

ENGINEERING OUR WAY TO A SUSTAINABLE BIOECONOMY

HEARING

BEFORE THE

SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY
COMMITTEE ON SCIENCE, SPACE, AND
TECHNOLOGY

HOUSE OF REPRESENTATIVES

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ENGINEERING OUR WAY TO A SUSTAINABLE BIOECONOMY

TUESDAY, MARCH 12, 2019

HOUSE OF REPRESENTATIVES,
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY,
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY,
Washington, D.C.

The Subcommittee met, pursuant to notice, at 10 a.m., in room 2318 of the Rayburn House Office Building, Hon. Haley Stevens [Chairwoman of the Subcommittee] presiding.

**U.S. HOUSE OF REPRESENTATIVES
SUBCOMMITTEE ON RESEARCH AND TECHNOLOGY
COMMITTEE ON SCIENCE, SPACE, AND TECHNOLOGY
HEARING CHARTER**

Engineering our Way to a Sustainable Bioeconomy

**Tuesday, March 12, 2019
10:00 am – 12:00 pm
2318 Rayburn House Office Building**

Purpose

On Tuesday, March 12, 2019, the Subcommittee on Research and Technology of the Committee on Science, Space, and Technology will hold a hearing to review the opportunities and challenges with new and emerging bioscience and biotechnologies with application in agriculture, energy, and manufacturing; to examine the role of the federal government in research and development (R&D) and oversight of such science and technologies; and to examine the status of U.S. leadership in engineering biology. An additional purpose of this hearing is to receive testimony on the *Engineering Biology Research and Development Act*, which would establish a federal R&D initiative in engineering biology.

Witnesses

- **Dr. Rob Carlson**, Managing Director of Bioeconomy Capital
- **Dr. Kevin Solomon**, Assistant Professor of Agricultural & Biological Engineering at Purdue University
- **Dr. Eric Hegg**, Professor of Biochemistry and Molecular Biology, Michigan State University; Michigan State University Subcontract Lead, Great Lakes Bioenergy Research Center
- **Dr. Sean Simpson**, Chief Scientific Officer and Co-Founder of LanzaTech
- **Dr. Laurie Zoloth**, Margaret E. Burton Professor of Religion and Ethics, and Senior Advisor to the Provost for Programs in Social Ethics at the University of Chicago

Overarching Questions

- What are the new and emerging biotechnologies and what are their potential applications for the energy, agriculture, and manufacturing sectors as well as potential benefits for the environment?

- What are the potential ethical, security, and other societal concerns related to engineering biology R&D. How should those concerns be integrated into governance for R&D and into engineering biology and related curricula and research training?
- What is the state of the workforce in engineering biology?
- What is the appropriate role of the federal government in supporting engineering biology R&D? Is there a need for a federal interagency initiative and strategy for engineering biology R&D as proposed in the *Engineering Biology R&D Act*? If so, does the legislative proposal adequately address what is needed to maintain U.S. leadership in engineering biology?

Engineering Biology and Applications

Engineering biology¹ is a multidisciplinary field at the interface of biological, physical, chemical, and information sciences and engineering. By applying tools from engineering, computing, and physical sciences to biological systems, researchers are able to study, mimic and design new biological systems to develop or improve existing products, processes, and systems. The applications to energy, agriculture, and advanced manufacturing are vast, and many such applications are already in the commercial marketplace. Researchers are also excited about the potential benefits to human and environmental health. Dr. Solomon, a witness for this hearing, does fundamental research to understand the design principles of microbial systems and to expand the toolbox for engineering biology for potential application across multiple sectors.

The growth of engineering biology has accelerated due to the increased speed and affordability of enabling technologies, including DNA sequencing and gene editing tools. In the case of DNA sequencing, the cost to sequence the human genome has fallen from the \$2.7 billion it cost in 2001 to sequence the very first human genome² to less than \$1000 in 2018³. The tools developed to sequence the human genome are being used to sequence the genomes of countless microorganisms and plants in research labs across the country.

The gene editing tool that is now driving a significant amount of research is CRISPR/Cas-9. This technology uses “molecular scissors” to create a break in DNA. Along with deleting DNA bases, these technologies can insert new DNA bases into the break. Besides being more precise, less expensive, and easier to use than older gene editing technologies, these new gene editing technologies are much faster.

¹ Presently, there is not an agreed upon name or definition for what to call the emerging research field at the intersection of biology, the physical sciences, engineering, and information technology. Some refer to this field as engineering biology; others call it synthetic biology.

² National Human Genome Research Institute <http://www.genome.gov/sequencingcosts/>.

³ <https://www.genome.gov/27541954/dna-sequencing-costs-data/>

There has been a lot of coverage of Chinese researcher He Jiankui's recent use of CRISPR to edit genes in the embryos of twin girls to help them resist HIV, including allegations that the Chinese government was fully aware of his plans all along.⁴ Dr. He's announcement was met with a tremendous outcry from U.S. and other scientists around the world. Current U.S. law prohibits any human germline editing, and the consensus among U.S. scientists is to continue to take a very slow and restricted approach.⁵ While human gene editing raises significant ethical and governance issues, the focus of this hearing is on gene editing and other engineering biology tools for application in microorganisms and plants for energy, agriculture, the environment, and manufacturing.

Energy Sector Applications

For the energy sector, engineering biology has the potential to reduce our dependence on fossil fuels by engineering microorganisms such as bacteria and algae to produce fuels and by developing more sustainable biofuel feedstocks. Although promising, advanced biofuels still struggle to compete with gasoline and other fossil fuels for market share because of the higher cost of production. As researchers at universities, Department of Energy National Labs, and companies continue to improve efficiency and bring down production costs through engineering biology, biofuels will become more competitive. LanzaTech, which will be represented by Dr. Sean Simpson on the panel, converts waste carbon from industrial processes to commodity chemicals and biofuels, including jet fuel. The DOE funded Great Lakes Bioenergy Center, represented on the panel by Dr. Eric Hegg, conducts engineering biology research on dedicated bioenergy crops to enhance their environmental and economic value.

Agricultural Applications

The ability to modify agricultural crops is not new. For centuries, people have been altering the genomes of plants using traditional breeding techniques. In the 1970s and 1980s, it became possible to use recombinant DNA techniques⁶ to modify the genomes of plants. Using those technologies, foreign DNA (usually a single engineered gene) is introduced into plant genomes to create a crop with a desired property such as insect resistance. New and emerging techniques, enabled by engineering biology, are more powerful than traditional techniques because they can construct, edit, and re-engineer the genomes of plants. They allow for multiple genes to be inserted, opening the door for creating crops with more desirable traits that cannot be achieved through a simple addition of a single gene. Additionally, these techniques could delete or edit multi-gene traits to produce better outcomes for food quality, storage, and processing. Moreover, engineering biology could create new feedstocks that would allow farmers to produce larger yields on smaller land.

⁴ <https://www.vox.com/2019/3/4/18245864/chinese-scientist-crispr>

⁵ <https://www.nap.edu/catalog/24623/human-genome-editing-science-ethics-and-governance>

⁶ Recombinant DNA technology uses enzymes to cut and paste together DNA sequences.

Manufacturing Applications

Traditional manufacturing of goods has relied on ingredients and production processes that have been known for hundreds of years. Engineering biology has led to a revolution in those processes by using microorganisms to make a synthetic version of the ingredients used in the traditional industrialization process. The benefits of having microorganisms make ingredients include using less energy and producing less waste, not relying on petroleum products, and the ability to make ingredients that are difficult and/or expensive to manufacture using traditional processes. Additionally, engineering biology could be used to improve the performance and sustainability of materials used across sectors and in our daily lives. Examples include bio-based packing materials and plastic replacements. Pharmaceutical manufacturing is also being revolutionized by engineering biology.

Ethical, Legal, Environmental, and Societal Issues in Engineering Biology

Since engineering biology will allow researchers to create biological systems that do not occur naturally and to re-engineer existing biological systems to perform novel tasks, there are myriad ethical, legal, environmental, and societal issues to be considered. These issues include any potential harm new systems could have on human health and the environment, as well as concerns about ensuring equitable distribution of benefits from engineering biology applications. Researchers in this field have discussed the need to build things like “kill switches”—self-destruction mechanisms for genetically engineered microbes once they are no longer useful or in case of an accidental or malicious release. Along with funding research in this area, it is important to support public outreach and public engagement for this research to ensure public health and safety as well as to educate the general public about the technology.

A 2015 Woodrow Wilson report on synthetic biology funding found that less than one percent of total U.S. funding was focused on risk research and approximately one percent was focused on the ethical, legal, and social issues. Dr. Zoloth is a bioethicist who works closely with scientists and engineers to help frame the ethics questions that should be considered in research and education in engineering biology, including for non-human health applications.

Security Issues for Engineering Biology

Especially with the democratization of technologies such as gene sequencing and gene editing, security is yet another significant concern for engineering biology R&D. Specific concerns include: intentional misuse of a pathogen for direct harm to a population or to disrupt markets; accidental misuse of a biological organism; misuse of biological information; supply chain insecurity; and the consequences of loss of U.S. leadership in engineering biology. The National Academies recently launched a new study, *Safeguarding the Bioeconomy: Finding Strategies for Understanding, Evaluating, and Protecting the Bioeconomy while Sustaining Innovation and*

*Growth*⁷, which will include a focus on economic and national security risks. Dr. Carlson will also testify about the security concerns.

Federal Investments in Engineering Biology

Due to the lack of an agreed upon definition for this field as well as a lack of federal strategy, it is difficult to get a figure for federal investment in engineering biology. GAO produced a report⁸ in 2018 at the request of the Science Committee that included some information about federal investments in synthetic biology, but was incomplete in that regard. They found that 10 agencies support synthetic biology research, and 6 of those 10 agencies reported a combined total of at least \$211.2 million in support of synthetic biology research in FY 2017.

- The Department of Energy has significant investments in synthetic biology. In 2007, DOE began supporting three bioenergy research centers with synthetic biology being core to much of their work. In 2017, DOE announced a “new phase” to this program with support for four bioenergy research centers funded at a total of \$90 million in FY 2019. DOE also funds the Joint Genome Institute to produce high-throughput sequencing in support of its biofuels and environmental mission, funded at \$69 million in FY 2019.
- The National Science Foundation (NSF) supports synthetic biology across multiple directorates, including computer and information sciences. They also support the Engineering Biology Research Consortium (EBRC)⁹ to lead a road-mapping effort for engineering biology R&D that will be completed this summer. In FY 2017, their total investment in synthetic biology research across the Foundation was approximately \$60 million.
- The National Institute of Standards and Technology (NIST) supports research in the area of measurement science and standards for engineering biology. NIST estimates its current investment to be \$35-\$40 million, including \$10 million in support of a biomanufacturing institute through the Manufacturing USA program, and \$4 million in internal research. Included in their overall total is a new effort on the microbiome and their work with industry to validate genome sequencing technologies and characterize biologics used in medicine.
- Multiple NIH institutes invest in foundational synthetic biology research to study disease as well as to understand and combat antibiotic resistance. NIH did not report a funding level to GAO.
- NASA supports synthetic biology to enhance the capability and reduce the risk of space exploration. NASA reported to GAO total investments of \$5.1 million in FY 2017.

⁷ <http://nas-sites.org/dels/studies/bioeconomy/>

⁸ <https://www.gao.gov/assets/700/694748.pdf>

⁹ Formerly SynBERC, a Science and Technology Center that was supported by NSF in its earlier form for 10 years.

- EPA uses synthetic biology among other things, to develop new tools - including synthetic tissues - for testing chemical toxicity. EPA reported to GAO total investments of \$4.5 million in FY 2017.
- The Defense Advanced Research Projects Agency (DARPA) increased their synthetic biology support significantly under the Obama Administration, including funding the Living Foundries Project to create biologically-based manufacturing platforms,¹⁰ and continues to support synthetic biology research in various projects. DOD reported to GAO total investments of \$114 million in FY 2017.

National Strategy for Engineering Biology

In 2012, the Obama White House released the “National Bioeconomy Blueprint” to lay out strategic objectives to realize the potential of the U.S. bioeconomy and to highlight early achievements toward those objectives. The National Bioeconomy Blueprint described five strategic objectives—supporting R&D bioeconomy investments; facilitating the transition of research into the market; developing and reforming regulations; updating training programs; and identifying and supporting public-private partnerships.

Since the release of the National Bioeconomy Blueprint, not much has been done to implement it. It’s not clear why, except that the Obama Administration was locked in a battle with Congress over the budget, with science budgets taking significant hits. The Trump White House convened an interagency working group on synthetic biology in 2018. In the meantime, other countries, including China, have made engineering biology a strategic national priority with significant funding. Dr. Rob Carlson’s testimony will include comparisons between the U.S. and its competitors in terms of the scale of investment as well as the size of the industry, to the extent that can be measured.

Engineering Biology Legislation

This hearing will serve as a legislative hearing for the *Engineering Biology Research and Development Act*, most recently introduced by Chairwoman Johnson and Rep. Sensenbrenner in the 115th Congress as H.R. 7171. The bill would establish a National Engineering Biology R&D Program. The bill would also establish a framework for greater coordination of federal investments in engineering biology; lead to a national strategy for those investments; expand public-private partnerships; focus on the education and training for the next generation of engineering biology researchers; and address any potential ethical, legal, environmental, and societal issues associated with engineering biology research.

¹⁰ The Living Foundries program established the 1,000 Molecules Project that has the goal of developing 1,000 new chemical building blocks for entirely new materials.

Chairwoman STEVENS. Good morning and welcome to the Research and Technology Subcommittee's first hearing of the 116th Congress. A warm welcome to our distinguished group of witnesses. We have a great panel this morning, and I'm looking forward to hearing your testimony. As a Michigan native, it's a great pleasure to welcome Dr. Eric Hegg, who joins us from Michigan State University. Congrats on Saturday's win, and thank you for being here with us. I'm sorry I'm not wearing my green.

As a Member of this Committee, we have the opportunity to learn about critical, new, and emerging technologies with the capacity to benefit society in a number of ways, and to consider how the Federal Government can best support the responsible development of these technologies. This morning, the Committee will discuss new and developing biotechnologies enabled by engineering biology research, and their potential applications in sustainable agriculture, advanced manufacturing, and bioenergy.

Engineering biology, a term which is used interchangeably with synthetic biology, is a multidisciplinary field at the intersection of biological, physical, chemical, and information sciences and engineering that allows researchers to re-engineer and develop new biological systems. While human gene editing is a hot topic of discussion in the public sphere, most of engineering biology research being done today, even the human health research, is on microorganisms and plants. Engineering biology, in addition to enabling whole new industries, may yield significant environmental and health benefits because of its potential to reduce our dependence on fossil fuels, improve food security and agricultural land use, make manufacturing processes much cleaner, combat antibiotic resistance, and even clean up legacy toxic waste sites.

Today, we will hear from the experts in academia and industry about the nature of engineering biology research, the current size of the commercial market and the potential for growth, how the U.S. stacks up against our foreign competitors, and the state of the U.S. biotechnology workforce. We will also hear from scholars on the ethical and security implications of engineering biology. It is essential that as we look to grow the U.S. investment in engineering biology R&D (research and development), we integrate the oversight framework necessary to protect the public and the environment, and to guard against national security risks.

In this Committee, it is easy to get excited about the potential for new technologies. But we need only to look at the unintended consequences of past technologies to understand that we also must take a look at the risks.

Given the tremendous economic potential buttressed with the potential risks for engineering biology R&D, we seek to maintain U.S. leadership in this area of research and technological development. We seek to develop and charter a national strategy as we currently do not have one, in the meantime, where other countries, including China, are well ahead of us in establishing engineering biology as a national priority and providing the necessary funding and political will to realize these goals.

In this hearing, we will specifically consider the merits of the *Engineering Biology Research and Development Act* introduced last Congress by the Chairwoman of the Full Committee, Ms. Johnson.

The bill would provide a framework for a strategic and coordinated Federal program in engineering biology R&D. It is long overdue that we take this legislation up in Committee.

I am sure today's hearing will give us some good feedback on how to improve this legislation so it helps ensure U.S. leadership in engineering biology R&D. I look forward to the expert testimony and to the discussion.

And with that, I yield back.

[The prepared statement of Chairwoman Stevens follows:]

**Committee on Science, Space, and Technology
Subcommittee on Research and Technology**

Opening Statement

Chairwoman Haley M. Stevens

Engineering Our Way to a Sustainable Bioeconomy

March 12, 2019

Good morning and welcome to the Research and Technology Subcommittee's first hearing of the 116th Congress. A warm welcome as well to our distinguished group of witnesses. We have a great panel this morning and I am looking forward to hearing your testimony. As a Michigan native, it is a great pleasure to welcome Dr. Eric Hegg, who joins us today from Michigan State University.

As Members of this Committee, we have the opportunity to learn about critical new and emerging technologies with the capacity to benefit society in a number of ways, and to consider how the Federal government can best support the responsible development of these technologies. This morning, the Committee will discuss new and developing biotechnologies enabled by engineering biology research, and their potential applications in sustainable agriculture, advanced manufacturing, and bioenergy.

Engineering biology, a term which is used interchangeably with synthetic biology, is a multidisciplinary field at the intersection of biological, physical, chemical, and information sciences and engineering that allows researchers to re-engineer and develop new biological systems. While human gene editing is a hot topic of discussion in the public sphere, most of the engineering biology research being done today-- even the human health research - is on microorganisms and plants. Engineering biology, in addition to enabling whole new industries, may yield significant environmental and health benefits because of its potential to reduce our dependence on fossil fuels, improve food security and agricultural land use, make manufacturing processes much cleaner, combat antibiotic resistance, and even clean up legacy toxic waste sites.

