francisco.

Dongxiao Zhang, dean of engineering and National Chair Professor, Peking University, has been granted **Honorary Membership** by the Society of Petroleum Engineers (SPE). Honorary Membership is the highest honor that SPE presents to an individual and is limited to 0.1 percent of the SPE total membership. This elite group represents individuals who have given outstanding service to SPE or have demonstrated distinguished scientific or engineering achievements in the fields within the technical scope of SPE. The Honorary Membership will be presented to Prof. Zhang in October 2017 during the SPE Annual Awards Banquet in San Antonio.

2017 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education

Left to right: Morton Schapiro, Northwestern University President; C. D. Mote, Jr., NAE President; Julio M. Ottino, Gordon Prize Winner; M. Ross Brown, Operations Manager, BMG Charitable Trust; and Daniel I. Linzer, Northwestern University Provost and Chief Academic Officer.

Julio M. Ottino, dean of the Robert R. McCormick School of Engineering and Applied Sciences at Northwestern University, accepted the 2017 Bernard M. Gordon Prize for Innovation in Engineering and Technology Education on May 30. The ceremony with students, alumni, faculty, friends, NAE members, and members of the McCormick Advisory Council took place in the Ford Motor Company Engineering Design Center.

The prize was awarded "for an educational paradigm that merges analytical, rational left-brain skills with creative, expansive right-brain skills to develop engineering leaders." NAE president **C. D. Mote, Jr.**, BMG Charitable Trust operations officer M. Ross Brown, and Northwestern University president Morton O. Schapiro presented the award on behalf of the National Academy of Engineering. The public lecture will take place October 8 during the 2017 NAE annual meeting.

Whole-brain engineering is a reimagining of engineering education: it merges the analytical and technical components of engineering (left brain) with creativity, design, and divergent thinking (right brain). This interdisciplinary approach for developing leaders has led to new Northwestern programs and initiatives for engineers and nonengineers and it has sparked partnerships between the McCormick School and Block Museum of Art, School of the Art Institute of Chicago, Shirley Ryan AbilityLab, Shedd Aquarium, and others.

In addition to his appointment as dean, Dr. Ottino is Distinguished Robert R. McCormick Institute Professor, Walter P. Murphy Professor of Chemical and Biological Engineering, and professor (by courtesy) of mechanical engineering. He started his career at the University of Massachusetts Amherst, has held chair and senior appointments at the California Institute of Technology and Stanford University, and has supervised more than 50 PhD theses. He is the founder and former director of the Northwestern Institute on Complex Systems (NICO).

Acceptance Remarks by Julio M. Ottino

Julio M. Ottino

Receiving this award is an incredible honor, and I share it with many people.

In cases like this, one is supposed to say something about how the idea emerged. With this there is a temptation to beautify the path of how things came about, describing things—to paraphrase someone famous, Hermann Helmholtz—as a smooth royal path rather than as a shaky ladder. Or, as Ludwig Wittgenstein put it, when reaching the top, to kick the ladder altogether, erasing the trail of missteps, errors, and difficulties, and often presenting things as epiphanies.

I do not believe in epiphanies, at least I cannot tell you I have ever had a clear one. I have had two, maybe three good ideas in my career. But for me, ideas emerge in a kind of cloudy state, with lots of components, some very amorphously defined, that sort of dance in your brain. Sometimes you have to let them self-organize, and at some point there is one piece, no more special than the others, that makes the picture more complete. In this case, it was coming up with the term "whole-brain engineering."

When I first began as dean, the school was largely disconnected. I needed to connect the school with the larger fabric of the university. This was more than creating structures. It was about creating the right kind of people. The people are the connectors. We had to change the culture through individuals.

The quickest way to do this was to change our undergraduate experience. By integrating right-brain thinking into the undergraduate curriculum, we could excite a new generation of engineers. This is the quickest way to do anything. If you give young students a match, they will bring you a forest fire.

We began to reframe engineering at Northwestern. We began to see ourselves not as a distinct school but as part of a system, a network of disciplines and ideas. We began to intertwine learning and doing, which is the way things work in the arts but a more uncommon approach in engineering. And we began to see collaborations as investments. We targeted activities with every school at Northwestern as well as partners outside the university.

Now if I look at this in hindsight, whole-brain engineering is really about something called complementarity or the principle of complementarity. Niels Bohr made sense of the quantum world by holding two separate ways of describing a system in his mind at the same time. Light is both a particle and a wave: light travels as a wave but interacts with matter as a particle. Both descriptions—light and wave—are correct and useful, but ultimately they are incompatible. It is about seeing two extremes at the same time.

Complementarity applies to art/science, abstraction/realism, rationality/intuition. F. Scott Fitzgerald said, "The test of a first-rate intelligence is the ability to hold two opposed ideas in your mind at the same time and still retain the ability to function." Complementarity is not about just being able to function. It is about thriving.

This is the view from 10,000 feet, which I have because I am the dean. But of course it must translate down to our many courses, majors, research projects, and programs, and for that I am grateful to the many, many people on whose shoulders I rest to be able to have this view.

For design, I thank Greg Holderfield, Bruce Ankenman, and Ed Colgate for their original vision in incorporating design into our curriculum and for continuing to innovate every day. I also benefited from many conversations with Walter Herbst, Don Norman, Bruce Mau, and others.

A big part of our design curriculum, the entry point to everything, is Design Thinking and Communication (formerly Engineering Design and Communication), and for that I thank Steve Carr, Ted Belytschko, and Penny Hirsch for their hard work in helping to create this course.

Another big part of our design efforts is the student initiative Design for America, for which I thank Liz Gerber, Mert Iseri, Yuri Malina, Hannah Chung, and Aaron Horowitz.

For our entrepreneurship efforts I must thank Mike Marasco and Mark Werwath, and for our leadership efforts I thank Adam Goodman. Joe Holtgreive has helped us to develop a truly distinctive vision of personal development.

Northwestern has been full of good partners, people who have stretched in multiple directions. Many are here today, such as Lisa Corrin of the Block Museum of Art, Saul Morson from Weinberg, and Daniel Diermeier from the University of Chicago. In this vein I should thank also Mark Mills of Forbes—I have exchanged views with him on a multitude of topics, including the very first published versions of the whole-brain paradigm.

