Open-Source Biology And Its Impact on Industry

BY ROBERT CARLSON
The Molecular Sciences Institute

In 50 years, you may be reading *IEEE Spectrum* on a leaf. The page will not actually look like a leaf, but it will be grown like a leaf. It will be designed for its function, and it will be alive. The leaf will be the product of intentional biological design and manufacturing.

Rather than being constantly green, the cells on its surface will contain pigments controlled by the action of something akin to a nervous system. Like the skin of a cuttlefish, the cells will turn color to form words and images as directed by a connection to the Internet of the day. Given the speed with which the cuttlefish changes its pigment, these pages may not change fast enough to display moving images, but they will be fine for the written word. Each page will be slightly thicker than the paper *Spectrum* is now printed on, making room for control elements (the nervous system) and circulation of nutrients. When a page ages, or is damaged, it will be easily recycled. It will be fueled by sugar and light.

DAVID PLUNKERT

Many of the artifacts produced in 50 years and used in daily living will have a similar appearance and a similar origin. The consequences of mature biological design and manufacturing will be widespread, and will affect all aspects of the economy, including energy and resource usage, transportation, and labor. Today, electronic paper and similar display technologies are just around the corner, but in the long run they will not be able to compete with the products of inexpensive, distributed biological manufacturing.

Growing engineered leaves for display devices may seem a complex biological engineering feat, but foundations for the technology are already being laid. Structurally simple replacement human tissues are currently being grown in the laboratory on frameworks of suture material. Projects to grow functional human heart tissue, and eventually a whole heart, are under way, with a timeline for completion of 10 years.

Genomic parts list

Within those 10 years, the genomes of many organisms will be sequenced, providing a parts list for the proteins forming the structural and control elements in those organisms. Biologists, engineers, and physicists are already collaborating on models that will help us understand how those parts work and fit together. The goal for these models is quantitative prediction of the behavior of biological systems, which will have profound implications for the understanding of basic biology and for improving human health.

Beyond initial biomedical consequences, models that can be used to predict the effects of perturbations to existing biological systems will become *de facto* design tools, providing an infrastructure for creating new technologies based on biology. When we can successfully predict the behavior of designed biological systems, then an *intentional biology* will exist. With an explicit engineering component, intentional biology is the opposite of the current, very nearly random applications of biology as technology.

For instance, the present debate over genetically modified foods is more indicative of the poorly planned use of an immature technology than a failure of the technology itself. At present we simply can't predict the effects of tinkering with a system as complex as crops and their pests. But as with the progression of every other human technology, from fire, to bridges, to computers, biological engineering will improve with time. Quantitative models for simple systems like viral infections of bacteria and yeast signal transduction pathways are already being tested. Computational methods developed in those efforts will soon be applied to higher plants and animals. It is a short step from successful prediction to design and the beginning of industrial applications.

Yet even before the advent of true biological design, more general lessons from biology are already transforming our economy. The potential impact on industrial practices of learning from biology is enormous and is explored in the book *Natural Capitalism*, by Paul Hawken and Amory and L. Hunter Lovins (Little, Brown, London, 1999).

The authors point out that structuring business practices along biological lines can significantly improve the bottom line. The human circulatory system, for instance, is optimized to minimize the work required to pump blood throughout the body. The majority of industrial pumping systems, however, are optimized to minimize the cost of the pipes during construction. This means smaller pipes are used, requiring large pumps that use vastly more energy than necessary.

Similarly, in the human pumping system, the heart has to work too hard when arteriosclerosis reduces the diameter of blood vessels. These vessels then require maintenance in the form of an angioplasty. Industrial pumping systems are designed with built-in arteriolosclerosis, and fixing them requires rebuilding from the ground up. Paying careful attention to several hundred million years of nature's trial-and-error design experience will save human industry considerable energy and resources.

A living industrial infrastructure

Borrowing a design aesthetic for industrial function from nature is just the beginning. The living world will also become part of our industrial infrastructure. Nature has already discovered how to fabricate materials and to finesse chemistry in ways that are the envy of human engineers and chemists. Many companies, both established and start-up, are now focusing on harvesting enzymes from organisms in the environment for use in industrial processes.

Popular examples of high-strength materials fabricated by biology at low temperature, pressure, and energy cost are spider silk and abalone shell. Yet increased resource efficiency and biomaterials are only the first steps in a revolution in manufacturing. Beyond using biology as a model for the structure and function of industrial production, the year 2050 will see humans using biology as the means of production itself.

Whereas most manufacturing today is highly centralized and materials are transported long distances throughout the assembly process, in the year 2050 human industry will use distributed and renewable manufacturing based upon biology. Renewable manufacturing means that biology will be used to produce many of the physical things we use every day.

In early implementation, the organism of choice is likely to be yeast or a bacterium. The physical infrastructure for this type of manufacturing is inherently flexible: it is essentially the vats, pumps, and fluid-handling capacity found in any brewery. Production runs for different products would involve seeding a vat with a yeast strain containing the appropriate genetic instructions and then providing raw materials.

To be sure, there will always be applications and environments in which biological fabrication is not the best option, and it is not clear how complex the fabrication task can be, but biology is capable of fabrication feats impossible for any current or envisioned human technology to emulate. In some ways, this scheme sounds a bit like Eric Drexler's nanotechnological assemblers, except that we already have functional nanotechnology—it's called biology.

The transformation to an economy based on biological manufacturing will occur as technical manipulations become easier with practice and through a proliferation of workers with the appropriate skills. Biological engineering will proceed from profession, to vocation, to avocation, because the availability of inexpensive, quality DNA sequencing and synthesis equipment will allow participation by anyone who wants to learn the details. In 2050, following the fine tradition of hacking automobiles and computers, garage biology hacking will be well under way.