Today we will hear from the experts in academia and industry about the nature of engineering biology research, the current size of the commercial market and the potential for growth, how the U.S. stacks up against our foreign competitors, and the state of the U.S. biotechnology workforce. We will also hear from scholars on the ethical and security implications of engineering biology. It is essential that as we look to grow the U.S. investment in engineering biology R&D, we integrate the oversight framework necessary to protect the public and the environment, and to guard against national security risks. In this Committee, it is easy to get excited about the potential for new technologies. But we need only to look at the unintended consequences of past technologies to understand that we must also take a serious look at the risks.

Given both the tremendous economic potential and the potential risks of engineering biology R&D, it is essential that the U.S. maintain leadership in this area of research and technological development. I am concerned that we do not currently have any kind of national strategy. In the meantime, other countries, including China, are well ahead of us in establishing engineering biology as a national priority and providing the necessary funding to realize their goals.

In this hearing, we will specifically consider the merits of the *Engineering Biology Research and Development Act*, introduced last Congress by the Chairwoman of the Full Committee, Ms. Johnson. The bill would provide a framework for a strategic and coordinated Federal program in engineering biology R&D. It's long overdue that we take this legislation up in Committee. I'm sure today's hearing will give us some good feedback on how to improve the legislation so it helps ensure U.S. leadership in engineering biology R&D. I look forward to the expert testimony and to the discussion.

And with that, I yield back.

Chairwoman STEVENS. The Chair now recognizes Mr. Baird for an opening statement.

Mr. BAIRD. Thank you and good morning. And thank you, Chairwoman Stevens. I appreciate the opportunity to be here and for holding this hearing. I'm looking forward to working with you on the Research and Technology Subcommittee as the Ranking Member. I'm also glad that engineering biology and the bioeconomy is the subject of our first Subcommittee hearing of the year. In my Central Indiana district, the emerging bioeconomy presents an opportunity to expand and enable new markets in agriculture, energy, and manufacturing. From the basic research that's conducted at Purdue University to the development and application of that research by the more than 1,700 biology science businesses in the State, Indiana is on the forefront of the biotechnology innovation.

Humans have used biotechnology since the dawn of civilization, manipulating biology to improve plants and animals through hybridization and other methods. Since my days in the lab working toward my Ph.D. on monogastric nutrition, there have been rapid advancements in scientific knowledge and technology that have given rise to the field of modern biotechnology making useful products to meet human needs and human demands.

We have a distinguished panel of witnesses today who will help us understand the state of science and engineering biology and advise us on how to maintain U.S. leadership in biology innovation. I particularly want to thank our witness, Dr. Kevin Solomon, from Purdue University, my alma mater, for being here today. I'm very interested to learn more about the cutting-edge research on engineering biology in the gut microbiome of cattle and other livestock. I hope that today's hearing will help inform research and a regulatory framework that continues to ensure safe and ethical development of biotechnology without stifling innovation.

Thank you, Madam Chairwoman. I yield back.

[The prepared statement of Mr. Baird follows:]

Opening Statement of Ranking Member Jim Baird at Research & Technology Subcommittee Hearing on Bioengineering

Mar 12, 2019

Opening Statement

Thank you, Chairwoman Stevens for holding this hearing. I am looking forward to working with you on the Research and Technology Subcommittee as the Ranking Member.

I am also glad that engineering biology and the bioeconomy is the subject of our first Subcommittee hearing of the year.

In my central Indiana district, the emerging bioeconomy presents an opportunity to expand and enable new markets in agriculture, energy and manufacturing.

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I hope that today's hearing will help inform a research and regulatory framework that continues to ensure safe and ethical development of biotechnology, without stifling innovation.

Thank you Madam Chairwoman, I yield back.

Chairwoman STEVENS. Thank you, Mr. Baird. He's correct. I, too, am looking forward to working with him on the Subcommittee for Research and Technology.

The Chair now recognizes the Ranking Member of the Full Committee, Mr. Lucas, for an opening statement.

Mr. LUCAS. Thank you, Chairwoman Stevens, and Ranking Member Baird for holding this hearing today and thank you to our witnesses.

In both the House Agriculture Committee and the Science Committee, we've held hearings on biotechnology research and regulation for years. But I can't remember a more exciting or challenging time for the field than today. New gene editing techniques like CRISPR (clusters of regularly interspaced short palindromic repeats) and the advancement of rapid genetic sequencing are driving innovations in agriculture, medicine, energy, and manufacturing. Since we first began cultivating crops and breeding livestock, humans have been trying to improve plant and animal genetics. Now we're developing the tools to do it with a precision, speed, and scale our ancestors could not have imagined.

In the Capitol there is a statue of Dr. Norman Borlaug, the father of the Green Revolution. Dr. Borlaug developed new crop strains that saved billions from famine and helped develop the abundant and affordable food supplies we enjoy today. His work set the stage for modern biotechnology which took off in 1973 when American scientists developed a technique that allowed the production of genetically engineered human insulin. It was the first biotech product approved for sale in the United States in 1982 and has improved the lives of millions of diabetics.

In addition to these improvements in agriculture and medicine, engineering biology could also transform the energy sector. Scientists are engineering biology to try to address energy challenges, such as enhanced oil recovery, environmental remediation, carbon sequestration, and new materials. Several of our panelists are working in this area, and I look forward to hearing more about their work. The U.S. was a key driver of biological innovation in the 20th century. But there is increasing global competition. Other countries recognize the benefits of biotechnology and are striving to capture its potential through new investments and friendly regulations. We must keep pace and set a research and regulatory framework that supports innovation, creates a marketplace for new ideas and products while setting the safety and ethical standards for the world to follow.

I look forward to working with Chairwoman Johnson to advance legislation that will promote a national research strategy around engineering biology to ensure the U.S. remains the global leader in biotechnology. I hope this hearing will help inform us about our work on legislation and our work in the future.

And with that, I yield back, Madam Chairman.

[The prepared statement of Mr. Lucas follows:]

Opening Statement of Ranking Member Frank Lucas at R&T Subcommittee Hearing on Bioeconomy

Mar 12, 2019

Opening Statement

Thank you, Chairwoman Stevens and Ranking Member Baird for holding this hearing today and thank you to our witnesses.

In both the House Agriculture Committee and the Science Committee, we've held hearings on biotechnology research and regulations for years. But I can't remember a more exciting or challenging time for the field than today.

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We must keep pace and set a research and regulatory framework that supports innovation and creates a marketplace for new ideas and products, while setting the safety and ethical standards for the world to follow.

I look forward to working with Chairwoman Johnson to advance legislation that will promote a national research strategy around engineering biology, to ensure the U.S. remains the global leader in biotechnology.

I hope this hearing will help inform our work on legislation and our work on into the future.

Thank you, I yield back.

Chairwoman STEVENS. Thank you. At this time I would like to introduce our witnesses. Our first witness, Dr. Rob Carlson, is the Managing Director of Bioeconomy Capital, a venture capital firm that invests in industrial biotechnology. He is the author of *Biology is Technology: The Promise, Peril, and New Business of Engineering Life*. Dr. Carlson holds a bachelor's degree in physics from the University of Washington and a Ph.D. in physics from Princeton.

Our next witness is Dr. Kevin Solomon. Dr. Solomon is an Assistant Professor of Agricultural and Biological Engineering at Purdue University. His work focuses on the development of sustainable microbials, a process to supply the energy, materials, and medicines of tomorrow. He holds a bachelor's degree in chemical engineering and bioengineering from McMaster University in Canada and a Ph.D. in chemical engineering from MIT.

Our third witness, Dr. Eric Hegg, is a Professor of Biochemistry and Molecular Biology at Michigan State University and is also the Michigan State University Subcontract Lead at the Great Lakes Bioenergy Research Center, a Department of Energy-funded research center working to develop sustainable biofuels and bioproducts. Dr. Hegg holds a bachelor's degree from Kalamazoo College and a Ph.D. from the University of Wisconsin-Madison.

After Dr. Hegg is Dr. Sean Simpson. Dr. Simpson is the Chief Scientific Officer and Co-Founder of LanzaTech, a biotechnology company that converts waste carbon from industrial processes into commodity chemicals and biofuels. Dr. Simpson received his master's in science from Nottingham University and his Ph.D. from the University of York in the United Kingdom.

Our final witness is Dr. Laurie Zoloth. Dr. Zoloth is the Margaret E. Burton Professor of Religion and Ethics as well as a Senior Advisor to the Provost for Programs in Social Ethics at the University of Chicago. Dr. Zoloth was previously the President of the American Society for Bioethics and Humanities. She holds a bachelor's degree in women's studies from the University of California-Berkeley and received a master's in Jewish studies and a doctorate in social ethics from the Graduate Theological Union.

Well, the Chair at this time would like to recognize our Chairwoman, Ms. Johnson.

Chairwoman JOHNSON. Thank you. I apologize for being late. Let me give a quick statement. First, let me welcome all of our witnesses and thank the Chairwoman and Ranking Member for holding this hearing.

Today we will hear about engineering biology research—you can tell I'm out of breath—and its applications in energy, agriculture, manufacturing, the environment, and human health.

We've invited academic researchers, a small company, as well as experts on ethics and security implications of engineering biology to help us understand how we can maintain U.S. leadership in engineering biology and achieve a sustainable bioeconomy. Engineering biology research allows researchers to safely re-engineer existing biological systems and to learn from and mimic existing biological systems to perform novel tasks and develop novel materials and products. Technologies enabled by engineering biology are exciting and have the potential to solve some of society's greatest challenges, including providing food for a growing population, reducing

our dependence on fossil fuels, and dramatically transforming manufacturing. They also have numerous implications for human health as well as for the environment.

Because of the great promise of this research and its applications, I introduced the *Engineering Biology Research and Development Act* in 2015. By then, several other countries had already prioritized engineering biology and developed national strategies for their investments. And I was concerned that the U.S. risks losing our leadership in an industry that we historically dominated.

Here we are 4 years later, and instead of pulling together the expert stakeholders to develop such a strategy, this current Administration is prompting massive cuts to our science budgets once again. There's no question that we would cede our leadership in engineering biology as well as in many other areas of science and technology if the President's proposed cuts to this Nation's R&D enterprise were to be enacted into law.

I intend for this Committee to set us on a more hopeful path for what and I hope we can work on a bipartisan basis to ensure that the whole Congress does likewise.

The *Engineering Biology Research and Development Act* would establish a framework for greater interagency coordination of Federal investments in engineering biology and lead to a national strategy for these investments.

The bill would also focus on expanding public-private partnerships, and on education and training for the next generation of engineering biology researchers. Importantly, the bill would ensure that we address any potential ethical, legal, environmental, and societal issues associated with engineering biology. It will also ensure that public engagement and outreach are an integral part of this research initiative.

The Committee was not given the opportunity to consider and move this bipartisan piece of legislation since 2015. However, it is on our agenda this year, and I look forward to working with our colleagues on both sides of the aisle so we consider amendments informed by experts and including on today's panel.

A sustainable bioeconomy is central to the future of U.S. competitiveness and the well-being of our population. And engineering our way to a sustainable bioeconomy begins with a national strategy and careful attention to societal implications.

I once again thank all of our witnesses for being here, and I look forward to the discussion. And I yield back. Thank you.

[The prepared statement of Chairwoman Johnson follows:]

Opening Statement
Ranking Member Eddie Bernice Johnson (D-TX)
Engineering Our Way to a Sustainable Bioeconomy
March 12, 2019

Thank you, Madam Chairwoman for holding this hearing.

And I want to thank you and the Ranking Member for putting together such a distinguished panel of witnesses.

This morning, we will hear about engineering biology research and its applications in energy, agriculture, manufacturing, the environment and human health. We have invited academic researchers, a small company, as well as experts on the ethics and security implications of engineering biology to help us understand how we can maintain U.S. leadership in engineering biology and achieve a sustainable bioeconomy.

Engineering biology research allows researchers to safely re-engineer existing biological systems and to learn from and mimic existing biological systems to perform novel tasks and develop novel materials and products.

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Administration is proposing massive cuts to our science budgets once again. There is no question that we would cede our leadership in engineering biology—as well as in many other areas of science and technology—if the President's proposed cuts to the nation's R&D enterprise were to be enacted into law. I intend for this Committee to set us on a more hopeful path forward and I hope we can work on a bipartisan basis to ensure that the whole Congress does likewise.

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I thank the witnesses for being here today. I look forward to today's discussion, and I yield back the balance of my time.

Chairwoman STEVENS. Thank you, Madam Chairwoman, of our Full Committee. If there are any Members who wish to submit additional opening statements, your statements will be added to the record at this point.

As our witnesses should know, you each have 5 minutes for your spoken testimony. Your written testimony will be included in the record for the hearing. When you all have completed your spoken testimony, we will begin with questions. Each Member will have 5 minutes to question the panel.

We will start with Dr. Carlson.

**TESTIMONY OF DR. ROB CARLSON,
MANAGING DIRECTOR OF BIOECONOMY CAPITAL**

Dr. CARLSON. Well, thank you first for having me here. I appreciate the opportunity to address the Committee and share what I've learned over the years about the size of the bioeconomy and how it's changing.

My name is Rob Carlson, and I am the Managing Director at Bioeconomy Capital in Seattle. We also have offices in San Francisco. I'm also a Principal at a consulting firm called Biodesic, which focuses on engineering strategy and security. And I've just recently rejoined the faculty in an affiliate position with the Paul Allen School of Computer Science and Engineering at the University of Washington. But I'm here on behalf of myself and Bioeconomy Capital today. And I was asked to share a few slides about what I've discovered about the size of the bioeconomy. And it's not small.

About 2007 or so I was in Hong Kong on a consulting trip discussing biofuels and biomaterials, talking to big banks about investment. And it occurred to me that maybe I should know how big it was. What was this thing I was talking about? What was the bioeconomy? And so I was taking a break in the middle of a thunderstorm in my hotel in Hong Kong, looking out over the bay. And with a metaphorical and literal flash of lightning, I realized nobody knew how big it was. I Googled the size of it, and there was no data. And there ensued about 10 years' worth of effort to try to put some numbers on this. And I finally published those in 2016 in *Nature Biotech*. And these numbers are updated as of this week to 2017.

[Slide]

There's no U.S. Government recordkeeping, statistical recordkeeping of this information. This is all sort of by hook and by crook. Wherever I can find data, I put it together and include it in the publications and then in the accounting that you see before you.

So biologics are about \$137 billion of revenue in the United States. Those are drugs that are mostly proteins but also now increasingly some other compounds. Genetically modified crops and seeds were in 2017 about \$104 billion. That goes up and down of course because crop prices go up and down. The penetration of genetically modified crops in each of the markets that they're in is nearly 100 percent, between 90 and 100. It varies a little bit every year.

The big number that surprised me when I first started doing this, and continues to surprise, is the industrial biotech sector which people don't usually discuss. That's enzymes and materials. And overall, I think it's worth noting here that the worldwide semiconductor revenues in 2016 were \$370 billion. So all of this biotech just in the United States is bigger than the global semiconductor industry.

The breakdown of those industrial biotech numbers are interesting to me. The biochemicals portion of that is about \$92 billion. That's business-to-business. So the consumer-level impact is certainly more than \$100 billion. Biofuels in the U.S. contribute only about \$4 billion.

So this is kind of an unheralded section of the economy that we don't really understand. This is now almost certainly in the U.S. Government supply chain, certainly in the Defense Department supply chain. And there's no way to track it. There's no way to know how big it is. There's no way to know who's making what or how many people are employed in this industry other than what private companies choose to share about that. And I think this is a serious oversight in the way we're understanding our economy, not that we should be managing it aggressively but we should certainly be understanding it.

Those revenues have grown quite significantly over the years. You can see the breakdown here.

[Slide]

The bars are data that I've been able to graph from various sources over the years, and the industrial data, I should say, is provided by Agilent the last few years. They're the only company that's publicly acknowledging a wide marketing study. But it's a marketing study. It's not based on government statistics and the way that you would draw on the NAICS, the North American Industrial Classification System, which is how we understand the rest of our economy. And then the growth rates there are shown. All of this is of course in my testimony. And I won't spend a lot of time on it here, but I'm happy to answer questions about it as we go forward.

Once you have that data, then you can start comparing the growth in biotech to the rest of the economy. And it is non-trivial. All right?

[Slide]

So now we're up at about 2 percent of GDP from biotechnology. This is from engineered biological systems. That's bigger than mining. It's bigger than several construction industries. It's bigger than some manufacturing subsectors in the United States. And it's quite intriguing there on that top line to see how much of U.S. GDP growth was contributed by biotechnology in the recent recession. It's a more stable industry than many. And again, I wish we understood this better.

And finally, I'll just close on some observations that originally were drawn from a Biodefense Net Assessment that I wrote several years ago trying to understand who was doing what in the world. And as we've heard from the opening statements, many countries are investing very heavily. China in particular is leading out with

serious investment and also potentially with—I think I have one more slide. No. We can discuss China in the questions.

I'd just close here by saying the definition of bioeconomy and what we include in our definition clearly is going to be different from other countries. Last spring at the Global Bioeconomy Summit the final communiqué said here's what we think the bioeconomy is. But really, you can define it however you like. And that's not super-useful for comparing across countries. And we should, I think, have a definition that's consistent over time, and then we can use that also to judge other countries. So at the moment, we can't know whether we're winning or losing because we're not measuring anything. But it's clear that other countries are investing very heavily and are making some progress.

Thank you.

[The prepared statement of Dr. Carlson follows:]

Robert Carlson, PhD

"Engineering Our Way to a Sustainable Bioeconomy"

Written Testimony for a hearing of the Subcommittee on Research and Development of the House

Committee on Space, Science, and Technology, U.S. House of Representatives

12 March, 2019

Ladies and Gentlemen, Members of this Committee, first let me thank you for the opportunity to testify today and to share what I have learned about the size and scope of the bioeconomy in the U.S., and also about the role of engineering biology for our physical and economic well-being and security. Before I continue, I would like to thank the Committee staff for their assistance in arranging my participation today.