Many of the McCormick Advisory Council members, represented here by Ken Porrello, have given many hours and words of advice as we charted this path, and for that I am grateful. I am especially thankful to the MAC members past and present who travelled here—there are at least four from California.

I have been tremendously lucky to have an outstanding team working with me. Thank you to the many members of the McCormick leadership team, particularly Rich Lueptow, Ajit Tamhane, Joe Schofer, Alice Kelley, and Wes Burghardt.

Finally, I have to thank my toughest critic, my wife Alicia, who keeps me grounded, humble, and on my toes.

I conclude by thanking Morty Schapiro and Dan Linzer—they have been very big supporters of these ideas—as well as many other members of Northwestern's leadership team, and my fellow deans, for allowing me to follow this vision throughout not only McCormick but the university.

Eventually, from one idea comes a network of ideas, and the network of ideas becomes a system and a culture. I am not going to be shy—the ultimate goal is to make Northwestern a whole-brain organization. I think that this is where we are going. This prize will allow us to keep plowing forward to make that a reality.

Thank you.

Georgia Institute of Technology Hosts NAE Regional Meeting on Data-Enabled Design and Manufacturing

The Georgia Institute of Technology hosted an NAE regional meeting April 19–20 at the Historic Academy of Medicine in Atlanta, attended by approximately 70 members of the engineering community.

The event began with a dinner at the Georgia Tech Hotel on April 19. **Rafael Bras**, Georgia Tech provost, welcomed the attendees and introduced the speaker, Brian Krzanich, CEO of Intel. Intel has a long-standing relationship with Georgia Tech as both a recruiter and benefactor and has played a significant role in funding Georgia Tech's efforts to recruit and retain underrepresented minority engineering students.

On April 20 attendees were welcomed by **C. D. Mote, Jr.**, president of the National Academy of Engineering, who congratulated Gary May, dean and Southern Company Chair of the Georgia Tech College of Engineering, on his new position as chancellor of the University of California, Davis in August. G.P. "Bud" Peterson, president of Georgia Tech, gave an overview of the institute and was followed by Dr. May, who discussed student innovation and the Grand Challenges Scholars Program, which gives students the opportunity to focus on one of the NAE's

14 Grand Challenges during their studies at Georgia Tech.

Professor Thomas Kurfess, of Georgia Tech's George W. Woodruff School of Mechanical Engineering, introduced the topic of data-enabled design and manufacturing, making the case that despite recent media reports manufacturing is alive and well in America. Pointing out that both Nissan and Honda have built manufacturing plants in the United States to serve overseas markets, he argued that America is still a global power in manufacturing but that in order to remain so policy and manufacturing must be driven by data. Dr. Kurfess then served as the moderator for the afternoon panel discussion.

Panelists gave background on their research and areas of expertise, explaining the role of data in their fields. Krishnendu Roy, director of the Georgia Tech Center for ImmunoEngineering, explained that cell therapy and manufacturing is in its infancy and that data will drive improvements in production. He stressed that there are no degrees of failure in cell manufacturing—the product is viable or not—so data must be used to recreate ideal manufacturing conditions.

Gary May, dean and Southern Company Chair of the Georgia Tech College of Engineering, with student Daphne Chen.

David Furrer, senior fellow and manager of manufacturing technology at Pratt & Whitney, discussed how incremental improvements have a significant cumulative impact on the fuel efficiency of airline engines. Larry Schneider, vice president and chief project engineer of the Boeing 777 program, explained the importance of using data in simulations during the design and evaluation process, saving both time and expense while improving outcomes. Professor Jianjun Shi, of the Georgia Tech H. Milton Stewart School of Industrial and Systems Engineering, tied the discussion together by sharing his research on system modeling, monitoring, diagnosis, and control.

The panel was followed by a reception and 16 student poster presentations showcasing the data-related research being conducted by Georgia Tech students. The depth and breadth of the research further enforced the critical role that data play across disciplines. The day concluded with an NAE business meeting and dinner.

NAE Regional Meeting Hosted by Northwestern University: "The Networked Body"

On May 16, NAE members and guests gathered at Northwestern University to learn about the latest developments in wearable and bio-integrated electronics at the NAE regional meeting and symposium, cohosted by the NAE and Northwestern's McCormick School of Engineering.

NAE president **C. D. Mote, Jr.** addressed approximately 20 NAE members at a business meeting and luncheon on campus. The members then joined Northwestern faculty, students, and staff, industry professionals, and guests at the symposium. Dr. Mote, Northwestern Engineering dean **Julio M. Ottino**, and Northwestern provost Daniel Linzer delivered welcoming remarks.

Researchers from academia, industry, and athletics introduced the symposium's 250 attendees to work being conducted at the intersection of science, technology, and medicine. **John Rogers**, the Louis Simpson and Kimberly Querrey

Professor of Materials Science and Engineering, Biomedical Engineering, and Neurological Surgery at Northwestern, delivered the opening lecture, "Electronics for the Human Body." A pioneer in the field of wearable electronics, Dr. Rogers develops biointegrated technologies, which fall into three categories: soft, tattoo-like electronic sensors; millimeter-scale wireless wearables; and skin-integrated microfluidic systems. He highlighted his "epidermal electronics," which are similar to temporary tattoos—ultrasoft, ultrathin, and waterproof. Not only are they comfortable to wear but they can produce clinically relevant measurements for temperature, blood pressure, heart rate, and more.

David Camarillo, the Tashia and John Morgridge Endowed Faculty Scholar at Stanford University, presented his work to monitor and potentially prevent concussions. His team designs smart biomedical devices that can measure the biomechanics involved in concussions, with the aim of developing equipment, such as better helmets, to reduce brain injuries.

Moderated by Robert C. Wolcott, cofounder and executive director of the Kellogg Innovation Network at Northwestern, an expert panel discussed the challenges and opportunities for integrating wearable technologies into athletics. The panel featured Bobby Basham, assistant director of minor league operations for the Chicago Cubs; Jon-Kyle Davis, research scientist at Gatorade Sports Science Institute; and Jeff Mjaanes, director of intercollegiate and health service sports medicine and head team physician at Northwestern. The panelists agreed that some athletes do not want to be monitored all the time because of privacy concerns. Younger athletes, however, have come to expect and want fitness monitoring and data collection to become more integrated in their sport so they can stay healthy and have longer careers.

