The Next Industrial Revolution: How We Will Make Things in the 21st Century and Why It Matters

by David Rejeski

David Rejeski is Director, Science and Technology Innovation Program, Woodrow Wilson Center.

In July 1945, an article appeared in the *Atlantic Monthly* by Vannevar Bush, then-director of the U.S. Office of Scientific Research and Development. Titled "As We May Think," the piece explored the possible future of computing and featured a device that Bush termed the *memex*, which bore an eerie resemblance to later-day computers and incorporated mass storage, hypertext, and a precursor to voice recognition.[1]

From a policy standpoint, the most exciting future is not how we may think about things, but how we will make things. We are looking at this future through the same haze that confronted Bush and his colleagues after World War II. It is a world of vague outlines, where the building blocks of a new fabrication paradigm have yet to coalesce into a coherent vision or an iconic industry. The closest we have to the memex may be the 3-D printer, a fascinating device that spits out objects rather than sheets of paper.

Imagine a world where the instructions for making just about anything can be downloaded to your home or office, or anywhere with an Internet connection. A basic 3-D printer now costs about $1,000 to $2,000, and an open-source depository for construction codes, called the Thingiverse, already exists (http://www.thingiverse.com/). Need a coat hanger, iPhone case, printable headphones, or parts for a drone? Download the instructions and make it. In the Thingiverse world, if you improve a design, you can upload it and share your idea. In the future, we will not even need precise instructions for creating something, just the characteristics of the end solution. Evolutionary programming techniques will create an initial solution set, optimize around functional requirements, and create the winning design though a Darwinian battle of virtual prototypes. We will reach a point where machines will make other machines (which will make other machines). With 3-D printing, "complexity is free," as Cornell University engineer Hod Lipson has noted, or at least very cheap.[2] This advance means the barriers to entry posed by old-fashioned machine tools and production techniques drop exponentially. The factory worker can turn back into the craftsman or -woman, but with global connectivity.

Such home-brew manufacturing is a piece of a larger concept called *additive manufacturing*, which dramatically alters how and where we produce, reshaping the supply and value chains along with distribution logistics. The 3-D printers are only the on-ramp to this new world where we have "an evolving suite of capabilities to turn data into things and things into data."[3] The *Economist* recently called this the next industrial revolution and stated that this approach will have as significant an impact on manufacturing as the assembly line had in early 20th century factories.[4]

Over the past three years, the additive manufacturing market is estimated to have grown by almost 20% to about $1.2 billion. It is already being used to make prosthetic devices, architectural components, parts for automobiles or airplanes, jewelry, textiles, sports equipment, and even specialty foods.[5] Over time, additive manufacturing will become cheaper and more precise and will enable construction down to a nano-scale, atom by atom.

But these changes are only the beginning. The ultimate fabricator is biology. Cells, those building blocks of life, just happen to be very good chemists. We could print a chair, but how about growing one by improving the characteristics of cellulose secreted by the gram-negative bacterium

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1. Vannevar Bush, *As We May Think*, Atlantic Monthly (July 1945), http://www.theatlantic.com/magazine/archive/1945/07/as-we-may-think/303881/ (last visited Jan. 22, 2013).
2. Matthew Knight, *3-D Printing: The Shape of Things to Come*, CNN, July 24, 2012, http://www.cnn.com/2012/07/20/tech/3d-printing-manufacturing-technology/ (last visited Jan. 22, 2013).
3. Neil Gershenfeld, *How to Make Almost Anything: The Digital Fabrication Revolution*, 91:6 Foreign Affairs 42-57 (2012), http://www.foreignaffairs.com/articles/138154/neil-gershenfeld/how-to-make-almost-anything?page=show (last visited Jan. 22, 2013).
4. *The Third Industrial Revolution*, Economist, Apr. 21, 2012, http://www.economist.com/node/21553017 (last visited Jan. 22, 2013).
5. Jürgen Gausemeier. Thinking Ahead: The Future of Additive Manufacturing—Analysis of Promising Industries (Direct Manufacturing Research Center, Univ. of Paderborn 2011).