I was asked to address specific questions in my testimony, which I reproduce below for the record:

1. What is the size of the U.S industry in engineering biology across various sectors? What is the potential for this technology across the economy?
2. How does the US compare internationally in terms of the level of investment in engineering biology R&D? Please provide a snapshot of other leading countries, including the extent to which those countries have developed national plans for engineering biology.
3. How can scientists and engineers collaborate with experts in the humanities, law, and social sciences to integrate social, legal, environmental, and other ethical considerations into the design and conduct of engineering biology R&D?
4. How can scientists and engineers collaborate with security experts to incorporate security concerns into the design and conduct of engineering biology R&D?
5. What recommendations, if any, do you have for improvements to the *Engineering Biology Act*? What additional recommendations, if any, do you have for Congress or for federal science agencies that fund engineering biology research?

Summary: Engineered biological systems already generate approximately 2% of US GDP on an annual basis. As biological engineering becomes more sophisticated and capable, it will have an increasingly broad impact on the economy. This potential has not been lost on other governments around the world, and the engineering of biology is seen by many nations as a low cost route to technological maturity and geopolitical influence. Engineering a sustainable bioeconomy in the U.S., and maintaining our technological lead, will require appropriate attention, investment, and nurturing; this includes broad public involvement in discussions of how taxpayer funds are spent on research and development. The result will be not just a more sustainable future, but a better future, as biology replaces existing products with more capable ones across the healthcare, food, and, in particular, materials industries. The core technical capability to engineer biology will have far reaching impacts well beyond the scope of products and manufacturing historically considered to be the business of biology.

Introduction

I have participated in the bioeconomy as an academic scientist, as an entrepreneur in technology companies, as a strategist, as a technical and economic analyst, as a consultant on economics and security to the U.S., other governments, and international organizations, and now as Managing Director of Bioeconomy Capital, an early stage venture capital firm with offices in Seattle and San Francisco. Over the years, I have written articles, a book, and patents on the topic of biological technologies, some of which are referenced as support for this testimony. In order to expand the conversation about how

**Estimated 2017 U.S. Biotechnology Revenues:
At Least \$388 Billion, or 2% of GDP**
(Sources: Bioeconomy Capital, Agilent)

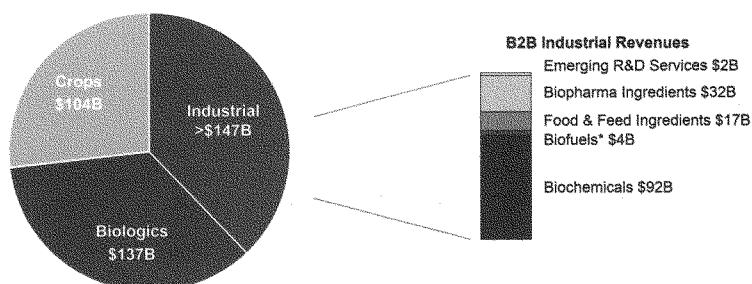


Figure 1: Estimated 2017 U.S. Biotechnology Revenues. Data and methods described at the Bioeconomy Dashboard: <https://bioeconomy.capital/bioeconomy-dashboard/>.

biological technologies may impact humans and the planet we live on, I have participated in many discussions across public and private forums, including The Hastings Center for Bioethics, the National Academies of Science, Engineering, and Medicine, The Presidential Commission for the Study of Bioethical Issues, the World Health Organization, and the Biological Weapons and Toxins Convention.

The Size of the Biotechnology Industry

U.S. revenues from engineered biological systems reached at least \$388 billion in 2017, or 2% of GDP¹. The figures in this testimony are based on an analysis published in *Nature Biotechnology*, with updates published at the Bioeconomy Capital website on the Bioeconomy Dashboard. For comparison, if considered as an industrial sector unto itself, biotechnology contributes more to the economy than mining, utilities, or a number of other construction and industrial sectors^{2, 3}.

Those biotechnology revenues comprise three sub-sectors, biologics (i.e., biologically manufactured drugs) at \$137B, genetically modified (GM) crops and seeds at \$104B, and industrial biotechnology, which includes materials, enzymes, and engineering tools, which is at least \$147B (see Figure 1).

I note here briefly that a broader definition of the bioeconomy, one that includes agriculture, forestry, fisheries, the impact of invasive species, and the value of water and air purification, could easily bring the economic impact of biology to 20% of GDP⁴. Given that we are already considering deploying biological

¹ Carlson, R., "Estimating the biotech sector's contribution to the US economy", *Nature Biotechnology*, 34, 247–255 (March, 2016). For updates, see the Bioeconomy Dashboard: <https://www.bioeconomy.capital/bioeconomy-dashboard/>

² Ibid.

³ BEA, GDP By Industry, https://apps.bea.gov/iTable/index_industry_gdplndy.cfm

⁴ Carlson, 2016.

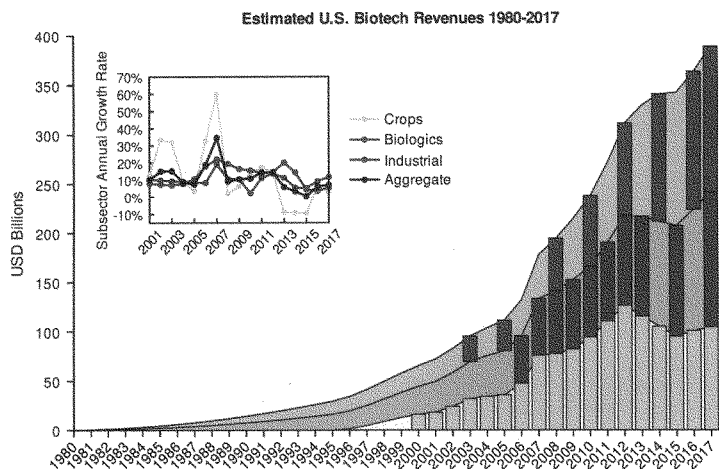


Figure 2: Estimated U.S. Biotech Revenues 1980-2017. Bars are data, shaded areas are generated using a numerical model, from which growth rates (inset) are calculated. Data and methods described at the Bioeconomy Dashboard: <https://bioeconomy.capital/bioeconomy-dashboard/>.

engineering to combat invasive pests, ranging from mosquitos to citrus tree pathogens, it would behoove us to better understand this broader economic contribution of biological systems to the nation's welfare.

Biologics

The U.S. accounts for about 73% of global biologics revenues, a fraction that has held nearly constant for most of the last decade. The \$137B figure does not include many billions in revenues from maintaining and selling model organisms such as genetically modified mice, nor does it include the value biotechnology provides to that portion of the pharmaceutical industry that develops and manufactures small molecule drugs, all of which depends heavily on biotechnological tools. That is, the revenues described here as "biologics" are certainly an underestimate of this portion of the bioeconomy, and proper accounting would in all likelihood significantly increase the total.

GM Crops

The GM crop revenues comprise GM seed revenues and farm scale revenues that farmers receive. The U.S. accounts for approximately 40% of total planted area of GM crops, and thus about 40% of global GM crop revenues. Not included in these figures are small, but growing, revenues from GM papaya, alfalfa, squash, apples, and potatoes. These revenues do not include additional significant economic benefits that GM crops provide to farmers and the environment, including reduced water and fuel use, and reduced time spent plowing and spraying. Beyond benefits to farmers who grow GM crops, several studies have estimated that as much as 70% of the total benefits from such crops accrue to farmers who

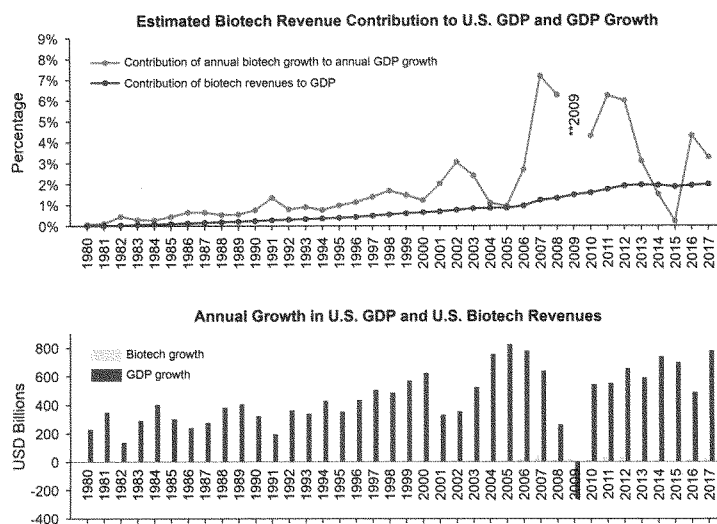


Figure 3: Top: Estimated biotech revenue contribution to U.S. GDP and GDP growth. The 2009 percentage contribution is omitted because GDP growth was negative that year. Bottom: Absolute annual growth in U.S. GDP And biotech revenues. Based on numerical model fit to data in Figure 2. Data and methods described at the Bioeconomy Dashboard: <https://bioeconomy.capital/bioeconomy-dashboard/>.

plant standard crops on adjacent fields, where those farms benefit from the so-called halo effect of pest suppression by the GM crops⁵. Again, a full and proper accounting of these added benefits would substantially swell the economic impact of GM crops to farmers in the United States.

Industrial Biotechnology

The breakdown of 2017 industrial biotechnology revenues in Figure 1 was graciously provided by Agilent's Gary Carter, and then corrected slightly by me to remove the cost of corn from biofuels revenues to avoid double counting. Note that the value added contribution of biofuels, which comes to mind for many as the primary example of an industrial biotech product, only amounted to \$4.3B. This should be compared to approximately \$91B of value added from biochemicals, which include higher value compounds such as plastics precursors, solvents, and other materials. This \$91B comprises business-to-business (B2B) revenues, and the final consumer level impact of these products could be 10–30% higher due to the increased margins in moving from wholesale to retail, and thus could be in the range of \$100B–\$120B.

⁵ Carlson, 2016.

Public and private investment in new biological engineering and manufacturing technologies is accelerating. Private capital is being invested in early stage companies at remarkable rates: \$1.7B in 2017 and more than \$3.7B in 2018^{6,7}. The U.S. government is investing in technology development via DARPA, the NSF, the NIH, and the DOE. While this is an excellent foundation, the potential of engineering biology to grow the economy requires that we invest even more.

Implications and Potential for the Future

Biotechnology has been a growing contributor to the economy for nearly four decades (see Figure 2). When compared to the economy as a whole, it is clear that biotechnology is increasingly important not merely for its absolute size, but also because it is apparently more stable and resistant to recessions than other sectors, with the caveat that swings in commodities prices can have large impacts on sector revenues through crop revenues (see Figure 3). Generally, when the rest of the economy slows or contracts, biotechnology has picked up the slack, contributing as much as 7% of annual GDP growth during the recent recession.

If the size of these revenue estimates comes as a surprise, that is because the U.S. government does not measure the contribution of biotechnology to the economy. The particular structural reason for this lack of data gathering is the absence of any codes for biotechnology within the North American Industrial Classification System (NAICS)⁸. The NAICS is used to categorize economic data from across the economy, including such details as value added by particular sectors, as well as employment, with the added benefit of geographical specificity. In lieu of having access to NAICS data, I published the first full estimates of biotech revenues in the U.S. in 2016 using data drawn from public company reporting, private consulting reports, marketing reports, and national and international surveys. This data is of varying quality, and sourcing and analysis frequently are poorly described. That article also examined the shortcomings of the current NAICS codes and suggested how to fix them⁹.

As one implication of poor measurement, consider the following surprising calculation. As best I can tell, the revenues described above demonstrate that biochemicals are directly outcompeting petrochemicals in the U.S. market on cost and performance, to the tune of somewhere between \$100B and \$120B in revenues annually. Depending on the source, and on how one adds up the subsectors, annual revenues from chemicals manufacturing in the U.S. are between \$350B and \$750B^{10,11}. It is currently not possible, given the structure of data based on NAICS codes, to know whether biochemicals revenues are included in the total reported for "chemicals" or if those revenues are going completely unreported in economic statistics. Consequently, if the biochemicals revenue estimates are accurate, biochemicals have quietly grown to constitute at least 17% of chemicals revenues in the U.S., and perhaps significantly more. Despite this uncertainty, it is clear that, far from simply being a technology with a bright future, the age of biomanufacturing is already upon us.

6 Calvin Schmidt, "These 33 synthetic biology companies just raised \$925 million", Synbiobeta, July 5, 2018, <https://synbiobeta.com/these-33-synthetic-biology-companies-just-raised-925-million/>

7 John Cumbers, at Safeguarding the Bioeconomy, National Academy of Sciences, 28 January 2019, Washington, DC.

8 Carlson, 2016.

9 Ibid.

10 BEA, GDP By Industry, https://apps.bea.gov/iTable/index_industry_gdpIndy.cfm

11 Statista: U.S. Chemical industry - Statistics & Facts. <https://www.statista.com/topics/1526/chemical-industry-in-the-us/>

And the future is very bright indeed. The economic impact of biochemical manufacturing is likely to grow significantly over the next decade. Government and private sector investments have resulted in the capacity today to biomanufacture not just every molecule that we now derive from a barrel of petroleum, but, using the extraordinary power of protein and metabolic engineering, to also biomanufacture a wide range of molecules that cannot plausibly be made using existing chemical engineering techniques. This story is not simply about sustainability. Instead, the power of biology can be used to imbue products with improved properties. There is enormous economic and technical potential here. The resulting new materials, manufactured using biology, will impact a wide range of industries and products, far beyond what has been traditionally considered the purview of biotechnology.

New Materials

For example, our portfolio company Arzeda is now scaling up the biomanufacturing of a methacrylate compound that can be used to dramatically improve the properties of plexiglass. This compound has long been known of by materials scientists, and long been desired by chemical engineers for its utility in improving such properties as temperature resistance and hardness, but no one could figure out how to make it economically in large quantities. Arzeda's biological engineers combined enzymes from different organisms with enzymes that they themselves designed, and that have never existed before, to produce the compound at scale. This new material will shortly find its way into such products as windshields, impact resistant glass, and aircraft canopies.

Similarly, our portfolio company Zymergen is pursuing remarkable new materials that will transform consumer electronics. Zymergen is developing a set of films and coatings that have a set of properties unachievable through synthetic chemistry and that will be used to produce flexible electronics and displays. These materials simply cannot be made using the existing toolbox of synthetic chemistry; engineering biology gives access to a combination of material properties that cannot be formulated any other way. Engineering biology will bring about a renaissance in materials innovation.

New Data Storage and Processing Technologies

Beyond manufacturing novel materials, biological technologies are being eyed as important functional components of systems now produced from silicon and metal. In addition to my role as an investor, I am fortunate to work as a consultant to Microsoft on a project to store digital information in DNA, and I have watched first-hand as this technology developed over just the last three years. I have become convinced that not only is this technology technically and economically feasible, it is inevitable and necessary.

The problem at hand is that the internet is expanding so rapidly that our need to archive data will soon outstrip existing technologies. If we continue down our current path, in coming decades we will need not only exponentially more magnetic tape, disk drives or flash memory, but exponentially more factories to produce these storage media, and exponentially more warehouses to store them. Even if this is technically feasible, it is economically implausible. Biology can provide a solution. DNA is by far the most sophisticated and densest information-storage medium we have ever encountered, exceeding by many times even the theoretical capacity of magnetic tape or solid-state storage.

A massive warehouse full of magnetic tapes might be replaced by an amount of DNA the size of a sugar cube. Moreover, whereas magnetic tape might last decades and paper might last millennia, we have

found intact DNA in animal carcasses that have spent 750,000 years frozen in the Canadian tundra. Consequently, there is a push to combine our ability to read and write DNA with our accelerating need for more long-term information storage. Encoding and retrieval of text, photos and video in DNA has already been demonstrated¹².

Governments and corporations alike have recognized this opportunity. Both are funding research to support scaling up the infrastructure to sequence and synthesize DNA, that is, to read and write DNA, at sufficient rates to support its use as a storage medium. In order to compete with a typical tape drive that is used for storage today, a single "DNA drive" must be able to write and read the equivalent of approximately ten human genomes a minute, which is more than ten times the current global annual demand for synthetic DNA. Consequently, when DNA data storage becomes a commercial reality, it is very likely that reading and writing arbitrary DNA sequences will cost orders of magnitude less than they do today, and will be even more widely distributed. That is, the scale of the demand for DNA storage, and the price at which it must operate, will completely alter the economics of reading and writing genetic information, marginalizing the scale of use by existing multibillion-dollar biotech markets while at the same time massively expanding capabilities to reprogram life. This sort of pull on biotechnology from non-traditional applications will only increase with time as our ability to engineer biology improves. In order to understand the consequent impact on the economy, and on the people who work in it, we must lay the groundwork for better measurement of that economy, in part to better invest in it, and in part to better protect it.

On the Need for Better Quantification of the Bioeconomy

The size of the economic contribution of biotechnology, the uncertainty about that size, and the inability to use NAICS codes to track products, means that biotech products could already be an important part of the supply chain for U.S. government acquisitions, including the Department of Defense, and there would be no way to easily track these products.

Consequently, not only does the U.S. government have no means to track the size and shape of the bioeconomy, it has no way to measure 1) the impact of federal R&D and procurement dollars, 2) nor the number of businesses involved in biotechnology, 3) nor the number of people employed in any of those businesses, other than what companies choose to disclose to investors. We do not know how big an enterprise the bioeconomy represents, nor how much other critical parts of our economy depend on biologically manufactured materials. Therefore, we do not understand the scope of our exposure to various risks. Moreover, our ignorance means that we are able to measure our progress and capabilities against other nations only through headlines and trumpeted achievements. Ultimately, we cannot tell if we are winning or losing.