Rajesh Naik, chief scientist in the 711th Human Performance Wing of the Air Force Research Laboratory, discussed ways that the military is working to monitor individuals and teams to both optimize performance and keep soldiers safe. Because fitness trackers are designed with a "one-size-fits-all" approach, 75 percent of them do not work well in soldiers' specialized training or battlefield environments. The military is developing its own technology to monitor the physiology and cognitive functions of soldiers when underwater, in confined spaces, exposed to fumes, and more.

David Mohr, psychiatry professor and director of Northwestern's Center for Behavioral Intervention Technologies, presented his work on using technology to improve physicians' abilities to treat mental health patients. Dr. Mohr found that the most effective technologies seamlessly sense patient behaviors rather than requiring patients to input their own information. His team developed "Purple Robot," a passive data collection system that monitors patients with depression or bipolar disorder through their smartphone's GPS.

Mark Chevillet, technical project lead at Facebook Building 8, presented work to develop brain-computer interface technology that would allow humans to write and send messages simply by thinking. His team is first figuring out how to use technology to decode text from brain activity in real time. Then it will tackle the issue of measuring brain activity in a noninvasive manner.

Northwestern's Ed Colgate, the Allen K. Johnnie Cordell Breed Senior Professor of Design, and Michael Peshkin, the Bette and Neison Harris Professor in Teaching Excellence, presented their work to put touch into the touchscreen by using haptics technology. Much of their work involves manipulating friction on glass by modulating electric or ultrasonic signals below the surface. Their technology can make smooth glass feel and sound like sandpaper, metal, or ceramic.

The day ended with a reception and demo session in which tech startups showcased their work. The session included John Rogers' company Wearifi, which develops miniaturized, biocompatible near-field communication devices for the consumer electronics industry.

NAE Members Explore the Future of the Internet at Akamai Technologies in Cambridge

The emergence of new technologies—from the Internet of Things (IoT) to virtual reality (VR) and artificial intelligence (AI)—presents unprecedented opportunities to share information, access new prospects, and collaborate across both geographic and cultural boundaries. Simultaneously, the reality of today's instant-access, always-on world means that a lot can—and often does—go wrong.

On May 25, NAE members gathered at the Cambridge, MA headquarters of Akamai Technologies (www.akamai.com) for an NAE regional meeting and symposium. Founded in 1998 based on academic research conducted at MIT, Akamai has grown to become the world's most trusted cloud delivery platform, accelerating and securing over two trillion web requests per day on behalf of its global customers.

The event, themed "The Future of the Internet," opened with remarks by Akamai's CEO and cofounder **Tom Leighton**. An NAE member since 2004, he explained how Akamai's engineers are working to solve the technical complexities required to enable the future: "Thousands of engineers…are working…to develop the technology that will be needed to support orders of magnitude more traffic [and] connected devices, ever higher demands for quality, and to provide the security that can hold up against ever more determined and well-funded adversaries."

He also presented his vision of future online capacities:

> As I look to the future of the Internet, it is not hard to imagine a world where billions of people are watching TV or video every day…online…and generating tens of thousands of Tbps [terabits per second] of traffic. (By the way, that's 3 orders of magnitude more traffic than we have on the Internet today.)
>
> But more than just watching TV online, I can imagine a world where virtual and augmented reality experiences have become commonplace. A world where…hundreds of millions of connected cars are engaging in billions of updates per second…while many billions of other devices in schools, hospitals, manufacturing plants, and our homes are sending enormous volumes of data to command-and-control systems for collection, analysis, and decision making…all in real time. A world where all financial transactions, including trillions of micropayments, are processed and secured online. A world where sensors are constantly monitoring your health and providing real-time alerts on anything that requires attention…. Or even a world where every golf ball, tennis ball, football, and hockey puck…and all your sportswear is equipped with sensors to record the trajectory of the ball…allowing you to compare your performance with your favorite professional athlete. And I can imagine a world where enterprise networks are actually secure…and where they provide instant access to all the information employees need to be productive—wherever they are across the globe. And it would be great to have a world where you don't have to worry about your identity or personal information being stolen or abused.

NAE president **C. D. Mote, Jr.** then reviewed the academy's strategic goals and the importance of collaboration with industry partners like Akamai.

Following Dr. Mote's remarks, attendees heard from several Akamai thought leaders on some of the most pressing technical challenges and opportunities facing the future of the Internet.

David Belson, senior director of industry and data intelligence, shared data from Akamai's state of the Internet research, which tracks the rise of global connection speeds and IPv6 adoption progress.

> Connection speeds for both fixed and mobile Internet connectivity are getting better, and Internet connectivity is becoming more widely available as well—incumbent wired and mobile carriers around the world continue to expand and improve their coverage. In addition, global platforms like Facebook and Google are getting into the last-mile game with technologies [such as] balloons and drones as well as more traditional fixed and mobile technologies.

In a presentation on the future of Web security, Senior Director of Security Products Pawan Bajaj outlined the evolving threat landscape, in particular the increasing prevalence of bots (Web robots) and credential abuse.

> A botnet with nearly 13,000 members is not an abnormal phenomenon in the current threat landscape.… We also see credential abuse attacks on the rise, with malicious actors striving to take over more and more compromised accounts.

In addition to security concerns, Lauren Van Wazer, vice president of public policy, spoke about the evolving impact of issues such as net neutrality and data privacy.

The event concluded with a tour of Akamai's Network Operations Command Center (NOCC), which is staffed 24 hours a day, 7 days a week by expert network operations personnel to provide monitoring and troubleshooting of all servers in the global Akamai network.

2017 China-America Frontiers of Engineering Held in Shanghai

Group photo of attendees at 2017 CAFOE.

The 2017 China-America Frontiers of Engineering Symposium was held June 22–24 at Tongji University in Shanghai. NAE member **Gang Chen**, Carl Richard Soderberg Professor of Power Engineering and head of the Mechanical Engineering Department at the Massachusetts Institute of Technology, and Zhihua Zhong, president of Tongji University, cochaired the symposium.

Consistent with the design of the bilateral FOEs, this meeting brought together approximately 60 engineers, ages 30–45, from US and Chinese universities, companies, and government labs for a 2½-day meeting to discuss leading-edge developments in four engineering fields. The session topics were Intelligent Transportation, Energy Storage, Synthetic Biology, and Robots Everywhere: Air, Sea, and in Close Proximity.

