

How good can we get at engineering living matter?

Pushing the limits of engineered living systems

This paper was published in June 2015. The ideas and recommendations within it are among dozens of suggestions that arose from the Stanford Engineering Future process. Share your thoughts with us at SoEFutureFeedback@stanford.edu.

Since the 1930s, scientists have studied natural living systems by characterizing the molecules that compose cells and organisms.

Forty years ago, Stanford researchers helped invent genetic engineering, enabling new approaches for exploring biology and sparking a modern biotechnology sector. Agricultural, industrial and health products now realized through genetic engineering tools accounted for approximately 2.5 percent of the U.S. gross domestic product in 2012 (about \$350 billion a year; about 12 percent annual growth).¹

A global research community has since formed with the goal of making biology easy to engineer. New tools and approaches for engineering living matter are being realized. For example, the cost of synthesizing the DNA encoding a gene has dropped a hundredfold in the past 12 years, from about \$4 to about 4 cents per base pair; several genome-scale synthesis projects have been realized, and Stanford's introductory bioengineering labs no longer teach genetic engineering but rather how to design and source synthetic DNA through commercial foundries. If these trends continue, the cost of synthesizing a human genome will equal a year's tuition at Stanford in approximately 21 years.

We can now foresee achieving exponential improvements in our capacity to engineer living systems and thereby more powerfully harnessing life's intrinsic capacity for organizing atoms. A greatly expanded capacity to engineer living matter would allow us to realize precision manufacturing on a global scale, using naturally distributed platforms that operate under normal environmental conditions. Such capacities could be used to:

- Remake our civilization's supply chains by enabling local and sustainable manufacture of high-value products.
- Open new frontiers in medicine wherein engineered cells sense, diagnose, prevent and treat diseases in place.
- Displace existing technologies, such using DNA as an abiotic data storage material.
- Enable the otherwise impossible, such as growing much of a Mars colony from matter already on Mars.
- Help us learn new ways to engineer complex integrated systems.

While Stanford Engineering is well positioned to sustain and lead efforts to dramatically advance our collective capacity to engineer living matter, we are not now organized or empowered to do so. We offer two observations and an integrated set of recommendations for consideration. We note that success would enable Stanford to help renew and diversify Silicon Valley's tradition of sustaining innovation and economic growth by developing tools that advance engineering.

¹<http://www.synthesis.cc/2014/01/the-us-bioeconomy-in-2012.html>

RECOMMENDATIONS

Biotechnology beyond bioengineering.

Stanford's Department of Bioengineering (BioE) provides a natural home for much of the necessary fundamental research. However, BioE is primarily focused on biomedical applications of biotechnology and has not yet fully developed capacities supporting agriculture, energy, manufacturing, art and the environment. Much of what will be needed might best be based in other departments. Possible examples include:

Aeronautics & Astronautics could lead work on bio-based *in situ* resource utilization.

Chemical Engineering could increase support for sustainable biosynthesis of materials and chemicals.

Civil & Environmental Engineering could further integrate biotechnologies into green manufacturing and resource recycling.

Computer Science could develop languages for programming multidimensional systems (i.e., autonomous patterning through growth). and resource recycling.

Electrical Engineering could advance hardware for engineering wetware and vice versa.

Management Science & Engineering could pioneer strategies for responsibly remaking civilization's manufacturing capacities.

Materials Science & Engineering could lead hybrid materials biosynthesis.

Mechanical Engineering could help develop computer-aided design, exploratory data analysis and rapid-prototyping tools for life.

RECOMMENDATIONS

Policy and leadership.

Political and cultural leadership on biotechnology will be at least as important as the science and technology itself. Stanford Engineering could truly separate from the pack by developing both aspects of biotechnology synergistically.

Advancing our capacity to engineer living matter is already disrupting supply chains (e.g., morphine from yeast instead of poppies), security (e.g., direct synthesis of viral pathogens), ecology (e.g., gene drives for eradicating invasive species) and cultural norms (e.g., human germline engineering).

As engineers, we must help initiate and lead discussions shaping whether and how future biotechnologies are developed, promulgated and practiced. Stanford's Center on Food Security and the Environment, the Woods Institute, the Center for International Security and Cooperation, the d.school, the Carnegie Institute's Plant Biology Department, and the Stanford-National Institute of Standards and Technology Joint Initiative for Metrology in Biology are partners unique to Stanford with immensely relevant capacities that we should engage.

RECOMMENDATIONS

Schoolwide initiatives.

Stanford Engineering should invest in a strategic schoolwide effort to create an apex ecosystem that initiates, enables and sustains advances in engineering living matter, defined by a schoolwide task force. Specific actions to consider include:

Fostering strategic faculty growth across all departments.

Resourcing shared facilities to advance and provide broad access to tools for engineering biology (such as a maker space for biotech).

Launching a diverse and inclusive affiliates program involving industry, government and civil society.

Enabling student entrepreneurs to readily translate innovations and to best remake and expand the commercial biotechnology sector.

Initiating and sustaining scholarship on biotechnology policy both within the school and beyond.