Acetobacter xylinum?[6] Angela Belcher at the Massachusetts Institute of Technology (MIT) is already building highly efficient rechargeable batteries by using viruses that have been engineered to coat themselves with iron and then attach to ultrathin carbon wires to form a conductive network. In May 2010, the J. Craig Venter Institute created the first synthetic cell, a bacterium that was controlled by deoxyribonucleic acid (DNA) produced in the lab (the cell's parent was a computer). So true synthetic life forms may not be far away, and with this advance comes the ability to program life in ways that are no longer limited and controlled by historical evolution. "Made in America" will become "Made by Synthetica."

Here, we see the outlines of a future where "the biological world [replaces] the machine as the general principle of design," as Neri Oxman at the MIT Media Lab has noted.[7] For instance, the emerging field of synthetic biology promises to make biology easier and faster to engineer. Many of the capabilities that enabled the last industrial revolution are finding their way into biology: the standardization of parts; interchangeability; and modularization. These changes will support reproducible precision processes built on rapid prototyping, compressed design-build-test cycles, and controlled variability—the hallmarks of flexible industrial production systems.

An open-source biological parts catalog is already online[8] and now contains more than 18,000 components with a broad range of functions, from biosynthesis to odor production and sensing. The catalog is creating a plug-and-play infrastructure for biological experimentation and construction. Using these parts as a starting point, hundreds of students per year now compete in iGEM, an international competition to create genetically engineered machines. As genetic sequencing becomes exponentially cheaper, users could download the code to produce the parts locally, further distributing innovation and production systems.

The public policy implications of these shifts are significant. Already, policymakers have raised red flags about safety and security issues involving 3-D printing and do-it-yourself biology at the same time that parts of the U.S. government are embracing the technologies as a source of potential innovation. Recently, a desktop manufacturing company seized a 3-D printer it had leased to an organization called Wiki Weapon, which was sharing open-source code to print guns.[9] Liability issues and protections have not been well-defined in open-source communities, either for the generators of data or the end users.

Historically, patterns of production have had profound effects on settlement patterns, labor, education, transportation systems, public health, and the environment. The production and movement of supplies have played critical roles in warfare and military operations, which is why the Defense Advanced Research Projects Agency (DARPA) now has a program called Living Foundries. The program focuses on engineering biology to allow on-demand production of new and high-value materials, devices, and capabilities for the U.S. Department of Defense.[10] This new world is full of questions.

Today, the energy and environmental implications of localized production are unexplored, the intellectual property protections remain ambiguous, and the educational and workforce requirements are poorly defined. We lack clear guidelines to reduce security threats from massively distributed production systems, and we have no processes in place to address potential public concerns—ethical or moral—that may arise as a result of such systems. At a more fundamental level, these techniques raise questions about our relationship to technologies that can simplify, accelerate, and abstract production—separating our head and our hearts from our hands.[11]

It took years for our governing institutions to get onto the information highway and craft policies that were appropriate to the digital age. A new highway is open, one where code, concept, and thing will merge. Now, we have an opportunity to short-circuit the earlier detour and create policy frameworks that support the transition to a new manufacturing paradigm—but first we need to have a conversation about what this world should look like and what policies are needed to make sure that both society and the planet will benefit.

6. Read about the Aseatobacter project at http://2012.igem.org/Team:NYU_Gallatin/.
7. Read more from Neri Oxman at http://www.thelavinagency.com/speaker-neri-oxman.html.
8. *See* iGEM Foundation, *Synthetic Biology Based on Standard Parts*, http://www.partsregistry.org (last visited Jan, 22, 2013).
9. Robert Beckhusen, *3-D Printer Company Seizes Machine From Desktop Gunsmith*, Wired, Aug. 12, 2012, http://www.wired.com/dangerroom/2012/10/3d-gun-blocked/ (last visited Jan. 22, 2013).
10. See the DARPA website's description of the Living Foundries program at http://www.darpa.mil/Our_Work/MTO/Programs/Living_Foundries.aspx (last visited Jan. 22, 2013).
11. *See, e.g.*, Richard Sennett, The Craftsman (Yale Univ. Press 2008).