By 2050, 70 percent of the world population is likely to be urban, with many living in megacities of more than 10 million people. Three major trends—connectivity and automation, electrification of transportation, and the shared economy—will play a role in alleviating the resulting traffic congestion challenges. The session on Intelligent Transportation highlighted technologies, policies, and strategies that will bring significant benefits such as more transport choices, greater affordability and accessibility, more livable cities, less vehicle use, and fewer greenhouse gas emissions. The first speaker described mechanisms of the shared economy underlying dynamic pricing and ride matching in car-sharing services. The next presenter focused on the development of electricity supply infrastructure to support large-scale adoption of electric vehicles. This was followed by a talk on parallel learning theory and its application in intelligent vehicles. The last speaker discussed new and disruptive research in the field of congestion reduction through vehicle automation and wave smoothing.

The United States and China are the leading producers of greenhouse gases, so alternatives to fossil fuel–based power generation and transportation are important for both countries. Electrochemical energy storage will play a major role in future transportation, grid-scale storage, and home storage applications. The session on Energy Storage provided an overview of several key topics in energy storage, including how nanomaterials have enabled unprecedented advances in battery science and technology; how fundamental research has enabled the design of novel high-performance materials from the bottom up, which leads to superior performance for lithium-ion batteries; the coupling of battery thermal-electrochemical characteristics, including heat-generating characteristics, boundary evaluation-thermal runaway, system propagation, and thermal stability throughout the life of the battery; and end-of-life and recycling issues related to energy storage devices from a sustainability perspective.

Synthetic biology is an emerging discipline that combines science and engineering approaches to control biological networks. The field is impacting biomedicine and bioengineering, automation science and engineering, biomaterials science and engineering, and biomolecular manufacturing. The first two talks demonstrated how synthetic networks can provide fundamental control of information flow in biological systems. The first speaker explained how, using the tools of synthetic biology, bacteria can be programmed to function differently with respect to time and space. The following presenter showed how synthetic biology and its controlled networks can be used to create biological computers. The next two talks illustrated the application of this information control to solve problems in energy and medicine. One presentation covered the reengineering of cells' electron transfer pathway for energy. The other reviewed the use of synthetic gene networks as a potential therapy for liver cancer.

Recent advances have made robotic systems increasingly ubiquitous—operating in close proximity with humans in work environments, becoming common household items, and in extreme cases becoming an extension of the human. In the session on Robots Everywhere: Air, Sea, and in Close Proximity speakers described the engineering challenges, advances, and new modalities for human-robot interaction, both physical and informational. The session started with a talk on the enabling technologies that change the role of robotics in factory automation, including robots programming themselves by taking loose guidance and social cues from humans. The next presentation covered research on prosthetic devices that augment and restore basic functions such as locomotion, as well as noninvasive brain-machine interfaces for command and control. This was followed by a talk on the working progress of the International Aerial Robotics Competition's shepherd task, which involves flight control, environment sensing from the air, and machine decision making. The final presenter described the characteristics of motion in fish as well as analysis and control for highly efficient and highly maneuverable motion in robotic fish and dolphins.

In addition to the formal presentations, a poster session preceded by flash poster talks on the first afternoon served as both an ice-breaker and an opportunity for all participants to share information about their research and technical work. The posters were left up throughout the meeting, facilitating further discussion and exchange during the coffee breaks.

On the second afternoon attendees visited the Gallery of Tongji University History and Tongji University Museum. An elaborate multicourse dinner was followed by an evening cruise on the Huangpu River to see the lights of both old and new Shanghai. On the last day, the group visited the Shanghai Synchrotron Radiation Facility and Shanghai Desano Pharmaceuticals Co. The program, list of attendees, and presentation slides are available at the CAFOE link at www.naefrontiers.org.

Funding for this activity was provided by The Grainger Foundation and the National Science Foundation. The next CAFOE meeting will be hosted by Qualcomm in the United States in 2019.

The NAE has been hosting an annual US Frontiers of Engineering meeting since 1995 and, in addition to CAFOE, has bilateral Frontiers of Engineering programs with Germany, Japan, India, and the European Union. The FOE meetings bring together outstanding early-career engineers from industry, academia, and government and provide an opportunity to learn about developments, techniques, and approaches at the forefront of fields other than their own. The program also facilitates the establishment of contacts and collaboration among the next generation of engineering leaders.

For more information about the activity, or to nominate an outstanding engineer to participate in a Frontiers meeting, go to www.naefrontiers.org or contact Janet Hunziker at JHunziker@nae.edu.

NAE Hosts Third Global Grand Challenges Summit

Ali Velshi, MSNBC; Scott Settar, Program Manager, Technology and Engineering Education and STEAM Integration, Fairfax County Public Schools; Pamela Brumfield, Principal, Thomas A. Edison High School, Alexandria, VA; Katherine Shirey, Senior Fellow, Knowles Science Teaching Foundation; and Francis Reyes, Global STEM Challenges Student, Edison High School.

On July 18–20, 2017, the third and largest Global Grand Challenges Summit (GGCS), jointly organized by the NAE, UK Royal Academy of Engineering (RAE), and Chinese Academy of Engineering (CAE), was held in Washington on the campus of George Washington University. Nearly 900 people attended, half of them students.

Based on the NAE Grand Challenges for Engineering, the GGCS series aims to inspire the next generation of change makers and to spark global collaborations that lead to innovative ways of addressing critically important engineering challenges and opportunities. The previous summits were held in London (2013) and Beijing (2015).

The 2017 GGCS focused on selected themes of the NAE Grand Challenges—sustainability, health, and joy of living—as well as education and public engagement. Workshops explored virtual reality and artificial intelligence, engineering and health care, sustainability, and reverse engineering the brain. The summit also included a brainstorming session on how to further the Grand Challenges movement.

One panel discussed the NAE Grand Challenges Scholars Program (GCSP), which combines curricular and extracurricular approaches to develop five capabilities in college students to prepare them for solving the Grand Challenges. More than 40 colleges and universities across the nation and around the world have implemented the program, and a panel of participating students described the successes of the GCSP. A secondary school using the NAE Grand Challenges in its curriculum—Thomas A. Edison High School in Alexandria, Virginia—was also featured. The principal, a county administrator, a curriculum developer, and a student described the school's pioneering Global STEM Challenges Program.