The U.S. government has solved similar problems in the past. The contribution of semiconductors to the American economy was tracked by the Department of Commerce at least as early as 1958, when it was less than 0.05% of GDP¹³. Even in 1958, it was obvious that quantifying the production of semiconductors, which was then a brand new technology, was already of critical importance to the Department of Defense, and thus to the nation. Biotechnology is nearly 40 years old as a commercial

¹² Organick, L., et al, "Random access in large-scale DNA data storage", *Nature Biotechnology*, 3 (36), 2018.

¹³ U.S Bureau of the Census, Annual Survey of Manufacturers 1971, U.S. Department of Commerce, 1973.
<https://books.google.com/books?id=mxhxSOQ0j0C>.

enterprise, and, as I have described, it is already quite clearly critical to the nation. It is well past time that we measure and understand the impact of biological technologies across the economy.

My reading is that the *Engineering Biology Research and Development Act of 2019* does not currently address quantifying the role of biotechnology in the economy¹⁴. Moreover, this legislation may not be the appropriate means to fix this knowledge gap. However, I would exhort this Committee to 1) at a minimum work with the appropriate Congressional and Executive Branch personnel to amend the NAICS codes to track biotechnology, and 2) if appropriate, take the stronger step of amending the language of the Act to direct the Economic Classification Policy Committee to issue supplementary codes as soon as possible to eliminate this knowledge gap.

In my view, the estimated size of this market, and the voluntary ignorance of the details of this market, represent a security threat to the United States that comes in two forms. Firstly, we are basing an increasingly large fraction of our economy on a technology that is having impacts that are not well understood and therefore cannot be managed with respect to investment and educational planning. Secondly, we therefore do not understand what our exposure is to risks from competition, theft, or direct physical threat. We continue in ignorance at our peril.

International Competition

At least 32 countries around the world have identified biological engineering as a strategic technology and are investing accordingly (see Table 1)¹⁵. However, just as the U.S. government is failing to adequately measure the domestic bioeconomy, we are failing to assess the capabilities and intent of other nations.

Africa (1) South Africa	Americas (5) Brazil Canada Chile Mexico United States	Ireland Italy Latvia Netherlands Norway Poland Portugal Russian Federation Slovenia Sweden Switzerland UK
Asia (8 plus Hong Kong) Australia China Hong Kong India Japan Korea Malaysia New Zealand Singapore	Europe (22) – EU has its own policy Austria Belgium Czech Republic Denmark Finland France Germany Greece Hungary	
Mideast (2) Israel Turkey		

Table 1: Countries that have stated strategies, or clear national or institutional interest, to develop advanced biological engineering capabilities. (Source: OECD)

The only semi-official U.S. government estimate of global biotechnology revenues was performed by me for the 2012 Biodefence Net Assessment (BNA), published by the Homeland Security Studies and Analysis Institute. This effort only scratched the surface of the problem by looking at five countries, including the U.S.¹⁶. In that Assessment, I used national biotechnology industry revenues as a proxy for

¹⁴ <https://www.congress.gov/bills/115th-congress/house-bill/7171>

¹⁵ Organisation for Economic Cooperation and Development. Emerging Policy Issues in Synthetic Biology, 2014.

¹⁶ Carlson, R., "Causes and Consequences of Bioeconomic Proliferation: Implications for U.S. Physical and Economic Security",

domestic technical capability, which is otherwise very difficult to assess. In the few years since that document was published, the list of countries expressing the intent to develop domestic biotechnology industries has grown significantly.

Many of the countries shown in Table 1 view domestic development of biotechnology and biomanufacturing as a less capital-intensive path to economic development than that pursued by the United States, Europe, and Japan in the 20th century. This is consistent with the stated strategic aims I uncovered in the course of my work for the BNA.

China, in particular, has clearly identified its intention to become a dominant global power via domestic development and mastery of biotechnology. Repeated statements by the country's leaders demonstrate that they believe biotechnology is a critical tool in their efforts to sustain both China's economic development and the health of its population. In 2002, President Jiang Zemin stated publicly that the government would use all means available to improve the health of the population, including genetic modification of its citizens¹⁷. In September of 2008, Premier Wen Jiabao stated, "To solve the food problem, we have to rely on big science and technology measures, rely on biotechnology, rely on [genetic modification]."¹⁸ The "food problem" to which the Premier referred is a combination of a still-increasing population and a recent, precipitous decrease in arable land¹⁹. On January 9, 2006, Premier Wen Jiabao announced a plan to "catch up with the most advanced nations in biotechnology" while strengthening "independent" or "indigenous" innovation²⁰. These plans and statements have continued apace for the last decade, resulting in significant domestic investment and innovation.

As of 2010, China reportedly generated an estimated 2.5% of GDP from biotechnology, with a 2020 target of 5–8% of GDP²¹. Last spring, at the World Bioeconomy Summit in Berlin, Yin Li, Deputy Director-General of Bureau of International Cooperation for the Chinese Academy of Sciences, reported that the bioeconomy in China is growing at 15% annually and in 2015 generated \$700B, or ~4% of GDP, with a government target to more than double this to \$1.6T by 2020. These figures are roughly in line with my projections from a decade ago.

Part of the strategy to improve China's domestic biotechnology capabilities has been to import knowledge and technology from abroad. In addition to ongoing efforts to lure home more "sea turtles" — students who had left China to study overseas, but have now "swum home", bringing knowledge with them — there are an increasing number of "seagulls" — Chinese professionals who transit multiple times between China, the United States, and Europe, maintaining collaborations around the world and serving as conduits for knowledge. To facilitate the transfer of knowledge and expertise to China, in 2008 the government launched the "Thousand Talents Program", which paid approximately 6,000 foreign and Chinese born scientists to relocate to China²². This program has come under scrutiny of late, in part due to action by the U.S. Congress. And yet the money is spent, and the people have moved, and the substantial support for these researchers is buttressed by additional investment in commercialization,

Biodefense Net Assessment 2012, Homeland Security Studies and Analysis Institute, 2011.

17 Carlson, 2011.

18 *ibid.*

19 *ibid.*

20 *ibid.*

21 *ibid.*

22 "China hushes up scheme to recruit overseas scientists", Yuan Yang and Nian Liu, *The Financial Times*, 9 Jan, 2019.

which has resulted in a profusion of biotech start-ups over the last decade²³. The U.S. government should expect that China will continue to vie for international leadership in the development of biotechnology.

Security

My charge for the 2012 BNA was to assess the implications for U.S. physical and economic security of rapidly spreading biological technologies. I concluded that the overall paucity of information about international industrial capability was of particular concern because,

*When combined with the torrid pace of economically-driven proliferation, this lack of information and awareness will eventually lead to surprises. In the context of this report "surprise" means an innovation by a particular actor that could not be easily foreseen by tracking the prior development of that actor and that may pose a risk to U.S. interests; i.e., "a threat."*²⁴

Two components of security that were outside the primary purview of my 2012 BNA report were IP security and foreign investment in biotechnology. These components turned out to comprise a different sort of surprise than anticipated by either myself or the Executive Review Panel for the 2012 BNA. Aggressive foreign acquisition of biological technologies via both upfront investment and outright theft have turned out to be a substantial threat to U.S. interests. I commend the Congress for its recent efforts to steward U.S. intellectual property, and the substantive biotechnology innovations funded by U.S. taxpayers, by bringing biotechnology explicitly into the remit of the Committee on Foreign Investment in the United States²⁵.

It appears that the added scrutiny brought to bear on investment in, and acquisition of, technologies developed domestically has slowed foreign investment, which, to be sure, has directly impacted the ease with which companies in our portfolio have been able to raise capital. Yet I would like to personally state for the record that it *should* be harder for foreign entities, particularly those backed implicitly or explicitly by foreign governments, to acquire critical early stage technologies developed in the United States, particularly those funded by U.S. taxpayers.

Domestically, the relationship between scientists and the security and law enforcement communities has not always been smooth. However, I would like to credit by name FBI Supervisory Special Agent Ed You for his yeoman efforts to develop outreach programs that have built trust and lines of communication between academic scientists, garage biology enthusiasts, entrepreneurs, and the U.S. government. The FBI now considers anyone interested in biology to be part of its early warning system for identifying potential misdeeds^{26, 27}. It is my personal experience that FBI agents in local offices are encouraged by their leadership to reach out and develop constructive relationships with those maintaining labs in their homes. These efforts will become increasingly important as the bioeconomy grows and incentivizes more commercial activity in the form of start-ups that will crop up in any working space that they can afford. The U.S. government should encourage this activity, rather than fear it or suppress it, but should also devote

²³ "China's great leap forward in biotech", Henry Sender, *Nikkei Asian Review*, 3 Oct, 2018.

²⁴ Carlson, 2011.

²⁵ "In New Slap at China, U.S. Expands Power to Block Foreign Investments", Alan Rappeport, *The New York Times*, 10 Oct 2018.

²⁶ "Biohackers of the world, unite", *The Economist*, 10 Sept, 2014.

²⁷ "On Patrol with America's Top Bioterror Cop", Antonio Regalado, *Technology Review*, 20 Oct, 2016.

resources to continuing engagement activities that are, in my experience, the best single step that the U.S. government has taken to improve security.

We all have a great deal of work ahead of us in shepherding the growing bioeconomy as it begins to impact an ever broader swath of the economy. The ongoing National Academies study "Securing the Bioeconomy", sponsored by the Office of the Director of National Intelligence, is in my view a significant step forward in identifying and highlighting the challenges faced by the United States in navigating the rapidly evolving world of biotechnology. I hope that similar efforts will continue to serve the dual purposes of informing the U.S. government about the critical role of biotechnology in the economy while also informing the scientific community about the reality of biotechnology being a powerful geopolitical tool on the global stage that must be respected and protected accordingly. We must do better in both the public and private sectors to develop and secure the bioeconomy.

Public Conversations

The public has a passion for learning about biology. It's understandable. We are biology. We eat biology. We are surrounded by biology. Human society and population levels today are viable only because over the last century our well-being and lifespans have been significantly impacted by biological technologies. Moreover, biotechnologies are rapidly improving in price and performance. It is natural that the public wants to know more about how new means to measure and manipulate nature might affect not just humans, but all life around us. It is incumbent upon the government to engage scientists, entrepreneurs, and the public on issues of safety, security, and ethics. This engagement is foundational to both science and democracy, particularly in the context of taxpayers' interests in how the government spends their money. But beyond the role of two-way communication in the future of engineering biology, is the growing, and critically important, participation of the public in the practice of biotechnology itself. As biotechnology becomes less expensive, and more capable, it is finding its way into community laboratories, garages, and other so-called "unconventional spaces", where members of the public are enthusiastically taking part. As rapidly as biological engineering is being developed in high-end academic, corporate, and government labs, it is migrating to the street.

The U.S. Economy Begins in Garages

The democratization of technical capability, and the distributed innovation it enables, is the foundation of modern innovation. According to a study for the U.S. Small Business Administration, nearly every technology that we now consider important in the modern economy passed through an unconventional space at some point in its development cycle²⁸. To summarize an argument from my book, *Biology is Technology*, there is every reason to expect the biotechnology industry to develop along these same lines and to depend heavily on entrepreneurs and small organizations in garages to produce innovation²⁹. Governments at local, regional, and national levels around the globe appear to agree, and continue to provide incentives for biotech start-ups and clusters with the goal of fostering economic development and technological competitiveness. This trend is only going to accelerate, and it should be embraced. The U.S. government would do well to develop a network of community laboratories that would provide access

²⁸ Baumol, W., *Small Firms: Why Market-Driven Innovation Can't Get Along Without Them*, 2005, U.S. Small Business Administration.

²⁹ Carlson, R., *Biology is Technology: The Promise, Peril, and New Business of Engineering Life*, Harvard University Press, Cambridge, MA, 2010.

to infrastructure, increase communication between innovators, and facilitate engagement with the U.S. government in regards to national security and national technology development goals³⁰. In addition to providing venues for education and public conversations, this strategy would facilitate economic development via start up formation, thereby accelerate job creation, and would dovetail nicely with the aforementioned existing FBI outreach activities.

The U.S. National Security Council determined nearly a decade ago that openness should be the foundation of biotech and health security strategy. Moreover, these security professionals concluded that restricting access is counterproductive and that only through openness and the development of collective norms can we reduce the emergence, and impact, of threats.

In particular, the 2009 National Strategy for Countering Biological Threats, which carried the signature of the President of the United States, explicitly set out policy to embrace and encourage garage biology³¹:

*The beneficial nature of life science research is reflected in the widespread manner in which it occurs. From cutting-edge academic institutes, to industrial research centers, **to private laboratories in basements and garages, progress is increasingly driven by innovation and open access to the insights and materials needed to advance individual initiatives.***
[emphasis added]

Our Strategy is targeted to reduce biological threats by: (1) improving global access to the life sciences to combat infectious disease regardless of its cause; (2) establishing and reinforcing norms against the misuse of the life sciences; and (3) instituting a suite of coordinated activities that collectively will help influence, identify, inhibit, and/or interdict those who seek to misuse the life sciences.

In other words, the National Security Council, after due study and deliberation, decreed that garage biology is good and necessary for the physical and economic security of the United States. The 2018 U.S. National Biodefense Strategy affirmed that "promoting American prosperity increasingly will depend on a vibrant life sciences and biotechnology enterprise"³². I have argued elsewhere that all nations who hope to sustain their physical and economic security must similarly embrace and encourage diversity in innovation and commercialization; those who do not will almost certainly place themselves at a disadvantage^{33, 34}.

The broader implications of this proliferation should, of course, be at the forefront of thinking about the future of biotechnology. We must confront any opportunity or threat with the attention due each. What will the world look like as more powerful biological technologies can be employed by a greater number, and diversity, of individuals around the world? We are about to find out.

³⁰ Carlson, R. "Building a 21st Century Bioeconomy: Fostering Economic and Physical Security Through Public-Private Partnerships and a National Network of Community Labs", Biodesic, 2011.

³¹ "National Strategy for Countering Biological Threats", National Security Council, 2009.
https://obamawhitehouse.archives.gov/sites/default/files/National_Strategy_for_Countering_BioThreats.pdf

³² "National Biodefense Strategy", The Executive Office of the President of the United States, 2018.

³³ Carlson, 2010.

³⁴ Carlson, R., "Causes and Consequences of Bioeconomic Proliferation: Implications for U.S. Physical and Economic Security", Biodefense Net Assessment 2012, Homeland Security Studies and Analysis Institute.

Recommendations

My first recommendation is to centralize the strategy formation and policy response functions of the United States government in regards to the bioeconomy. The responsibility to understand, prepare for, and respond to threats to the bioeconomy is balkanized, and therefore dysfunctional, spread across at least nine Departments and Agencies within the Executive Branch: Health and Human Services, Agriculture, Commerce, Energy, Defense, Homeland Security, Justice, as well as the special responsibilities of the CDC and the Intelligence Community. That the bioeconomy touches so many of the functions of the U.S. government should clarify the scope of the problem. Whether your immediate concern is infectious disease response, antibiotic resistant pathogens, food security, farming, bioterrorism, invasive species, or the DOD supply chain, all these problems involve biology. We do not benefit from maintaining a fragmented perspective. These interagency problems require a full time position to integrate and coordinate across the U.S. government in order to streamline decision making.

Let me clarify here that the very last thing I want to do to this nascent and important enterprise is to smother it with bureaucracy or overly precautionary regulation. Nevertheless, I strongly recommend that Congress find ways to encourage coordination across government agencies and industry to develop and execute a strategy for keeping the United States at the forefront of technology development and of economic realization of the fruits of engineering biology. It is my personal experience that biosecurity, inclusive of both natural and artificial threats, and of both economic and physical well being, is disjointed and inadequately funded. I have come to the conclusion that this failing is due to the lack of a strategic function, and of an individual who is responsible for advocating to Congress. This headless fragmentation puts the United States at a distinct disadvantage with respect to countries that have proceeded with a clearly stated industrial policy and clearly understood lines of communication, if not clear lines of authority. Our laissez-faire approach does have its advantages, but also its costs, where the latter now negatively impact our security.

Next, I would strongly recommend that, in addition to legislation aimed at bolstering the strategic understanding and prominence of biological engineering and manufacturing in the economy, this Committee also broaden its focus to examine the net contribution of all of biology to U.S. physical and economic security. While this task may sound daunting and complex, the rationale is very simple: just as we do not quantitatively understand the role of engineered biological systems in our economy, and just as this lack of understanding constitutes a security risk, we also do not understand the role of natural biological systems in supporting our economy, which ignorance may represent an even more significant security risk. Without the air, water, and food supplied by natural biological systems, without the fire suppression, flood control, and coastal protection respectively provided by forests, wetlands, and coral reefs, the rest of our economy has no value at all. In that regard, our entire economy is synonymous with the bioeconomy, which should be afforded the same level of attention as we pay to the rest of the enterprise.

Entities ranging from small farmers, to the all of the States of the Union, to the Department of Defense are already facing the reality that their dependence on finite biological resources constitute physical and economic risks, which in each case could cost tens to hundreds of billions of dollars to remediate with technology or other interventions, if that is even possible.

To be sure, these risks may be addressable through greater biological engineering capabilities, and I strongly suggest that this Committee include such remediation within the scope of the biological engineering strategy and projects considered in any legislation. But relying on that technical capability, which could take decades to develop, clearly must be secondary to first measuring, and then preserving, the utility of natural systems to provide those same services.

Finally, I close with a quote from my recent *Nature Biotechnology* article, which encapsulates my perspective on the challenges we face going forward:

Biosecurity has typically been interpreted as the physical security of individuals, institutions and the food supply in the context of threats such as toxins and pathogens. These will, of course, continue to be important concerns. Yet governments can no longer limit their concern to the proverbial white powder produced in a state-sponsored lab, a 'cave' in Afghanistan, or a garage in Seattle. Safeguarding the large and rapidly growing bioeconomy requires embracing a more substantial challenge; it is essential to have a refined and ongoing understanding of what must be secured and from where threats might arise. Economic demand is driving technological proliferation, [which] must necessarily inform the evolving definition of biosecurity. Alongside the preexisting bioeconomy, we are building a system composed of inherently 'dual-use' engineering technologies that will constitute critical infrastructure for the future economy. ...Biosecurity is now clearly synonymous with economic security. The focus of biosecurity policy must shift from protecting specific targets from specific threats to securing the bioeconomy as a system that increasingly drives economic growth and employment and, ultimately, enables humans to thrive on a global scale.³⁵

Thank you for your attention, and thank you for the opportunity to address this Committee.