> **Paying careful attention to several hundred million years of nature's trial-and-error design experience will save human industry considerable energy and resources**

Considerable information is already available on how to manipulate and analyze DNA in the kitchen. A recent *Scientific American* Amateur Scientist column provided instructions for amplifying DNA through the polymerase chain reaction (PCR), and a previous column dealt with analyzing DNA samples on homemade electrophoresis equipment. The discussion was immediately picked up in a slashdot.org thread where participants provided tips for improving the yield of the PCR process.

More detailed, technical information can be found in any university biology library in *Current Protocols in Molecular Biology*, which contains instructions on how to perform virtually every task needed in modern molecular biology. This printed compendium has recently joined the myriad resources maintained on-line by universities and government agencies, thereby becoming all the more accessible. Open-source biology is already becoming a reality.

As the "coding" infrastructure for understanding, troubleshooting, and, ultimately, designing biology develops, DNA sequencers and synthesizers will become less expensive, faster, and ever simpler to use. These critical technologies will first move from academic labs and large biotechnology companies to small businesses, and eventually to the home garage and kitchen. Many standard laboratory techniques that once required a doctorate's worth of knowledge and experience to execute correctly are now used by undergraduates in a research setting with kits containing color-coded bottles of reagents. The recipes are easy to follow.

This change in technology represents a democratization of sorts, and it illustrates the likely changes in labor structure that will accompany the blossoming of biological technology.

Distributed biological manufacturing

The course of labor in biological technology can be charted by looking at the experience of the computer and Internet industries. Many start-up companies in Silicon Valley have become contract-engineering efforts, funded by venture capital, where workers sign on expecting the company will be sold within a few years, whereupon they will find a new assignment. The leading edge of the biological technology revolution could soon look the same. However, unlike today's integrated circuits, where manufacturing infrastructure costs have now reached upward of US $1 billion per facility, the infrastructure costs for renewable biological manufacturing will continue to decline. Life, and all the evolutionarily developed technology it utilizes, operates at essentially room temperature, fueled by sugars. Renewable, biological manufacturing will take place anywhere someone wants to set up a vat or plant a seed.

Distributed biological manufacturing will be all the more flexible because the commodity in biotechnology is today becoming information, rather than things. While it is still often necessary to exchange samples through the mail, the genomics industry has already begun to derive income from solely selling information about gene expression, or which genes are turned on in a particular population of cells.

In a few decades it will be the genomic sequence that is sent between labs, there to be re-synthesized and expressed as needed. It is already possible to synthesize sufficient DNA to build a bacterial genome from scratch in a few weeks using chemical means. Over the coming decades, that time will be reduced to days, and then to hours, eventually via the development of directed, template-free, enzymatic synthesis—a DNA "synthase."

It is possible that the evolution of open-source biology will be delayed by retrenchment on the part of corporations trying to protect intellectual property. However, the future model of biology as a technological instrument of any corporation can be found by simply looking at the way life currently makes use of biological technology. Only very rarely is it the case that advantage is conferred on an organism via a biochemically unique enzyme or pathway.

The toolbox of biochemistry, the parts list—"the kernel," to stretch the software analogy—is shared by all organisms on the planet. In general, organisms differ from one another because of their order of gene expression or because of relatively subtle perturbations to protein structures common to all forms of terrestrial life. That is, innovation in the natural world in some sense has always followed the idea of a service and flow economy. If the environment is static, only when an organism figures out how to use the old toolbox to provide itself, or another organism, with a new service is advantage conferred.

The analogy to future industrial applications of biology is clear: When molecular biologists figure out the kernel of biology, innovation by humans will consist of tweaking the parts to provide new services. Because of the sheer amount of information, it is unlikely that a single corporate entity could maintain a monopoly on the kernel. Eventually, as design tasks increase in number and sophistication, corporations will have to share techniques and this information will inevitably spread widely, reaching all levels of technical ability—the currency of the day will be innovation and design. As with every other technology developed by humans, biological technology will be broadly disseminated.

Bypassing conventional infrastructure

As open-source biological manufacturing spreads, it will be adopted quickly in less developed economies to bypass the first world's investment in industrial infrastructure. Given the stressed state of natural resources throughout much of the developing world, it will not be possible for many of those countries to attain first-world standards of living with industrial infrastructure as wasteful as that of the United States. The developing world simply cannot afford industrial and energy inefficiency.

A short cut is to follow the example of the growing wireless-only communications infrastructure in Africa and to skip building systems to transport power and goods. It is already clear that distributed power generation will soon become more efficient than are centralized systems. Distributed manufacturing based upon local resources will save transportation costs, simplify customization, require less infrastructure investment, and, as a result, will likely cost less than centralized manufacturing.

Distributed biological manufacturing is the future of the global economy. With design and fabrication power spread throughout the world to the extent suggested here, it is necessary to consider possible dangers. The simple answer is that those dangers are real and considerable.

This technology enables the creation of new organisms potentially pathogenic to humans, or to animals and plants upon which we rely. It is already clear that the social and biological consequences of extending human life span and human germline engineering will consume considerable public debate time over the next few decades. Moreover, the underlying infrastructure and methods are already so widespread that no one country will be able to manipulate the development of biological technology by controlling the research within its borders.

But fear of potential hazards should be met with increased research and education, rather than closing the door on the profound positive impacts that distributed biological technology will have on human health, human impacts on the environment, and increasing standards of living around the world.

Technology based on intentional, open-source biology is on its way, whether we like it or not, and the opportunity it represents will just begin to emerge in the next 50 years. ●

This essay won a Silver Award in *The Economist/Shell World in 2050* essay competition held last year.