Summit speakers included the following:

Michael Abrash, chief scientist, Oculus
Deanne Bell, founder and CEO, Future Engineers; host, CNBC's "Make Me a Millionaire Inventor"
Alec Broers, member, UK House of Lords
Dame Sally Davies, chief medical officer, United Kingdom
Jeffrey Dean, senior fellow, Google
Deng Zhonghan, cofounder, chair, and CEO, Vimicro
Ding Yihui, senior advisor, China Meteorological Administration
Tim Kaine, US senator (D-VA)
Dean Kamen, inventor, entrepreneur, and founder, FIRST Robotics
Christof Koch, president and CSO, Allen Institute for Brain Science
Rikky Muller, cofounder, Cortera Neurotechnologies; assistant professor, electrical engineering and computer science, UC Berkeley

Rajiv Shah, president, Rockefeller Foundation
Molly Stevens, professor, biomedical materials and regenerative medicine, Imperial College London
Wu Zhiqiang, vice president, Tongji University

On July 18 five teams of undergraduate students from each of the host countries competed in Student Day, presenting ideas and business plans for addressing one or more of the NAE Grand Challenges. The winners of the Student Day Business Model Competition were:

- First Place: "Worldcare Technologies" – Allison Duchnak, Martin Hartel, Kirk Hutchison, Christopher Liu, Yajur Maker, and Caitlyn Smith of the University of California, San Diego
- Second Place: "More Water" – George Huish, Sean Irving, Jessica Mountfield, Andrew Petty, Mike Thundow, and Sam Watkins of Bournemouth University, United Kingdom
- Third Place: "Dream House" – Yizheng Bao, Yufang Gao, Jingyong Huo, Chunyu Ji, Qun Mou, Xiaoqing Sun, Lifeng Wang, and Huixia Xi of Shanghai University

The first place winners received $25,000, the second place winners $15,000, and the third place winners $10,000.

The summit also included an opportunity for university students to present posters related to research on the NAE's 14 Grand Challenges for Engineering. Undergraduate and graduate winners were chosen in three categories—originality, impact, or design—and received $2,000 each.

The undergraduate winners of the Student Poster Competition were:

- Originality: "Ultra Clean: An Ultrasonic & Vacuum Wear-Free Washing Machine" by Shida Zheng of China
- Impact: "Nomadic Resource Generation" by Cristóvão Mario Cacombe, Daniel Kokocinski, João Martins Nunes, Morgan Pierre-Mitchell, and Ali Younessi of the United Kingdom
- Design: "Point-of-Care Health Informatics for Proactive Epilepsy Seizure Alert" by Stefan Manoharan of the United States

The graduate winners of the Student Day Poster Competition were:

- Originality: "Network Design for In-Motion Wireless Charging of Electric Vehicles in Urban Areas" by Mamdouh Mubarak of the United States
- Impact: "Virtual Reality Enhanced Intelligent Upper-Arm Exoskeleton for Rehabilitation of Stroke Patients" by Rana Soltani-Zarrin of the United States
- Design: "Encapsulated Biomaterial-Enabled Microsensor for Pancreatic Health Monitoring" by George Banis of the United States

All student winners received certificates and were recognized during a special session of the summit.

"How to Change the World," a student activity conducted in collaboration with the RAE and University College London, enabled attending students to team with those from other schools or countries to produce a podcast, based on their experiences at the summit, about how engineering can improve the health, security, and sustainability of the planet. The students met during and immediately after the summit to work on their podcasts and get advice from engineering mentors. The podcasts were evaluated by a judging panel and the winner, Bethany Gordon of the University of Virginia, will receive an all-expenses-paid trip to the 2019 GGCS in London.

Students also met with representatives of the 2017 summit sponsors: the Boeing Company, Lockheed Martin Corporation, Northrop Grumman Corporation, and Shell. Students got to try out virtual reality goggles, augmented reality gadgets, and flight simulators with sponsors, and have their resumes reviewed during a networking event.

The 2017 GGCS was held in conjunction with the inaugural FIRST Global robotics competition at DAR Constitution Hall. Teams of high school students from nearly 160 countries competed in a contest based on the NAE Grand Challenge to "Provide Access to Clean Water."

Video of the summit is available on the NAE website (www.nae.edu).

Caryn Cochran Joins NAE Membership Office

Caryn Cochran

Caryn Cochran joined the NAE Membership Office on July 10 as a membership associate. In this role she maintains all member records and committee rosters for the NAE in the institution's shared database system, and generates reports and prepares membership data analyses. She brings 35+ years of administrative and database experience at several associations, most recently 21 years with the American Diabetes Association (ADA). At ADA she managed membership outreach, the distribution and fulfillment of ADA member periodicals and publications, and the membership database, ensuring accuracy of processes and reporting for membership systems. She was also project manager/coordinator for numerous membership database conversions.

During her first few months with the NAE, Caryn has been working closely with the National Academies' IT staff and outside website consultants to ensure the data integrity of NAE's online directories and the prompt resolution of any member login access issues. She is also assisting with the NAE 2017 annual meeting and section meetings.

In her spare time Caryn enjoys several creative interests including jewelry making and stained glass work. She also volunteers for a dog rescue transport organization and is a committed Baltimore Ravens fan.

Member Philanthropy: Dale and Jeanne Compton

Jeanne and Dale Compton

W. Dale Compton (NAE '81) and his wife Jeanne were longtime supporters and friends of the National Academy of Engineering. Dale, elected for "exceptional leadership in developing advanced automotive technologies, individual achievements in engineering physics, and innovative contributions in promoting university-industry relations," was a strong advocate of industry and engineering education. He also worked to advance the NAE's Frontiers of Engineering (FOE) program and was instrumental in getting it off the ground. We were deeply saddened to learn of his passing on February 7, 2017 (Jeanne died September 19, 2016).

Dale and Jeanne were very active in the NAE. Dale served on the NAE Council and as home secretary from 2000 to 2008, and Jeanne made a point of greeting new members at the annual meeting.

As members of the Einstein and Heritage Societies, they are exemplars for their generous support of the NAE. In addition to their lifetime giving, they named the NAE a beneficiary of their IRA. Their unrestricted bequest provides flexibility and helps secure the financial future of the NAE while honoring their years of dedicated service and contributions to the NAE.