/END

³⁵ Carlson, 2016.

Dr. Rob Carlson is the Managing Director of Bioeconomy Capital, an early stage venture capital firm focussed on building the bioeconomy of the 21st century.

Rob is also a Principal at Bidesic, a strategy, engineering, and security consulting firm in Seattle that provides services to governments and corporations around the globe. He is Affiliate Faculty in the Paul Allen School of Computer Science and Engineering, University of Washington, Seattle

At the broadest level, Dr. Carlson is interested in the future role of biology as a human technology. He has worked to develop new biological technologies in both academic and commercial environments, focusing on molecular measurement and microfluidic systems. Dr. Carlson has also developed a number of new technical and economic metrics for measuring the progress of biological technologies. Carlson is the author of the book *Biology is Technology: The Promise, Peril, and New Business of Engineering Life*, published in 2010 by Harvard University Press; it received the PROSE award for the Best Engineering and Technology Book of 2010 and was named to "Best Books of 2010" lists by writers at both *The Economist* and *Foreign Policy*. He is a frequent international speaker and has served as an advisor to such diverse organizations as The Hastings Center, the PICNIC Design Festival, the UN, the OECD, the US Government, and companies ranging in size from startups to members of the Fortune 100. Carlson earned a doctorate in Physics from Princeton University in 1997.

In 2012 Dr. Carlson was a Senior Lecturer in the Department of Computer Science and Engineering at the University of Washington, where he taught a class on developing strategy and policy in the context of rapid technological change. From 2002 to 2007, Carlson was a Senior Scientist in the Electrical Engineering department at the University of Washington. From 2003 to 2008, he provided technology analysis and strategic consulting as a Senior Associate at Bio-Economic Research Associates (Bio-era), writing extensively on pandemic preparedness, synthetic vaccines, biofuels, and biological technologies, and presenting briefings on these subjects to executives and government officials around the world. From 1997 to 2002 he was a Research Fellow at The Molecular Sciences Institute in Berkeley, CA. Links to additional articles and a weblog can be found at www.synthesis.cc.

Chairwoman STEVENS. The Chair now recognizes Dr. Solomon.

**TESTIMONY OF DR. KEVIN SOLOMON,
ASSISTANT PROFESSOR OF AGRICULTURAL AND
BIOLOGICAL ENGINEERING, PURDUE UNIVERSITY**

Dr. SOLOMON. Chairwoman Stevens, Ranking Member Baird, and Members of the Committee, good morning. My name is Kevin Solomon, and I am an Assistant Professor of Agricultural and Biological Engineering at Purdue University. Thank you for inviting me to speak to you today about my work at the intersection of engineering, synthetic biology, and the microbiome.

My lab develops microbial systems that have diverse applications for agriculture, bioenergy, and biomanufacturing. Our work is currently supported by the National Science Foundation, and we rely on user facilities provided by the Department of Energy's Office of Science.

One specific example I would like to share from my work that showcases a potential of engineering biology has to deal with our work studying in the microbiomes, the gut microbiomes of cattle and other livestock. These tiny microbes that live within these animals, they are critical for digestion and providing nutrition to the host animal. However, their ability to degrade its plant material to provide this nutrition also has an ability to revolutionize bioenergy production.

At the same time, these microbes, they produce antibiotic-like compounds that we believe may be harnessed into new medicines in the future. And my lab is very much interested in understanding, controlling, and imitating these microbes because they have a potential to naturally enhance food production in cattle and other livestock, to overcome a key hurdle in bioenergy, and potentially provide us with new tools to combat antibiotic resistance.

So based on this example, we can see that engineering biology research can simultaneously affect multiple domains and multiple mission areas within the Federal Government. And so the coordinated Federal Research Program for Engineering Biology as envisioned by the *Engineering Biology and Research and Development Act of 2019* will enable the U.S. to continue its leadership in engineering biology.

In my written testimony I elaborate more on the state of research and training in this area and outline how the bill may advance these areas. However, I'd like to provide a brief overview of four key goals that I think the bill should address.

First, the bill should provide a forum for interagency collaboration and information sharing as well as multi-agency funding mechanisms that enable game-changing technologies. The current funding mission is very mission-driven and relies on the ability of scientists to correctly match agency needs to their science, regardless of innovation. A coordinated framework can help remove these artificial institutional barriers to innovation and help us better recognize and support innovating and cross-cutting ideas that will be key to maintaining the preeminence of American technology. And hopefully, these mechanisms should consider these ideas for funding from all relevant agencies.

Second, we should provide sustained research funding to critical research programs in engineering biology at mission agencies. So many Federal agencies currently benefit from engineering biology, and agencies such as the Department of Energy, NASA, they have selected topics of interest that they rotate in a 4-year cycle. However, these topics, because they're not coordinated currently, they may overlap in a given year which leads to lapses in funding in subsequent years. And what that does is that those gaps in funding, they discourage and slow the development of emerging leaders with innovative ideas and that can cause the U.S. to fall behind, to follow, rather than lead, in these critical areas. And so a coordinated framework can help provide a more sustained commitment to research.

Third, we should ensure a variety of funding mechanisms to ensure a broad ecosystem of researchers along with focused multi-disciplinary centers. Major center opportunities are an important component of the engineering biology ecosystem, as they act as nexuses for student training, interdisciplinary research, and commercialization of technology. As a graduate of one of these, I am an advocate for them. However, it's also important that individual researchers have the opportunity to contribute to ensure a broad and healthy ecosystem of research.

And finally, we should also increase U.S. capacity and the number of people with skills in engineering biology by providing direct support for experiential training programs. Currently, student research is essential to preparing the emerging engineering biology workforce and train the researchers of the future. For example, within this community, we have developed and we have embraced the International Genetically Engineered Machines Competition, or IGEM, which has trained more than 40,000 students from across the globe. And these students are high school students, undergraduate, and also graduate students. Their combined efforts have led to a number of startups, some of them in excess of a valuation of \$1 billion. These student-led teams that engage in authentic research to solve societal problems; develop critical skills in leadership, communication, and entrepreneurship; and they learn key values such as biosecurity, safety, and ethics. Funding mechanisms for teams that participate in these programs would be very helpful to sustain these efforts.

In closing, a coordinated initiative in engineering biology will greatly enhance American competitiveness and innovation. And I just want to thank you again, the Committee here, for your work on this important issue and for supporting our community. Thank you.

[The prepared statement of Dr. Solomon follows:]

Testimony

**Before the Committee on Science, Space and Technology,
Subcommittee on Research and Technology
Of the US House of Representatives**

On

Engineering Our Way to a Sustainable Bioeconomy

**Kevin Solomon, Ph.D.
Assistant Professor of Agricultural & Biological Engineering
Purdue University
March 12, 2019**

Chairwoman Stevens, Ranking Member Baird and Members of the Committee,

My name is Kevin Solomon and I am an Assistant Professor of Agricultural and Biological Engineering at Purdue University in West Lafayette, IN. Thank you for inviting me to speak to you today about my work at the intersection of engineering, synthetic biology, and the microbiome.

Historical context and potential of engineering biology

I have had the distinct privilege of being at the forefront of the emerging discipline of Engineering Biology for the past 13 years. I was in the inaugural class of trainees in the pioneering Synthetic Biology Engineering Research Center (SynBERC) funded by the National Science Foundation in 2006. This decade marked a transition in genetic engineering from an art to a rigorous engineering discipline. Precise genetic constructs could be developed for the first time. Quantitative models accurately predicted biological behavior and illustrated common biological design principles. More importantly, implementing seemingly simple designs based on these models replicated much of the rich complexity that we observe in biology, and also created novel behaviors never observed before. In other words, we were able to engineer biology for the first time.

Emboldened by this success, US researchers began to envision the ways in which we could apply these capabilities to solve grand societal challenges. Biological systems have remarkable biosynthetic capabilities that capture abundant CO₂ and transform it into myriads of chemical compounds with precise composition. These chemical compounds are frequently identical to those currently produced by traditional chemical industry. Moreover, biological systems more easily make complex molecules with higher purity than traditional synthesis, and can create novel materials with unique properties. That is, biological systems can be used as sustainable biomanufacturing platforms for medicines, fuels, materials, and other important molecules. Biological systems are also self-sustaining and responsive to their environment, and thus do not need traditional industrial infrastructure to perform specific actions. Systems can be decentralized to act only where needed to form truly innovative solutions to old problems

Envisioned applications include bacterial sentinels that detect and eradicate cancer in the body¹, gut health monitoring systems that cure infections before patients display symptoms of illness², and plant sentinels in public spaces that non-invasively sample the environment to detect and provide alerts for biological or bomb threats³. The genetic tools that allow the creation of these systems are valuable in their own right as they enable us to envision cures to “incurable” diseases such as cystic fibrosis⁴. This early work has led to hundreds of startups that have raised more than \$5 billion domestically in investments in the last 4 years⁵. It has also led a renaissance in innovation at more mature companies in the biotechnology sector.

The rapid progress of the field has revealed a wealth of untapped biological potential. My lab aims to characterize the potential of novel microbes and develop them to address societal needs. Specifically, we focus on applications in bioenergy, biomanufacturing, nanomaterial synthesis, and agriculture. Our work is currently supported by the National Science Foundation (NSF), and we rely on user facilities of the Department of Energy’s (DOE) Office of Science.

One specific example I would like to share from my work is about anaerobic fungi that are an essential part of the gut microbiome of cattle and other livestock. These fungi digest ingested plant material to provide nutrition to the host animal. They also secrete molecules that affect animal health and production. My lab uses cutting-edge mid-scale research infrastructure, provided by federally supported user facilities, to dissect the capabilities of these novel organisms and develops approaches to control them for biotechnology. For example, we are working to exploit the ability of anaerobic fungi to degrade crude plant material as it may advance bioenergy research by overcoming one of the most significant hurdles to economical biofuels: the ability to convert inexpensive, renewable biomass into sugars for fermentation. Similarly, we are trying to understand the biosynthetic capabilities of anaerobic fungi. Like penicillin from *Penicillium* fungus, the secreted compounds of anaerobic fungi may form the basis of powerful new medicines such as novel antibiotics, which are needed to combat drug-resistant infections. Finally, understanding and controlling these activities within the digestive tracts of animals may *naturally* enhance food production to meet a growing population while reducing the need for additives currently used to meet production demands.

Student training

Research integrity, ethics, and (bio)security are always of utmost concern when engineering biology. My lab’s research complies with existing federal, state, and institutional guidelines and is subject to regular review. Beyond this, I train my students to consider the implications of their work. While our work does not currently suffer from the ethical dilemmas found in some aspects of the field, my students are sensitive to issues in this space. In my grad-level course on engineering biology, taken by upper-level undergraduates and all my graduate-level researchers, our lesson on Day 1 begins with a discussion on “Human Practices”. Human Practices describe

¹ Zhou S, Gravekamp, C, Bermudes, D, and Liu K. *Nature Reviews Cancer* **18**, 727–743 (2018)

² Claesen, J. and Fischbach, MA. *ACS Synthetic Biology* **4**, 358–364 (2014).

³ Antunes, MS et al. *PLOS One*, **6**, e16292 (2011).

⁴ <https://labiotech.eu/tops/crispr-technology-cure-disease/>

⁵ SynbioBeta, Synthetic Biology Annual Investment Report, September 2018. <https://synbiobeta.com/wp-content/uploads/2018/11/Synthetic-Biology-Annual-Investment-Report.pdf>

how technological innovation serves society and how its development is informed by societal values. Students are trained to identify all possible stakeholders of new technologies (e.g. government, entrepreneurs, consumers, special interest groups, etc) and discuss their different perspectives on safety, biosecurity, perceived risks, societal impact, and ethics. In so doing we not only determine *whether* a project should be undertaken, but *how* it should be executed. We identify valid concerns that should be addressed via design (e.g. a failsafe self-destruct to prevent environmental damage in case of accidental release) and discuss strategies to educate groups on the severity of a perceived technical risk.

Technicians, scientists and engineers that engineer biology come from a number of fields in the biological sciences, physical sciences, agricultural sciences, information sciences, and engineering. We bring unique disciplinary perspectives that are critical to the innovative advances of the field (e.g. quantitative models of emergent biological phenomena introduced by physicists and engineers). What unites us, however, is our shared desire to solve grand societal challenges, and our passion for the power of biological systems. While programs across the country, such as those at Purdue, offer specialized concentrations that focus on engineering biology within more traditional disciplines, most training is experiential. Students learn through authentic research projects in labs such as my own or in collective DIYBio⁶ spaces. To increase the number of formal training opportunities for students, our community has developed and embraced educational programs such as iGEM, the International Genetically Engineered Machines competition, which has trained more than 40,000 high school, undergraduate and graduate students from across the globe in the past decade. I advise and mentor Purdue's team in this competition. Student-led teams engage in authentic research to solve societal problems, and develop critical soft skills in leadership, communication and entrepreneurship. Integrated in the design process is an explicit consideration of Human Practices. Projects are frequently ambitious in scope and have led to several startups with a total valuation in excess of \$1 billion^{7,8}.

Recommendations

As a product of the federal government's initial investments in engineering biology, I am grateful for your renewed commitment to our field in the proposed *Engineering Biology Research and Development Act of 2019*. I benefited greatly from the interdisciplinary and forward-thinking approach of the Engineering Research Center (ERC) program and believe that centers such as these will continue to be key nexuses of American innovation and entrepreneurship. Your current investments in specialized facilities power my own research, and your funding support enables me to train future generations of scientists in this space. Please continue to support these initiatives.

From the ongoing research in my lab, we can see that tools that advance technological progress in bioenergy will be similar, if not identical, to those that would advance innovation in agriculture. Therefore, future advances in engineering biology will likely be cross-cutting with

⁶ Do-It-Yourself Biology, a growing movement to democratize biotechnology research that supports the creation of open source equipment and the informal training of community members in engineering biology. <https://diybio.org/>
⁷iGEM, 2019, <https://igem.org/Startups>

⁸Buhr, S, 2017, <https://techcrunch.com/2017/12/14/gingko-bioworks-secures-275-million-in-series-d-valuing-the-company-at-over-1-billion/>

significant impact to several agency missions. A coordinated federal research program for engineering biology as envisioned in the *Engineering Biology Research and Development Act of 2019* will provide long-term investments that recognize and support the fundamental basic science that drives American innovation in multiple areas, and continue its leadership in engineering biology. Given my experience with the current funding landscape and training programs, I share the following recommendations beyond the current bill provisions:

1. **Provide a forum for inter-agency collaboration and information sharing, as well as multi-agency funding mechanisms that enable game-changing technologies.** The current funding system is mission driven and relies on the ability of researchers to correctly match agency needs to their science, regardless of innovation. Just as proposals may be transferred intra-agency to more appropriate programs, mechanisms to transfer innovative high reward ideas across agencies for consideration are needed. Similarly, joint funding programs would accelerate innovation in multiple areas simultaneously. A coordinated framework should reduce artificial institutional barriers to funding by recognizing truly innovative and cross-cutting ideas that will maintain the preeminence of American technology and consider these ideas for funding from all relevant agencies.
2. **Ensure a variety of funding mechanisms to ensure a broad ecosystem of researchers along with focused multi-disciplinary centers.** Major center opportunities are an important component of the engineering biology ecosystem, as these act as nexuses for student training, interdisciplinary research, and commercialization of technology. It is also important that individual researchers have opportunities to contribute to ensure a broad and healthy ecosystem-that enables high-risk, high-reward research. Fundamental basic research that is needed to drive the next wave of innovation can be easily overlooked as the applications that meet agency needs may not occur within a standard grant timeline (< 5 years). To overcome this, more seed funding for high risk, high reward ideas and fundamental science that will enable game-changing technologies across missions is needed.
3. **Provide sustained research funding to critical federal programs in engineering biology at mission agencies.** Federal agencies such as the DOE, and NASA rotate their research topics for funding support in a cycle of 4 or more years. Similar topics may overlap at several agencies in a given year leading to lapses in funding in subsequent years. These gaps discourage young investigators and slow the development of emerging leaders with innovative ideas causing the US to follow, rather than lead, in these critical areas. This can lead to the permanent loss of talented researchers. Early success in the careers of academic researchers is a job requirement. Without federal support to catalyze these early successes, researchers may exit the field and be unable to contribute their innovative ideas over the standard 20-30 year period of an academic career. This loss has a multiplicative effect as it also includes the dozens of trainees that researcher would have gone on to influence and shape. A coordinated research framework will provide a sustained commitment to development in emerging areas by staggering rotation schedules or providing consistent (joint) funding to ensure American leadership in these areas.

4. **Increase US capacity and the number of people with skills in engineering biology by providing direct support for experiential training opportunities.** Student research is essential to prepare the emerging engineering biology workforce and train the researchers of the future. The premier experiential research training program in engineering biology is the iGEM competition. Students learn through experience by developing biological solutions to real problems. For example, Purdue's most recent entries have developed biological systems to capture phosphorus pollution from storm runoff to reduce damaging algal blooms, and envisioned using the natural microbiomes of our lungs to remove cancer-causing air pollutants. Our entry this year seeks to "vaccinate" plants with natural rhizobacteria to protect against crop pathogens. Students develop technical skills in the field, hone marketable soft skills, and consider ethics and security in their research. In a few cases, these projects bloom into exciting new commercial ventures. However, in recent years American entries have been eclipsed by European and Chinese teams that, unlike American teams, receive significant government support. Funding mechanisms for student-led research with significant budgets (~\$50-100K/year/team) would improve the quality of this training and potentially enhance American innovation while encouraging the development of American industrial capacity.