Dale and Jeanne are greatly missed.

Calendar of Meetings and Events

September 25–27	US Frontiers of Engineering Symposium East Hartford, Connecticut
October 6–7	NAE Council Meeting
October 8–9	**NAE ANNUAL MEETING**
October 11–12	OEC Expansion Project—Year 4 Meeting
October 13	Joint NAE/IEEE TechEthics Event
November 3	Workshop on the Adaptability of the US Engineering and Technical Workforce
November 16–18	EU-US Frontiers of Engineering Symposium University of California, Davis

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

In Memoriam

JOHN W. CAHN, 88, professor, University of Washington, died March 14, 2016. Dr. Cahn was elected to the NAE in 1998 for work on the kinetics and thermodynamics of phase transformations, interfacial phenomena, and quasicrystals.

MICHAEL M. CARROLL, 79, Burton J. and Ann M. McMurtry Professor of Mechanical Engineering Emeritus, Rice University, died January 17, 2016. Dr. Carroll was elected to the NAE in 1987 for unique contributions in the development of physically based models for geological materials and in related applications to the mechanics of porous materials.

GEORGE E. COOPER, 101, retired consultant and chief, Flight Operations, NASA Ames Research Center, died April 8, 2016. Mr. Cooper was elected to the NAE in 1992 for outstanding contributions to quantifying aircraft handling qualities, to flight crew training requirements, and to flight safety.

STEPHEN C. COWIN, 81, CUNY Distinguished Professor, Departments of Biomedical and Mechanical Engineering, City University of New York, died October 19, 2016. Dr. Cowin was elected in 2004 for contributions to orthopaedic biomechanics, the mechanics of granular materials, and the mechanics of anisotropic elasticity.

DALE L. CRITCHLOW, 84, retired fellow, International Business Machines Corporation, died May 6, 2016. Dr. Critchlow was elected to the NAE in 1991 for technical leadership and key contributions to the development of metal-oxide semiconductor (MOS) devices and dynamic random access memory (DRAM) technology.

PETER T. FLAWN, 91, president emeritus, University of Texas at Austin, died May 7, 2017. Dr. Flawn was elected to the NAE in 1974 for leadership in the development of environmental geology and engineering.

JERRIER A. HADDAD, 94, retired vice president, International Business Machines Corporation, died March 31, 2017. Mr. Haddad was elected to the NAE in 1968 for invention and leadership in the development and exploitation of computer technology and applications.

JOHN M. HANSON, 84, independent consultant and Distinguished Professor Emeritus, Department of Civil Engineering, North Carolina State University, died May 26, 2017. Dr. Hanson was elected to the NAE in 1992 for extraordinary contributions to the investigation and evaluation of structural damage, deterioration, and failures.

L. LOUIS HEGEDUS, 76, retired senior vice president, Research & Development, Arkema Inc., died May 24, 2017. Dr. Hegedus was elected to the NAE in 1989 for contributions to the design and performance of catalysts and catalytic reactors.

DAVID S. JOHNSON, 70, visiting professor, Columbia University, died March 8, 2016. Dr. Johnson was elected to the NAE in 2016 for contributions to the theory and practice of optimization and approximation algorithms.

T. WILLIAM LAMBE, 96, retired consulting geotechnical engineer, died March 6, 2017. Dr. Lambe was elected to the NAE in 1972 for contributions to knowledge of soil structure and behavior, settlement control, foundation performance, and earth structures.

OCTAVE LEVENSPIEL, 90, professor emeritus, Chemical Engineering Department, Oregon State University, died March 5, 2017. Dr. Levenspiel was elected to the NAE in 2000 for contributions in chemical reaction engineering and introducing these into the profession as a cornerstone of the basic curriculum.

MARVIN L. MINSKY, 88, Toshiba Professor of Media Arts and Sciences Emeritus, Massachusetts Institute of Technology, died January 24, 2016. Dr. Minsky was elected to the NAE in 1989 for outstanding contributions to artificial intelligence.

WARREN G. SCHLINGER, 93, retired laboratory manager and director, Texaco Inc., died February 10, 2017. Dr. Schlinger was elected to the NAE in 1991 for the development of advanced coal gasification processes.

LAWRENCE E. SWABB JR., 94, retired vice president, Corporate Services, Exxon Research & Engineering, died April 15, 2017. Dr. Swabb was elected to the NAE in 1977 for leadership in synthetic fuels research, particularly in the development of the hydroforming process for hydrocarbon conversion.

ROBERT W. TAYLOR, 85, retired director, Systems Research Center, Digital Equipment Corporation, died April 13, 2017. Mr. Taylor was elected to the NAE in 1991 for innovative management of research leading to major advances in networks, user interfaces, and workstations.

ALFRED A. YEE, 91, president, Yee Precast Design Group Ltd., died April 21, 2017. Dr. Yee was elected to the NAE in 1976 for pioneering in the development of precast prestressed concrete construction for various types of land and sea structures.

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 NW–Keck 360, Washington, DC 20055. For more information or to place an order, contact NAP online <*www.nap.edu*> or by phone (888.624.6242). *(Note: Prices quoted are subject to change without notice. There is a 10 percent discount for online orders when you sign up for a MyNAP account. Add $6.50 for shipping and handling for the first book and $1.50 for each additional book. Add applicable sales tax or GST if you live in CA, CT, DC, FL, MD, NY, NC, VA, WI, or Canada.)*

Overcoming Challenges to Infusing Ethics into the Development of Engineers: Proceedings of a Workshop. On January 11–12, 2017, the NAE Center for Engineering Ethics and Society (CEES) held a workshop designed to help the engineering community identify institutional and cultural challenges to instilling ethics in engineering programs and to develop approaches, programs, strategies, and collaborations to overcome those challenges. The workshop was a follow-on activity to the 2016 CEES report *Infusing Ethics into the Development of Engineers: Exemplary Education Activities and Programs*. This publication summarizes the workshop presentations and discussions.

NAE members on the advisory committee were **Gerald E. Galloway Jr.** (chair), Glenn L. Martin Institute Professor of Engineering, University of Maryland, College Park; **Paul F. Boulos**, retired president, COO, and CTO, Innovyze; **Thomas F. Budinger**, Professor of the Graduate School, University of California, Berkeley, E.O. Lawrence Berkeley National Laboratory; and **Glen T. Daigger**, president, One Water Solutions LLC. Free PDF.

Assessment of Solid-State Lighting, Phase Two. The standard incandescent light bulb, which still works mainly as Thomas Edison invented it, converts more than 90 percent of the consumed electricity into heat. Newer lighting technologies convert a greater percentage into useful light and can thus decrease the amount of energy used for lighting in both commercial and residential applications. Besides compact fluorescent lamps (CFLs), solid-state lighting (SSL) stands to help greatly decrease US energy consumption for lighting. Significant recent increases in SSL penetration have been accompanied by a dramatic dislocation and restructuring of the SSL marketplace, as cost reductions for light-emitting diode (LED) components reduced profitability for LED manufacturers. At the same time, new applications for SSL may create new marketing opportunities for the SSL industry. This report reviews the progress of SSL commercialization and acceptance as well as the technical advances and challenges in achieving higher efficacy for LEDs. It also describes recent trends in SSL manufacturing and opportunities for new applications, and the role of the Department of Energy (DOE) Lighting Program in SSL development.

NAE members on the study committee were **John G. Kassakian** (chair), professor of electrical engineering and computer science emeritus, Research Laboratory of Electronics, Massachusetts Institute of Technology; **Michael Ettenberg**, principal, Dolce Technologies; **Evelyn L. Hu**, Tarr-Coyne Professor of Applied Physics and Electrical Engineering, Harvard University; **Maxine L. Savitz**, retired general manager, Technology/Partnerships, Honeywell Inc.; and **Ching Wan Tang**, Doris Johns Cherry Professor of Chemical Engineering, Chemistry, and Physics, University of Rochester. Paper, $64.00.

A Review of the Department of Transportation Plan for Analyzing and Testing Electronically Controlled Pneumatic Brakes. Congress directed DOT to reconsider the ECP braking requirement for certain trains carrying high-hazard flammable liquids, and a committee of the NRC Transportation Research Board (TRB) reviewed DOT's plan to evaluate the emergency performance of ECP brakes with other braking systems. The resulting letter report recommends improvements to ensure that DOT's plan will lead to objective, accurate, and reliable tests of key DOT assumptions in its comparisons, to reduce the incidence and severity of spills of crude oil or ethanol from derailments. In the second phase of this project (being carried out in 2017), the committee will review the conduct and results of DOT's tests and report findings on the performance of ECP brakes relative to other braking systems tested by DOT.

NAE members on the study committee were **Louis J. Lanzerotti** (chair), Distinguished Research Professor, Department of Physics, New Jersey Institute of Technology, and retired Distinguished Member, Technical Staff, Bell Laboratories, Alcatel Lucent, and **Roger L. McCarthy**, consultant, McCarthy Engineering. Free PDF.

Review of the Draft Climate Science Special Report. The US Global Change Research Program (USGCRP) is moving toward a sustained assessment process that allows for more fluid and consistent integration of scientific knowledge in the mandated quadrennial National Climate Assessment. As part of this process, the USGCRP is developing the Climate Science Special Report (CSSR), a technical report that details the current state of science relating to climate change and its physical impacts. This NRC report assesses whether the draft CSSR accurately presents the scientific literature in an understandable, transparent, and traceable way; whether the CSSR authors handled the data, analyses, and statistical approaches in an appropriate manner; and the effectiveness of the report in conveying the information clearly for the intended audience. It provides recommendations for strengthening the draft CSSR.

NAE member **Dennis P. Lettenmaier**, Distinguished Professor, Department of Geography, University of California, Los Angeles, was a member of the study committee. Paper, $55.00.

Undergraduate Research Experiences for STEM Students: Successes, Challenges, and Opportunities. Many researchers point to undergraduate research experiences (UREs) as crucial to their career success. Complementing efforts to improve undergraduate science, technology, engineering, and mathematics (STEM) education by increasing students' active engagement and decreasing traditional lecture-based teaching, UREs may be a key strategy for broadening participation in STEM. But there are questions about student participation in UREs, best practices in URE design, and evidence of beneficial outcomes from UREs. This report reviews current and rapidly evolving types of UREs in an effort to improve understanding of their content, context, diversity of student participants, and opportunities for learning. The study analyzes UREs in the context of a learning system shaped by national policy, institutional leadership, and departmental culture as well as interactions among faculty, other mentors, and students. The report provides questions to be considered by those implementing UREs and an agenda for research on these experiences.

NAE member **Eli Fromm**, Roy A. Brothers University Professor and professor of electrical and computer engineering, Drexel University, was a member of the study committee. Paper, $64.00.

Report Series: Committee on Solar and Space Physics: Heliophysics Science Centers. The newly constituted NRC Committee on Solar and Space Physics (CSSP) has been tasked with monitoring the progress of recommendations from the 2013 decadal survey *Solar and Space Physics: A Science for a Technological Society*. The committee held its first meeting as part of Space Science Week in Washington, DC, on March 28–30, 2017. In advance of the meeting, and in response to discussions with the leadership of NASA's Heliophysics Division and the Geospace Section of the NSF Division of Atmospheric and Geospace Science, the committee identified the decadal survey's recommendation to create NASA-NSF heliophysics science centers (HSCs) as a timely topic for discussion. This report provides options for NASA and NSF to consider for the creation of HSCs, including how to make them unique from other research elements and strategies for implementation.

NAE member **Steven J. Battel**, president, Battel Engineering, was a member of the study committee. Free PDF.

Preparing for Future Products of Biotechnology. Since 1973 the ways to manipulate DNA to endow new characteristics in an organism (i.e., biotechnology) have advanced, enabling the development of products that were not previously possible. What will the likely future products of biotechnology be over the next 5–10 years? What scientific capabilities, tools, and/or expertise may be needed by the regulatory agencies to ensure they make efficient and sound evaluations of those products? This report analyzes the future landscape of biotechnology products and seeks to inform future policymaking. It identifies potential new risks, frameworks for risk assessment, and areas in which the risks or lack of risks relating to the products of biotechnology are well understood.

NAE member **Richard M. Murray**, Thomas E. and Doris Everhart Professor of Control and Dynamical Systems and Bioengineering, California Institute of Technology, chaired the study committee. Paper, $74.00.