Closing Remarks

Engineering biology is poised to form the basis of the next technological revolution with applications across diverse areas. To train skilled workers for this field, US universities have developed concentrations and certificates in engineering biology that complement rigorous training in more traditional disciplines. However, the most impactful training is experiential. The United States needs to invest in more basic research that will drive this revolution, in part through inter-agency consideration of proposals and more sustained funding in research areas, while providing direct funding for training opportunities. I am eager to see how the *Engineering Biology Research and Development Act of 2019* creates opportunities to enhance American competitiveness in this burgeoning area of possibilities. Thank you again for the opportunity to speak to you, and for your continued support of our field.

Dr. Kevin Solomon is an Assistant Professor of Agricultural and Biological Engineering at Purdue University. His work focuses on the development of sustainable microbial processes to supply the energy, materials, and medicines of tomorrow. He holds a bachelor's degree in Chemical Engineering and Bioengineering from McMaster University (Canada) and a PhD in Chemical Engineering from MIT. Dr. Solomon was part of the inaugural class of trainees in the National Science Foundation's Synthetic Biology Engineering Research Center (SynBERC), the first American interdisciplinary research center dedicated to engineering biology. As part of his graduate work, Dr. Solomon developed new tools to increase biomanufacturing efficiency. His research and mentorship, at the intersection of metabolic engineering and synthetic biology, were recognized with multiple awards including a Lemelson Presidential Fellowship, an NSERC Julie Payette Award, and a Science Education Leadership Award from SynBERC. As a postdoctoral fellow at UC Santa Barbara, he applied the latest advances in sequencing technologies to interrogate how microbes interact with their environment and identify new tools for synthetic biology. Using these techniques, he spearheaded efforts to molecularly characterize in depth a class of elusive microbes with tremendous potential for biofuel production, agriculture, and drug discovery. Dr. Solomon has published more than 20 peer-reviewed publications, is a holder of 1 US patent, and has several pending and provisional patents that are currently licensed to multinational corporations.

Chairwoman STEVENS. Thank you. The Chair now recognizes Dr. Hegg.

**TESTIMONY OF DR. ERIC HEGG,
PROFESSOR OF BIOCHEMISTRY AND MOLECULAR BIOLOGY,
MICHIGAN STATE UNIVERSITY, AND
MICHIGAN STATE UNIVERSITY SUBCONTRACT LEAD,
GREAT LAKES BIOENERGY RESEARCH CENTER**

Dr. HEGG. It is my honor to testify today on the opportunities of new and emergent technologies associated with engineering biology. I am representing myself, and the views I express are my own.

By way of background, I am a biochemistry professor at Michigan State University (MSU). And in this role, I've experienced the critical collaborative partnerships that exist between the Federal Government and universities. At MSU, DOE (Department of Energy) and NSF (National Science Foundation) funding make up approximately 50 percent of the total Federal research budget. These funds support vital cutting-edge research, train future scientific leaders, and develop new economic sectors.

My research focuses on understanding how nature uses metals to perform difficult transformations. Obtaining a deeper understanding of nature's strategies may enable us to produce better catalytic systems for industrial processes. In each of my research projects, there are clear potential applications in bioenergy, environmental research, or human health.

It is imperative to remember that in basic research, discoveries made in one field can provide profound and unexpected benefits in other areas. It is therefore nearly impossible to overestimate or predict its full impact on the economy or quality of life.

In addition to my personal research, I also serve as the MSU Subcontract lead for the Great Lakes Bioenergy Research Center (GLBRC) which is administered by the University of Wisconsin. The GLBRC's mission is to perform the basic research needed to enable an economically viable and environmentally sustainable biofuel industry.

Success in this area has the potential to boost future U.S. energy security, lower greenhouse gas emissions, and create jobs in rural America. To accomplish this mission, the GLBRC performs a broad range of research including engineering-improved bioenergy crops, engineering microbes to convert biomass into biofuels, and optimizing field-to-product integration that is crucial to the biofuels industry. Essentially all GLBRC research focuses on potential applications, and a large fraction of our research relates to engineering biology whereby we harness the power of nature to improve plants and microbes.

GLBRC research and technology has led to over 100 licenses and options, highlighting industrial relevance of this work and its impact on the economy.

When performing this research, ethical considerations are always critical to our decisionmaking process. For example, to avoid competing with food production, we focus on dedicated bioenergy crops grown on lands not currently used for farming. Similarly, we give significant consideration to the plants and microbes we engineer,

especially those that might get deployed or released into the environment.

Key questions we consider include the possibility of engineered plants and microbes out-competing native species and the likelihood and potential ramifications of genes inadvertently being transferred to other organisms.

Teaching on outreach is a critical mission at land grant institutions such as MSU. This includes ensuring its students and the community are educated about the important ethical considerations of our research. When discussing genetic engineering in the classroom or to the public, my goal is to provide information to enable people to make informed decisions about the risks versus the benefits.

Interest in the biological sciences at MSU has grown steadily, and students are eager to gain real-world experiences. Their interest in hands-on research can be seen in the large number of applications to summer undergraduate research programs. Competition for these programs is intense, and typically there are far more qualified applicants than there is funding. Additional Federal funding would significantly strengthen these programs. Meaningful research experiences teach critical thinking, encourage creativity, and provide vital skills, thereby significantly impacting the size and quality of the future workforce.

The proposed *Engineering Biology Act* would enhance the country's competitive advantage by increasing support for research and education and accelerating commercialization. Engineering biology is likely to grow in global economic importance, and increased interagency coordination can help ensure U.S. leadership. The coordination proposed in this bill will be especially powerful as this Subcommittee works closely with other authorizing committees and agencies that fund engineering biology research, including the NIH (National Institutes of Health), DOD (Department of Defense), and USDA (United States Department of Agriculture). It is imperative, however, that any new initiatives be supported with a commensurate level of new funding. In times of tight physical budgets, it is essential that both investigator-initiated and center-level efforts be encouraged.

Thank you for this opportunity to testify, and I would be happy to answer any questions you may have.

[The prepared statement of Dr. Hegg follows:]

**Witness Testimony of Eric Hegg
Michigan State University (MSU)
Professor of Biochemistry & Molecular Biology
MSU Subcontract Lead for the Great Lakes Bioenergy Research Center**

**Before the House Science, Space & Technology
Subcommittee on Research & Technology
Hearing on
Engineering Our Way to a Sustainable Bioeconomy
March 12, 2019**

Chairwoman Stevens, Ranking Member Baird, thank you for the invitation to testify today. It is my great pleasure to contribute to the ongoing discussion of the opportunities and challenges of new and emerging technologies in the biological sciences, with key applications in agriculture, energy, and manufacturing. I look forward to today's review of the role of the federal government in research and development, the oversight of this critical area of science and technology, and the status of U.S. leadership in engineering biology. I am representing myself at today's hearing. The views I express are my own. To best serve the goals of the subcommittee, I have broken my written testimony into answers to the questions previously submitted to me and my fellow witnesses.

1. Please provide an overview of your research and its potential applications, as well as which federal programs support your research. To what extent is your research shaped by consideration of potential applications?

I serve as both a Professor in the Department of Biochemistry & Molecular Biology at MSU and as the MSU Subcontract Lead for the Great Lakes Bioenergy Research Center (GLBRC). In both of these roles I have observed and experienced the critical collaborative partnerships that exist between the federal government and universities. At MSU alone, support from the Department of Energy (DOE) and the National Science Foundation (NSF) each make up approximately 25 percent of its total federal research funding. These funds provide vital support for cutting-edge fundamental research, for the training of future leaders in science and technology, and for the development of new sectors of our economy. MSU itself is part of the University Research Corridor, an alliance of MSU, the University of Michigan, and Wayne State University, whose mission is to strengthen innovation and economic growth in Michigan. Together, the three institutions – one of the top eight academic clusters in America – contributed an estimated \$18.7 billion to our state's economy in 2017.

My own personal research focuses on the role of metal ions in biological systems, and more specifically, on understanding how nature uses metal ions to perform difficult and important chemical transformations. Obtaining a deeper understanding of the strategies used by nature may enable us to mimic these processes and produce better catalytic systems for industrial processes, or potentially harness the power of enzymes directly. Over the years, I have used this approach to study cellular

respiration, O_2 activation, biological H_2 production, enzymes involved in the global nitrogen cycle, and biomass deconstruction and conversion to biofuels and bioproducts.

In each of these cases, there are clear and timely potential applications in bioenergy, environmental research, and human health, among others. I have been fortunate to work with the MSU Technologies office, which facilitates commercialization of faculty members' research with the goal of moving new technologies out of the lab and into the marketplace, contributing to the strengthening of Michigan's economy and communities as well as the solidification of U.S. leadership in innovation worldwide.

In addition, it is imperative to remember that in basic research, discoveries made in one field can provide profound and unexpected benefits in other research areas, often many years later. It is therefore nearly impossible to overestimate or predict the full impact of basic research on the economy or quality of life. Over the years, my research has been funded by the National Institutes of Health (NIH), the NSF, the United States Air Force (AFOSR), the United States Department of Agriculture (USDA), and three different agencies within the DOE, including Basic Energy Sciences (BES) and Biological and Environmental Research (BER) from the Office of Science, and the Bioenergy Technologies Office (BETO) from the Office of Energy Efficiency & Renewable Energy. I am very grateful to these funding agencies. The contributions to society that I have had the opportunity to make both directly through my own research and indirectly via the GLBRC is a direct result of the financial support of these agencies.

The GLBRC is administered by the University of Wisconsin-Madison with MSU as a major partner. It is one of four bioenergy research centers established by the Office of Biological and Environmental Research Program within the DOE's Office of Science. The mission of the GLBRC is to perform the basic research needed to enable an economically viable and environmentally sustainable biofuel and bioproducts industry derived from dedicated energy crops. Success in this area has the potential to boost future U.S. energy security, lower greenhouse gas emissions, and create jobs in rural areas in Michigan, the Midwest, and throughout the country.

To accomplish this mission, the GLBRC performs a broad range of research, including (1) engineering dedicated bioenergy cropping systems with improved value and sustainability, (2) engineering microbes to enhance the efficient conversion of biomass into biofuels and bioproducts, and (3) optimizing field-to-product integration that will be crucial to the economic and environmental success of the emerging biofuels industry. Within that context, essentially all of the GLBRC research is focused either directly or indirectly on potential applications, and a large fraction of our research relates to engineering biology, whereby we harness the power of nature to improve a process or a desirable plant or microbe trait.

Important new technologies where plants or microbes have been engineered to contain desirable traits have led to the development of improved organisms, including: (1) trees with accelerated growth, increased density, and tunable energy content, (2) trees with modified lignin (a complex structural compound in plant cell walls) that enhances deconstruction, facilitating both biofuel and paper production, (3) plants with enhanced oil content in leaves to improve the energy density of both forage and bioenergy crops, (4) plants capable of producing oils with unique and desirable properties or co-producing oils and specialty biofuels and bioproducts, (5) forage and bioenergy crops with increased biomass yield and digestibility, (6) microbes with enhanced stress tolerance, sugar consumption, and biofuel yield, (7) bacteria that can produce high quantities of desirable fatty acids, and (8) bacteria that can convert lignin into useful biofuels and bioproducts. In addition, new tools have also been

developed, such as one that enables high throughput genome editing in fungi. In many of these cases, the technology has already been licensed or optioned. Since 2007, GLBRC research and technology has led to over 100 licenses or options, highlighting the industrial relevance of our bioengineering work and the impact it is having on the economy.

2. How do you integrate ethical and security considerations into the design and conduct of your research? To what extent is ethics a focus of discussion in engineering biology classrooms and research labs? To what extent is security a focus?

Ethical considerations are an important aspect of the research design and implementation for all of my teams and collaborations. While we comply with all university, state, and federal rules and regulations, such as those related to the responsible conduct of research and the use and release of genetically modified organisms, we also carefully consider the larger picture. For example, to avoid competing with food production, GLBRC researchers focus on dedicated bioenergy crops grown on marginal lands (*i.e.*, non-forested lands not currently used for farming food). This is a conscious and deliberate decision made to ensure that the production of biofuels does not adversely affect our regional and national food supply or impinge on conservation areas. The use of marginal lands for the production of dedicated bioenergy crops, however, could theoretically result in increased water and fertilizer use; increased fertilizer use is especially problematic because of it can lead to reduced water quality and increased greenhouse gas emissions. To address these and related concerns, a significant fraction of GLBRC research is dedicated to understanding carbon and nitrogen cycling and water use in marginal lands, mitigating potential negative impacts, and ensuring the environmental sustainability of our bioenergy cropping systems.

We are also motivated by the ethics and long-term costs of *not* doing this research. To stand by while the climate continues to warm or to produce biofuels in an unsustainable way is also an ethical consideration. It is worth noting, however, that performing research that enables the sustainable production of bioenergy crops does not necessarily guarantee that they will be grown in such a fashion. Ensuring sustainability requires sound policy, which this subcommittee could influence.

Similarly, we give significant consideration to the plants and microbes engineered, especially those that might get deployed or released into the environment. Key questions considered include the possibility of engineered plants and microbes outcompeting native plants and microbes, and the likelihood and potential ramifications of genes inadvertently being transferred to other organisms. Fortunately, many of the engineered traits we are introducing (*e.g.*, increasing the energy content and ease of degradation in plants or funneling carbon and energy from cell growth to biofuel production in microbes) are expected to make these engineered organisms less competitive with native organisms in natural, unmanaged conditions, thereby significantly limiting the concern. Nevertheless, potential off-target consequences are carefully considered and researched as appropriate.

As a whole, faculty at large land-grant institutions, such as MSU, take the teaching and outreach mission of their institution very seriously. Part of this mission, of course, involves ensuring that students and the community are educated about the important ethical considerations of our research. In my own personal experience, when I discuss biofuels in the classroom, we consider not only the need for biofuels and bioproducts, but also the challenges associated with producing them in an economically

and environmentally sustainable manner. Ethical issues invariably arise, including not only the risks associated with engineering transgenic plants and microbes, but also the risks associated with doing nothing. As part of the GLBRC, I have also been involved both directly and indirectly with numerous outreach activities at MSU, explaining to the public what biofuels are, how they are produced, and how they can help both the environment and the community. Together with my colleagues, we explain what genetically modified organisms are and the different ways they can be engineered. When interacting with the public, my goal is to give them information that will enable them to make informed decisions about the risks versus benefits of using engineered biological systems.

3. **Are the nation's colleges and universities educating and training enough skilled technicians, scientists, and engineers in the field of engineering biology to maintain U.S. leadership in this area? If not, what recommendations do you have for additional actions by institutions of higher education, the private sector, and government?**

Interest in the biological sciences at MSU has grown steadily, as has the number of undergraduate majors. My understanding is that other universities are seeing similar trends. In addition, the number of teams participating in the International Genetically Engineered Machine (iGEM) competition (where students engineer organisms to perform a new function or develop tools to enable genetic engineering) continues to rise, with nearly 80 U.S. teams competing in 2018. Thus, students are not only interested in subjects related to engineering biology, they also want to get into the lab and perform research, applying what they have learned in the classroom to real-world problems.

This interest in hands on research can also be seen in the large number of applications to the many summer undergraduate research programs at MSU and other universities around the country. Competition for these summer research programs is typically intense. For many programs, including those that support the GLBRC, there are often far more qualified applicants than there is funding to support them. To help balance this mismatch, it would be helpful if the federal government provided additional new funding to help support these undergraduate research programs, including those that integrate both field and laboratory research. Meaningful research experiences that employ the scientific method help reinforce key concepts, teach critical thinking, and encourage creativity, thereby laying the groundwork for the skills and training needed for scientists, technicians, and engineers at all levels. Thus, investing in these relatively inexpensive summer research programs can significantly impact the quality of the future workforce engaged in engineering biology.

Another initiative that universities themselves could do to improve education and training in STEM fields is to increase emphasis on writing. The ability to express oneself clearly and logically is critical to the dissemination of results, the transfer of knowledge, and the exchange of ideas. In addition, clear writing encourages critical thinking. Simply put, communication is critical in science, but this is an area that is too often underemphasized at the undergraduate level. This is perhaps especially true at large universities, due at least in part to the expense of the one-on-one instruction necessary to train effective writers. Thankfully, I believe this is changing, and university science departments are beginning to put more emphasis on written and oral communication skills. This is encouraging, and I hope the resources are available to keep this trend going in the right direction.

4. **What recommendations, if any, do you have for improvements to the Engineering Biology Act? What additional recommendations, if any, do you have for Congress or for federal science agencies that fund engineering biology research, including any recommendations for improving interdisciplinary and interagency funding mechanisms?**

The proposed Engineering Biology Act has a number of key compelling aspects. Enhancing the country's competitive advantage in engineering biology by increased support for research and education and accelerated commercialization is vital. These fields are likely to continue growing in global economic importance in the coming decades. Likewise, obtaining a better understanding of the factors that lead to societal acceptance and adoption of new products, processes, and technologies based on engineering biology will ensure a steady consumer base. Increased coordination among the agencies under the purview of the House Science, Space, and Technology Committee will help accomplish these goals. This coordination could be especially powerful if expanded to include other federal agencies that fund engineering biology research, including the National Institutes of Health, the Department of Defense, and the U.S. Department of Agriculture. I am confident in the Committee's longstanding leadership in working to achieve this goal with the other committees that have jurisdiction over these agencies. As these discussions move forward, however, it is imperative that any new initiatives be supported with a commensurate level of new funding. In times of tight fiscal budgets, it is essential that both single-investigator and center-level efforts be encouraged. Single-investigator research encourages the creativity that has been the hallmark of U.S. innovation leadership and can lead to profound and unexpected breakthroughs. Center-level research provides synergies with similar benefits. It is important to maintain a healthy balance between these two broad funding models.