The Value of Social, Behavioral, and Economic Sciences to National Priorities: A Report for the National Science Foundation. Nearly every major challenge the United States faces—from unemployment to terrorism—requires an understanding of the causes and consequences of people's behavior. Even societal challenges that at first glance appear to concern only medicine or engineering or computer science have social and behavioral components. The diverse disciplines of the social, behavioral, and economic (SBE) sciences—anthropology, archaeology, demography, economics, geography, linguistics, neuroscience, political science, psychology, sociology, and statistics—all produce fundamental knowledge, methods, and tools that enhance understanding of people and how they live. This report evaluates whether the federal government should fund SBE research at the NSF, and whether such research furthers the NSF mission to advance national priorities in the areas of health, prosperity and welfare, national defense, and progress in science; advances the missions of other federal agencies; and advances business and industry. It identifies priorities for NSF investment in the SBE sciences and important considerations for NSF strategic planning.

NAE members on the study committee were **Edward H. Kaplan**, William N. and Marie A. Beach Professor of Operations Research, professor of public health, and professor of engineering, Yale School of Management, and **Yannis C. Yortsos**, dean, Viterbi School of Engineering, University of Southern California. Paper, $50.00.

Review of the Research Program of the US DRIVE Partnership: Fifth Report. The vision of the US DRIVE (Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability) Partnership is that American consumers have a broad range of affordable personal transportation choices that reduce both petroleum consumption and harmful emissions from the transportation sector. Its mission is to accelerate the development of precompetitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles and related energy infrastructure. Guidance for the partnership's work, priority setting, and targets for needed research, are provided by joint industry-government technical teams, a structure that has proven effective. Research and development and technology validation programs have been pursued in the following technical areas: internal combustion engines (ICEs) potentially operating on conventional and alternative fuels, automotive fuel cell power systems, hydrogen storage systems (especially onboard vehicles), batteries and other forms of electrochemical energy storage, electric propulsion systems, hydrogen production and delivery, and materials that enable vehicle weight reductions.

NAE members on the study committee were **Alexis T. Bell**, professor, Department of Chemical and Biomolecular Engineering, University of California, Berkeley; **Bernard I. Robertson**, retired senior vice president, Engineering, Technologies and Regulatory Affairs, and general manager, Truck Operations, DaimlerChrysler Corporation; **Alan I. Taub**, chief technology officer, American Lightweight Materials Manufacturing, Innovation Institute, professor of materials science and engineering, University of Michigan, and retired vice president, Global R&D, General Motors Company; and **Kathleen C. Taylor**, retired director, Materials and Processes Laboratory, General Motors Corporation. Paper, $68.00.

An Assessment of ARPA-E. In 2005 the Academies report *Rising Above the Gathering Storm* recommended a new way for the federal government to spur technological breakthroughs in the energy sector. It proposed the creation of a new agency, the Advanced Research Projects Agency–Energy (ARPA-E) as an adaptation of the Defense Advanced Research Projects Agency model, widely considered a successful experiment that has funded out-of-the-box, transformative research and engineering that made possible the Internet, GPS, and stealth aircraft. ARPA-E was meant to tackle the nation's energy challenges in a way that could translate basic research into technological breakthroughs while addressing economic, environmental, and security issues. Congress authorized ARPA-E in the 2007 America COMPETES Act and requested an assessment after six years of operation to examine the agency's progress toward achieving its statutory mission and goals. This publication summarizes the results of that assessment.

NAE members on the study committee were **Pradeep K. Khosla** (chair), chancellor, University of California, San Diego; **Maxine L. Savitz** (vice chair), retired general manager, Technology/Partnerships, Honeywell Inc.; **Terry Boston**, president and CEO, Terry Boston LLC; **Supratik Guha**, director, Nanoscience and Technology Division, Argonne National Laboratory; **Charles V. Shank**, senior fellow, Howard Hughes Medical Institute; and **John C. Wall**, retired vice president and CTO, Cummins Inc. Paper, $64.00.

Acquisition and Operation of Polar Icebreakers: Fulfilling the Nation's Needs. This letter report, mandated by the Coast Guard Authorization Act of 2015, advises Congress on the number and type of polar icebreakers to fund and an acquisition strategy that achieves a lower cost. The authoring committee developed an independent cost estimate using available concept designs to determine whether the US Coast Guard's cost estimates for heavy and medium icebreakers are reasonable. It also compared operating costs of the current fleet to the prospective operating costs of new vessels. The committee recommends a science-ready design for new icebreakers and the use of an enhanced maintenance program to ensure continuity of operations for existing icebreakers.

NAE Member **R. Keith Michel**, president, Webb Institute, was a member of the study committee. Free PDF.

Foundational Cybersecurity Research: Improving Science, Engineering, and Institutions. Despite considerable investments of resources and intellect, cybersecurity continues to pose serious challenges to national security, business performance, and public well-being. This report focuses on foundational research strategies for organizing people, technologies, and governance to ensure the sustained support needed to create an agile, effective research community, with collaborative links across disciplines and between research and practice. The report is aimed primarily at the cybersecurity research community, but takes a broad view that efforts to improve foundational cybersecurity research will need to include many disciplines working together to achieve common goals.

NAE members on the study committee were **Steven M. Bellovin**, Percy K. and Vida L.W. Hudson Professor, Department of Computer Science, Columbia University; **Steven B. Lipner**, executive director, SAFECode; and **Steven J. Wallach**, engineering director, Micron Technology. Paper, $47.00.

GIVING AT THE NAE

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Gifts to the NAE Independent Fund provide essential unrestricted support to vital NAE programming and initiatives that inform public policy and educate the public about the value of engineering's contributions to the nation and world. Without the support of generous individuals like you, many projects the NAE leads wouldn't be possible. In addition, your support of the NAE Independent Fund reflects an active and engaged membership that in turn helps us leverage additional funding to advance engineering education and the profession. *Thank you* to all who have made a gift this year.

If you are interested in making a gift to further increase public awareness and understanding of the crucial role of engineering in our society and the world, contact Radka Nebesky, Director of Development, at 202.334.3417 or RNebesky@nae.edu. You can also learn more and make a gift online by visiting www.nae.edu/giftform.

Thank you to our newest giving society members this year*

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