Thank you for the opportunity to appear before the Subcommittee. I welcome the opportunity to address any questions.

ERIC HEGG

Biography

“Engineering Our Way to a Sustainable Bioeconomy”

House Science, Space & Technology Subcommittee on Research & Technology Hearing

March 12, 2019

Dr. Hegg is a professor of biochemistry and molecular biology at Michigan State University (MSU). He received his B.A. in Chemistry and History in 1991 from Kalamazoo College and a Ph.D. in 1996 from the University of Wisconsin–Madison. It was during his time at Wisconsin that he became interested in metalloenzymology, studying the role of metal ions in enzymes that hydrolyze DNA, RNA, and proteins. After receiving his Ph.D., Dr. Hegg completed a National Institutes of Health postdoctoral fellowship at the University of Minnesota where he studied non-heme iron dioxygenases and established his long-standing interest in understanding how nature synthesizes and activates small molecules such as H_2 and O_2 . Following his postdoctoral work, Dr. Hegg and his family moved to Salt Lake City in 1999 where he joined the faculty of the University of Utah and began his independent research career. He received a National Science Foundation Career Award in 2004 and the Cottrell Scholars Award in 2002. When the opportunity arose, Dr. Hegg and his wife returned to the northern Midwest to join the faculty at MSU in 2006 where he is a professor of biochemistry & molecular biology and the MSU Subcontract Lead for the Great Lakes Bioenergy Research Center. In addition to studying heme biosynthesis and O_2 utilization, he is involved in developing renewable bioenergy, converting biomass into ethanol and other transportation fuels as well as using microbes to generate H_2 . Dr. Hegg has recently participated in two leadership activities at MSU. In 2016, he was a Big Ten Academic Alliance Leadership Program Fellow and in 2017, was an Academic Advancement Network Leadership Fellow. When Dr. Hegg is not busy in the lab, he enjoys running, hiking, and most outdoor activities.

Chairwoman STEVENS. Thank you. The Chair now recognizes Dr. Simpson.

**TESTIMONY OF DR. SEAN SIMPSON,
CHIEF SCIENTIFIC OFFICER AND CO-FOUNDER, LANZATECH**

Dr. SIMPSON. Thank you, Madam Chairwoman, Members of the Committee. My name is Sean Simpson. I am the Chief Scientific Officer and Founder of a startup biotech company called LanzaTech. We have developed and now commercialized a process that allows the conversion of wastes and residues into both biofuels and chemicals. Our process allows emissions from industry, wastes from society, and waste from agriculture to all equally be used in the production of fuels that reduce greenhouse gas emissions and increase local energy security.

The process is biologically based. We have developed organisms that use gases: Carbon monoxide, hydrogen, and carbon dioxide as the source of carbonate energy for fuel and chemical synthesis. This allows us to place a conversion facility at a steel mill and convert the wastes inevitably produced as a function of steel manufacture into a low-carbon fuel that displaces gasoline.

We have commercialized our process and now operate a facility in China where a waste stream from a steel mill is used to produce over 46,000 tons annually of fuel ethanol that enters the local market as a fuel additive. We currently have a number of commercial prospects. We are commercializing our process here in the U.S., in California, using agricultural waste; in Europe, using again a steel mill waste; in India, using a waste stream from an oil refinery; in South Africa, using waste from ferroalloy production; and in Japan, using municipal solid waste. In each case our biology converts these waste streams into fuel and chemicals that are used in everyday life.

Through the use of engineered biology, we are able to not only produce fuels but also an array of important commodity chemicals. By converting these waste streams in high volumes into commodity chemicals, we're able not only to add much greater value to the resources we can process but also achieve carbon capture and sequestration in everyday materials. Imagine a world where carbon can be captured and fixed into everyday plastics, rubbers, and other materials. That is the opportunity offered by engineered biology.

In our case, we've very excited by the prospects of this field and have invested heavily in the opportunity to leverage engineered biology technologies in order to not only improve the profitability but also the efficiency of our process. We're also enormously excited by the recognition given to engineered biology in the Act. One thing we would encourage, however, is that the Committee recognizes that not all resources that can be processed by biology come from a biological origin. We represent a process whereby we can take waste streams produced by industry that maybe start their life as coal but are used in industry to produce, say, steel that are emitted as a waste that can then be converted by biology into a sustainable fuel or a sustainable chemical. Thereby, we are able to achieve a degree of circular economic growth not only here in America but throughout the world through technologies developed here domestically by biological scientists.

With that, I'd like to thank the Committee and look forward to your questions.
[The prepared statement of Dr. Simpson follows:]

Engineering our way to a sustainable economy

Statement of :

Dr Sean Simpson (PhD)

Chief Scientific Officer, LanzaTech Inc.

Before the

Committee on Science, Space, and Technology

Subcommittee on Research and Technology

U.S. House of Representatives

March 12th 2019

1. Please provide a brief overview of your company and its technologies.

LanzaTech Inc is a Chicago-based start-up company pioneering the commercialization of a complete process platform to allow the continuous production of sustainable fuels and an array of chemical intermediates from gases at scale. Using a proprietary biological conversion technique known as gas fermentation, the LanzaTech process leverages local, abundant, low-cost waste resources as feedstocks. The technology has been successfully demonstrated using a diverse range of feedstocks composed of carbon monoxide (CO), hydrogen (H₂), carbon dioxide (CO₂), or methane (CH₄), including waste gases from industrial sources (e.g., steel mills, or refineries), syngas generated from any resource (e.g. unsorted and unrecyclable municipal solid waste or agricultural waste), or biogas. LanzaTech operates a licensing business model, offering customers a full process package having developed the process engineering, biology and chemistry of this waste valorization technology.

The first commercial plant demonstrating fuel ethanol production from gas residues produced by the steel industry was commissioned in China in May 2018. To date this plant has produced over 5 million gallons of low carbon ethanol from a waste stream from steel making. Further commercial plants are in design or under construction, including one in the US using biomass residues. To expand the product portfolio from these plants, LanzaTech has pioneered the development of synthetic biology techniques for genetic engineering of gas fermenting organisms. This capability has been reduced to practice by developing organisms capable of producing high value chemical intermediates such as acetone (used in the manufacture of acrylic glass), isopropanol (used for the production of polypropylene plastics), and isoprene (used in the production of synthetic rubber). Indeed, LanzaTech has used its synthetic biology platform to produce improved industrial microbes and demonstrate the production of over 50 valuable chemical intermediates from the low value high volume gas streams that can be accessed by gas fermentation. The commercial deployment of bacteria able to produce different chemical intermediates from gases paves the way for the

operation of “product flexible” conversion facilities that can switch between final products by deploying different bacterium in their bioreactors according to market dynamics.

2. Please describe your company’s history with federal funding, and any current partnerships with federal agencies, including through the National Laboratories.

LanzaTech has benefited from numerous partnerships with federal agencies since 2010. These have taken multiple forms: competitive grants and cooperative agreements awarded to LanzaTech or to our university and industry partners; direct funding to national lab partners for projects cost-shared by LanzaTech; and funding to consortia engaged in research relevant to our technology. Partnerships related to biological engineering have been funded by DARPA, DOE Bioenergy Technologies Office (BETO), DOE Office of Science, and ARPA-E. Example outcomes of these partnerships are fundamental knowledge of our microbe and the gas fermentation process, tools for high throughput genetic engineering of anaerobic bacteria, analytical and data mining methods and models to enable rapid development of pathways to new fermentation products, and demonstration of new processes such as acetone production from gases. Current partnerships include university-led research programs to develop new genetic modification tools and a Clostridia-based Biofoundry based on automation and cell-free tools, supported by BETO and DOE Office. Another group of partnerships is investigating ways to convert carbon dioxide into chemicals and fuels by combining electrochemistry with our gas fermentation. In more focused projects, we are optimizing the production of acetone and higher alcohols from gas streams.

Additional partnerships to develop bioreactor technology and catalytic processes that convert our direct fermentation products into downstream fuels and chemicals such as sustainable aviation fuel and butadiene have been supported by BETO, ARPA-E, DARPA, and FAA. In current partnerships, we are scaling up technology to produce sustainable aviation fuel from ethanol and supporting projects at Pacific Northwest National Lab to produce higher value products through catalytic conversion of ethanol.

3. What is the potential for engineering biology technologies across different sectors?

In every field in which biological processes are used, engineering can be used to improve these biological processes in terms of the efficiency of the process or the value of the outcome. Below we have provided a snapshot of engineered biology can play a role in various industry sectors:

- Transportation
 - Fuel Ethanol, Diesel, Jet, novel fuel blend components
- Materials (Commodity chemicals)
 - Textiles, Plastics, Rubber, Building materials, etc
- Household (Solvents, Specialty chemicals, Industrial Enzymes)
 - Detergents, Cleaners, Fragrances, Cosmetics, Coatings, Colors, Dyes, etc
- Nutrition (Proteins, Vitamins, Amino Acids)
 - synthetic meat and milk protein, Sweeteners, Vitamins, Amino acids, Omega-3’s, Flavors (e.g. Vanilla), Fish/Animal Feed

- Agriculture (Advanced crops, Natural products)
 - Advanced crops, Crop protectants, fertilizers, etc
- Medicine (pharmaceuticals, vaccines)
 - Antibiotics, drugs (e.g. Anti-Malaria), vaccines, antibodies
- Communication
 - Sensing/Detection/Memory, Communication/Electronics (e.g. Nanowires)

In manufacturing, biological processes can offer numerous advantages over traditional production strategies:

- More sustainable, fewer GHG emissions, using renewable and waste resources
- Avoiding hazardous effects on health and environment during production process
- Advanced properties, e.g. biodegradability, strength/durability (e.g. spidersilk)
- Potential for reduced production cost and security of supply

4. How can the federal government and universities best partner with the private sector to advance research and innovation in engineering biology?

Private companies can offer both a valuable commercial context and potential path to commercial application for innovative engineering biology technologies being developed in federal government laboratories and universities. Many technological developments in engineering biological systems have the potential to be applied in numerous industry sectors. This provides an opportunity for there to be multiple potential pathways to commercializing a mature technology development in this area of science. However, in the early stages of the development of such technologies, companies partnering with government or university research groups will necessarily take a significant up-front risk on the efficacy and value of a research project. Therefore, in-order to encourage the formation of these valuable early partnership events between companies and researchers in universities and the federal government, recognition should be made in terms of preferential or dedicated technology access rights within a given field of application.

5. How does LanzaTech integrate ethical and security considerations into your technology development plans?

Our company has developed and now commercialized a technology to biologically convert a range of gases into valuable fuel and chemical products. Workplace and environmental health and safety has been a priority for LanzaTech throughout our company's history. Not only do we follow and comply with all standard regulations and biosecurity rules from EPA, and OSHA, we also actively operate an in-house Health and Safety program / culture that places priority on early hazard identification and remedy as a strategy to mitigate the potential for more serious incidents to occur within the workplace.

The biological catalyst used in our gas conversion process is called *C. autoethanogenum* (*C. auto*). This biological catalyst has been well characterized on a physiological level and classified by the World Health organization (WHO) in the lowest risk group (WHO risk group 1), the same as Baker's yeast. *C. auto* is

non-pathogenic and unlikely to cause human or animal disease. As a strict anaerobe, it is unable to survive in presence of oxygen or in air. The strain developed by LanzaTech has further been selected on the basis that it is unable to sporulate.

In our lab we follow standard laboratory procedures in accordance to OSHA and EPA. We minimize release of organisms through sterilization and bleaching, and have stringent biowaste policies.

In a commercial setting, the bacterial culture would be contained in bioreactors that are designed to maintain a strict anaerobic (no oxygen) environment, which forms a primary, environmental containment for the organisms. In case of spills or leaks, process plants are designed with physical containment in the form of a dyke to contain any liquid spills in order that these can be properly treated before disposal. Waste treatment together with heat treatment are an integral part of the process, forming a third layer of containment.

We consistently and routinely screen all new genetic or other elements used in the development of our biological catalysts to ensure that they are in no way associated with or precursors to toxic or pathogenic agents. In this way we ensure that the products of our engineering biology program can be deployed without risk to humanity the environment or agriculture. To aid this screening the U.S. Department of Health and Human Services (HHS) issued the *Screening Framework Guidance for Providers of Synthetic Double-Stranded DNA*. This voluntary Guidance outlines the U.S. government's recommendations for screening double-stranded DNA to ensure that existing Select Agent Regulations (SAR) and Export Administration Regulations (EAR) are followed, to encourage best practices in addressing biosecurity concerns, and to reduce the risk that individuals with ill intent could exploit the application of DNA synthesis technology to obtain genetic material derived from or encoding Select Agents or Toxins, or agents on the EAR's Commerce Control List (CCL).

In accordance with the HHS guidance, the U.S. Department of Energy Joint Genome Institute (JGI) has developed a DNA screening pipeline (BLISS – Black List Sequence Screening) to screen all sequences that it synthesizes through its DNA Synthesis Science program. LanzaTech has incorporated the BLISS pipeline into its inhouse genetic research routines.

6. What recommendations, if any, do you have for improvements to the *Engineering Biology Act*? What additional recommendations, if any, do you have for Congress or for federal science agencies that fund engineering biology research?

We are very pleased to see that the Congress recognizes the importance of Engineering Biology, as reflected in the Act. Interagency cooperation will be a key to accelerating the development of this area. We have identified one area for improvement. New biological platforms, of which ours is just one example, can process a wide variety of wastes and residues into sustainable fuels, chemicals and materials. Not all of the wastes and residues derive from plants or algae, which are traditionally thought of as the basis for “biofuels” and “bioproducts”. Therefore, we recommend that the Act include language that references all technologies that have a biological component, either through biologically-derived feedstocks or biological processing, including biological carbon capture and storage.

In terms of recommendations for agencies that are funding engineering biology research, we recommend that programs be designed to promote industrial partnerships at the earliest stages of

research. The historical progression of research programs has been to perform basic research in research and national labs, which is then transitioned to industry for applications. Incorporating industry experience, expertise and awareness of applications needs into basic research projects will increase the effectiveness of the federal government's research investments and accelerate the uptake of research results. This will expand the benefits of these investments for the U.S. bioeconomy and increase U.S. leadership in biotechnology.

Dr. Sean Simpson is a Co-founder and Chief Scientific Officer of LanzaTech, a global leader in gas fermentation. Under Dr. Simpson's leadership, the company has developed and scaled a gas fermentation process technology and established a broad and unique patent portfolio covering all areas of gas fermentation, including fermentation processes and microbes, gaseous feedstock handling, and product and waste handling. Dr. Simpson has over 20 publications and 200 patents. He has received a number of awards including the 2015 US Environmental Protection Agency (EPA) Presidential Green Chemistry Award, the 2014 Sanitarium, NZ Innovator of the Year Award, the 2013 Kea NZ World Class New Zealander in Science Award, the 2013 Bio Spectrum Asia-Pacific Entrepreneur of the Year Award, the 2011 NZBIO Young Biotechnologist of the Year, and the 2011 Ernst and Young Entrepreneur of the Year, New Zealand.

Chairwoman STEVENS. Thank you. The Chair now recognizes Dr. Zoloth.

**TESTIMONY OF DR. LAURIE ZOLOTH,
MARGARET E. BURTON PROFESSOR OF RELIGION AND
ETHICS, AND SENIOR ADVISOR TO THE PROVOST FOR
PROGRAMS IN SOCIAL ETHICS, UNIVERSITY OF CHICAGO**

Dr. ZOLOTH. Chairman Stevens, Ranking Member Baird, and Members of the Subcommittee, my name is Laurie Zoloth. I'm professor of religion and ethics and senior advisor to the provost in social ethics at the University of Chicago. And I want to thank the Committee for asking me to testify about the ethical issues that arise in the research and the development of engineering biology and for inviting a scholar of religion and moral philosophy to your deliberations about science. Now, I'm going to describe the ethical challenges that will surely be a part of this research, but I want to say at the beginning of my testimony that I am very supportive of this basic science, intrigued by the stunning possibilities it will offer, and very grateful that your Committee is seriously considering what I believe is a very strong bill.

When researchers, however, talk about genetics, Americans begin to worry about probable ethical problems. The first are the usual questions that genetic alteration of any sort in the natural world raises. We have begun to think of our DNA as fundamental to our identity. It is in our DNA, is a common phrase to describe the values we think are a part of our being as Americans. So, any changing of this DNA code raises issues of what can be changed, who should decide, and who has control over the power to make such changes.

Now, you can point out, as many of you did, that humans have been breeding plants and animals for millennia and that engineering biology is not, in principle, different. But still, we like to think of nature as fixed, as perfectly in balance and even normative or morally good. And we worry about the threat of the sanctity of the natural world in this way or the essential dignity inherent to intact beings to whom we owe respect.

Safety concerns are also important. Are the projects safe when used as intended? How dangerous are they when used in unintended ways and how likely is that to occur? How likely are mistakes? If harm occurs, is it reversible? And genuine concern is raised around the issue of informed consent. When biological engineering projects are intended to affect whole populations or whole geographies, will the benefits and burdens be distributed equally within the population? And if not, will the benefits accrue disproportionately to those already disadvantaged and burdens to those already disadvantaged. And to the extent that those new technologies create burdens for some, will it be accompanied by offsetting policies, whether economic or social, that ameliorate those effects?

What distinguishes these technologies that affect the genetic structure of beings is how it alters the very biological technologies that affect our relationship to humanity itself and to nature itself. And Americans are committed to the idea of equality regardless of the situation of one's birth. And while we know that genetic lottery

can always be unfair, we don't want it to be fixed. We worry about imbedding the choices we make today across generations. And linked to this concern are basic ethical questions of justice, justice and the choice of research goals, in the way that test as hypothesis, and finally the distribution of the social goods that emerge from the research.

But a new sort of problem emerges when researchers talk about making entirely new *de novo* creations or making synthetic chemical versions of DNA or creating entirely new living entities, in essence, using a string of chemicals to make new life.

This is in principle different from altering already-existing organisms. Here we confront issues of mastery, control, and of course profound and unknowable uncertainty. And here as well, we're going to disagree on issues that can be fairly called ontological and theological.

Ought we to tremble when we cross such a threshold of human knowledge? Of course we should. Are we going to worry that we're going too far and too fast? Of course. But we have ways to ameliorate these questions.

Ethics asks the question, what is the right act and what makes it so? It's not a question that emerges from science itself. But in the past, ethicists have been asked to think about science projects. When the NIH proposed the mapping of the human genome, it gave 5 percent of its budget to work on the ethical, legal, and social implications of the Human Genome Project. And the ELSI (Ethical, Legal and Social Implications) Human Genome Project showed that scholars of humanities and law are very eager to think about science. What is needed now are incentives for scientists to understand humanities, law, and policy questions. Young scientists will choose the virtues that guide them very early in their careers and need to be sure that they see being honest and humble and just is part of what it means to be a good scientist. And this means they must study historical debates about ethics and learn the complexities of competing moral appeals. We also need to educate bioethicists, I might add, before they opine on the ethical questions that such science raises.

We need to regulate this research, and we need to figure out how to do that. All such research will have enormous impacts on the human future, and that's why we need the engineering biology we've heard today, for our future has serious challenges, a change in climate, a rising need for energy, and a growing, hungry population. And thus we need both new technologies and new social policies to regulate them.

We know our world is very closely connected in complex webs with the smallest form of life. And engineering microorganisms, new vectors for disease, all moving at the microscopic level, and all these can be critical to human survival.

Now, the National Academies have been able to structure some interesting new guidelines, but at stake is how they are enforced and the regulation. And consideration of whether and how engineering biology can proceed ethically cannot only be a discussion among academics or science experts because these big engineering projects are intended in many cases for widespread and self-sustained use. Community consent processes have to be regulated as

well. Ideally, mandated citizen stakeholder engagement should be part of every project that's publicly funded. And these engagement sessions should start at the beginning of the projects and should involve a wider reach than has previously been imagined, including members of trade unions, parent/teacher associations, rural communities, and religious and cultural groups.

I suggest that other countries have developed public discussions about this phase of their science and more structured leadership about ethics as well. Being a leader in engineering biology is a tremendous responsibility. It will mean leadership in ethical, social, legal, and environmental research as well as in science research. It'll mean creating a deep and sustained relationship with the larger international research community that already is frankly ahead of us.

In my testimony, I've recommended a few things, a new Ph.D. program in ethical decisionmaking, sources or moral appeals, the history of ethics and science needs to be funded along with programs for the science itself so the next generation of scholars in ethics can be trained.

Two, jointly administered Ph.D. and M.A. cohorts will train scientists in the humanities and social science and humanities scholars in science.

Three, funding for environmental impact studies in every project that propose any public use.

Four, public meetings to think carefully about projects that are more successful if we can expand our ideas about democracy and inclusion. Our American capacity for democratic decisionmaking can be an important part of our scientific leadership plan, but funding for widespread education and inclusion must reach far beyond the academy.

And finally, norms and regulations created by such forces as the National Academies must be supported by administrative regulations that Congress establishes, along with consideration to the creation of a national oversight committee, both in the early stages of research and beyond.

The economy, the environment, and the human world in which we live is shaped by biology, our history, our needs, our limitations, even our imagination. At stake is how we as a society will be able to respond to this new challenge, and when we respond, how we can do so with both courage and thoughtful humility. Other countries have already matured efforts both in engineering biology and in the public discussions about their use. Your efforts will be central to our American response.

Thank you for this bill, and for having the wisdom to support and the courage to lead.

[The prepared statement of Dr. Zoloth follows:]

United States House of Representatives Committee on Science, Space, and Technology

Testimony for House of Representatives Subcommittee on Research and Technology;
 “Engineering Our Way to a Sustainable Bioeconomy”
 March 12, 2019

The Ethical Issues in Engineering Biology

Laurie Zoloth, Ph.D., University of Chicago

Chairwoman Stevens, Ranking Member Baird and members of the subcommittee:

My name is Laurie Zoloth, and I am Professor of Religion and Ethics and Senior Advisor to the Provost on Programs in Social Ethics at the University of Chicago. I want to thank the committee for asking me to testify about the ethical issues that arise in the research and development of engineering biology, and for inviting a scholar of religion and moral philosophy to your deliberations about scientific research. While I will describe the ethical challenges that surely will be a part of this research, I want to say at the beginning of my testimony that I am supportive of this basic science research, intrigued by the stunning possibilities it might offer, and grateful that your committee is seriously considering what I believe is a strong and thoughtful bill to recommend funding and publicly supporting this research. I am particularly glad to see the inclusion of ethics education in this bill, and I will urge you today to extend that support still further.

Your talented staff has asked me consider four questions. I will address them one at a time.

1. What are the range of ethical questions around engineering biology and what funding is available to address these questions?

When researchers talk about genetics, Americans worry about a range of possible problems. The first are the usual questions about any genetic alteration of nearly any sort in the natural world. We have begun to think of our DNA as fundamental to our identity. “It is in our DNA” is a common phrase to describe values we think are a part of our being Americans. So, any changing of genetic codes raises issues of which can be changed, who should decide and who has control over the power to make such changes. Now, you can point out that humans have been breeding plants and animals for millennia, and that engineering biology is not, in principle, different. Still, we like to think of nature as fixed, as perfectly in balance, even normative, even moral, or morally good, and there are a series of questions raised about the threat to the sanctity of the natural world. In the type of engineering projects that begin with existing organisms and then altering them, or using them to perform different tasks, ethical concerns are raised about the uncertainty of outcome, or about the complex errors that have occurred in the past, or about the essential dignity inherent to intact beings to whom we owe respect.

Safety concerns are also important: how will engineering biology affect humans or animals? Are the projects safe when used as intended? How dangerous are they when used in unintended ways, and how likely is that to occur? How likely are mistakes and unintentional

releases? If harm occurs, is it reversible? Are there ways to minimize risks while preserving benefits to individuals and society at large? In 1972, when *e coli* were first altered in the labs of Stanford, Columbia, and the University of California, early concerns were raised about safety, fears arose about out of control mutations, perhaps leading to cancers, for example. Members of the public questioned then whether sophisticated weapons could be fashioned from these technologies, and as early as 1973, ethical discussions began about how to regulate early genetic alterations. Now, in 2019, concerns about more sophisticated engineering technologies are raised about safety, accidents and the possible use of technology for nefarious ends. Projects that use naturally occurring evolutionary phenomena, such as self-sustaining gene drives are intended to be released and then continue in the natural environment, and while this has the potential for remarkable effectiveness in controlling deadly vector borne disease, it raises new questions about human power, and human error.

Genuine concern is raised around the ethical issues of informed consent or refusal, when biological engineering projects are intended to affect whole populations, or whole geographies. Will the benefits and burdens be distributed equally within the population? If not, will the benefits accrue disproportionately to those already advantaged, and burdens to those already disadvantaged? And to the extent that new technologies create burdens for some, will they be accompanied by offsetting policies – whether economic or social – that will ameliorate these effects? These questions can be asked about advances in computing, robotics, engineering, neuroscience etc. What distinguishes technologies that affect the genetic structure of beings is how it alters the very biological identity of organisms, leading to concerns about its effects on how we define nature and the human place in relationship to that concept, and the permanence of the effects. Americans are committed to the idea of equality, regardless of the situation of one's birth, and while we know that the genetic lottery can be unfair, we do not want it to be a fixed game. We worry about embedding choices we make today across generations. Linked to this concern are basic ethical questions of justice, justice in the choice of research goals, in the way the project tests its hypothesis, and, finally, in the distribution of the social goods that emerge from the research. Will access be open, or will it be constrained by the market? These justice issues are all familiar concerns, arising across all scientific and technical research intended to address human needs. As in all such biotechnology, there are concerns about patents, profits and publication credit.

But a new sort of problem arises when researchers talk about making entirely new, *de novo* creations, making synthetic chemical version of DNA sequences for example, or creating entirely new living entities, in essence, using a string of chemicals to make new life. This is in principle different from altering already living organisms. Here, we confront issues of mastery, control, and of course profound and unknowable uncertainty, and here we will disagree on issues that can fairly be called ontological and theological.

Ought we to tremble when we cross such a threshold of human knowledge? Ought we to worry that we may be going too far or too fast? Of course, for this sort of power raises difficult questions about our human limits and obligations toward a world we might make, to know and to see things which were impossible to know or see a decade ago. Of course, we need to think soberly about the possibility that the research may fail utterly, or that it may

succeed but lead us into a place of great unpredictability—that is the very nature of research—that is what makes us both free and responsible.

Ethics asks the question: What is the right act and what makes it so? It is not a question that emerges from science itself, or within engineering, which ask questions, typically, about how things work. In the past, when NIH pursued the mapping of the human genome, it gave 5% of the budget to work on the Ethical, Legal and Social Implications (ELSI) of the project. “The National Human Genome Research Institute's (NHGRI) Ethical, Legal and Social Implications (ELSI) Research Program was established in 1990 as an integral part of the Human Genome Project (HGP) to foster basic and applied research on the ethical, legal and social implications of genetic and genomic research for individuals, families and communities. The ELSI Research Program funds and manages studies, and supports workshops, research consortia and policy conferences related to these topics.”¹ Similarly, the NIH and then the FDA housed the workings of the Recombinant DNA Advisory Committee (the RAC) which reviewed, initially, every funded clinical trial that used genetic interventions on humans. The National Academies have held a series of reviews about ethical issues on engineering biology, the human germ line research, and gene drives. Yet while the ELSI program allowed serious research on the ethical issues surrounding the mapping of the human genome, funding has been more limited for research on other biotechnologies.

2. How can scientists and engineers collaborate with experts in the humanities, law, and social science to integrate social, legal, environmental and other ethical concerns into the design and conduct of engineering biology R and D?

Engineering biology is a relatively new field, and it has, from its inception, been welcoming to other disciplines, seeking out scholars such as myself in ethics, in anthropology, in theology, law and policy and social science. The study of ethics and what the field calls “human practices,” a name given by an anthropologist, has always been integrated into an important educational project called iGEM which brings international undergraduate students to the United States to a competition of between their synthetic biology projects. The first academic research collaboration, called SYNBERC and current ongoing academic research collaborations such as the Engineering Biology Research Consortium, or Target Malaria, an international academic consortium for gene drive research have always included social scientists, ethicists and policy scholars. This has been largely informal, and largely unfunded—these projects are interesting, creative, powerful, and potentially vastly socially important—this attracts scholars from my field. Critical to the growth of the field and to America’s leadership will be the inclusion of scholars who will question the first assumptions of R and D, which is the selection of research targets, and the shaping of the research towards targets that aim to improve life for all of society.

The ELSI HGP showed that scholars of humanities and law are eager to think about science. What is needed now are incentives for scientists to understand humanities, law, and policy questions. Raising the ethical issues early in education will be critical. NIH grants typically mandate a course in human research protocols, but too often these are cursory. Much more needs to be done. Young scientists will choose the virtues that will guide them

early in their careers, and we need to be sure that they see being honest, humble, and just is part of what we mean by being a good scientist, and this means they must study historical debates about ethics and learn the complexities of competing moral appeals. We also need to educate bioethicists, scholars of philosophy, religion, law and political science for they need to understand science before they opine on the ethical questions it raises. Too often the debates about genetics and biology are reminiscent of science fiction movies, a danger if they are led by scholars without a serious background in science. Joint Ph.D. programs that admit young scholars in science and humanities at the same time would allow for a cohort of jointly trained scholars in the field and should be funded robustly.

3. Do we need any kind of governance for non-human, non-animal cell engineering biology R and D e.g. plant and microbial research? If so, what might that governance look like and who should develop guidelines?

Yes.

All such research will have enormous impacts on the human future (and that is why we need engineering biology) for our future has serious challenges - a changing climate, a rising need for energy, and a growing, hungry population- that need new technologies and new social policies. We know that our world is very closely connected in complex webs with the smallest forms of life. Emerging microorganisms, viruses, new vectors for disease all moving at the microscopic level, and all can be critical to human survival. The National Academies have been able to structure science guidelines with the help of directly involved scientists and scholars of ethics with open public involvement. At stake is who will enforce the guidelines, and for this, academic norms need to be supported—as they are in other countries—with state regulations. Protections for human subject research, IRBs, DSMBs and IACUCs are models of a norm-and-regulation-based system. One of the important strengths of the bill under consideration today is the structure of academic and regulatory oversight. Your committee should give consideration for how ongoing ethics oversight is a part of the proposed new office.

The regulation and consideration of whether and how engineering biology can proceed ethically cannot only be a discussion between academics or among scientific experts. Because these big engineering projects are intended in many cases, for wide-spread and self-sustained use, a community consent or refusal process needs to be constructed. Ideally, mandated citizen stakeholder engagement should be a part of every project that is publicly funded, and these engagement sessions should start at the beginning of the projects and should involve a wider reach than has previously been imagined, including members of trade unions, parent-teacher associations, rural communities and religious and cultural groupings.

4. What recommendations do you have, if any, for improving the *Engineering Biology Act*? What additional recommendations, if any, do you have for Congress or the federal science agencies that fund engineering biology research?

I would propose more robust and integrated consideration of ethical issues—how do we decide what to research and how the research is framed is also an ethical issue. Other countries have more developed public discussions about this phase of their science and more

structured leadership about ethics as well. Being a leader in engineering biology is a tremendous responsibility. It will mean leadership in ethical, social, legal, and environmental research as well, and it will mean creating a deep and sustained relationship with the larger international research community.

In my testimony, I have recommended:

- a. New Ph.D. programs in ethical decision making, sources of moral appeals, the history of ethics and science need to be funded along with programs for the science itself so the next generation of scholars can be trained.
- b. Jointly administered Ph.D. and MA cohorts that will train scientists in the humanities and social science, and humanities scholars in science.
- c. Funding for environmental impact studies with all projects that propose public use.
- d. Public meetings to think carefully about projects are more successful if we can expand ideas about democracy and inclusion. Our American capacity for democratic decision making can be an important part of our scientific leadership plan, but funding for widespread education and inclusion must reach beyond the academy.
- e. Norms and regulations created by the National Academies' processes and supported by administrative regulations, with consideration to the creation of a national oversight committee in the early stages of research and development.

The economy, the environment, and the human world in which we live is shaped by biology—our history, our needs, our limitations and our imagination. At stake is how we as a society will be able to respond, and when we respond, how we can do so with both courage and thoughtful humility. Other countries have already matured efforts both in engineering biology and in the public discussions about its use. Your efforts will be central to our American response. Thank you for this bill, and for having the wisdom to support and the courage to lead.

¹ www.genome.gov/10001618/the-elsi-research-program/

Biographic Summary: Laurie Zoloth, Ph.D.

Professor Laurie Zoloth is the Margaret E. Burton Professor of Religion and Ethics and Senior Advisor to the Provost for Programs in Social Ethics at the University of Chicago. She has a long and distinguished career as a bioethicist, scholar of religion, and of Jewish ethics, writing or editing 7 books, and over 300 articles. She has also served as Dean of the Divinity School at the University of Chicago.

She was a Charles Deering McCormick Professor of Teaching Excellence, and the Founding Director of Brady Program in Ethics and Civic Life at Weinberg College of Arts and Sciences at Northwestern University, and was the director of The Center for Bioethics, Science and Society at Northwestern University's Feinberg School of Medicine where she taught in the Medical Humanities and Bioethics Program, the Jewish Studies program and as of Professor of Religious Studies. From 1995-2003 she was a founder and Director of the Program in Jewish Studies at San Francisco State University.

She was elected both as President of the American Academy of Religion and as President of the American Society for Bioethics and Humanities. She was member of its founding board, receiving its Distinguished Service Award in 2007. She was a founder and vice president of the Society for Jewish Ethics. She was elected to the National Recombinant DNA Advisory Board in 2012. She served for two terms as member of the NASA National Advisory Council, the nation's highest civilian advisory board for NASA, for which she received the NASA National Public Service Award in 2005, the Executive Committee of the International Society for Stem Cell Research, and she was the founding Chair of the Howard Hughes Medical Institute's Bioethics Advisory Board. She has also been on the founding national boards of the Society for Bioethics and Humanities, the International Society for Stem Cell Research, The Society for Scriptural Reasoning, and NASA's International Planetary Protection Advisory Committee. In 2005 she was honored as the Graduate Theological Union's alumna of the year, and she has received distinguished teaching awards at Northwestern University and San Francisco State University.

Her book, Health Care and The Ethics of Encounter, on justice, health policy, and the ethics of community, was published in 1999. She is also co-editor of six books, Notes From a Narrow Ridge: Religion and Bioethics, with Dena Davis; Margin of Error: The Ethics of Mistakes in Medicine, with Susan Rubin; The Human Embryonic Stem Cell Debate: Ethics, Religion and Policy, with Karen LeBacqz and Suzanne Holland; and Oncofertility: Ethical, Legal, Social and Medical Perspectives. Published in 2010, with Teresa Woodruff, Lisa Campo-Edelstein, and Sarah Rodriguez, The John Evans Committee Report, with Carl Smith, Andrew Koppleman, Peter Hayes, and Jews and Genes, with Elliott Dorff published in 2015.

Chairwoman STEVENS. Thank you. Thank you to our expert panel and our witnesses who've joined us today. This is one of the privileges of this job, which is to bring forward your voices and your testimony.

At this point, we will begin our first round of questions. And the Chair recognizes herself for 5 minutes. In that vein, allow me to say that your expert testimony means a lot to our Committee and our work. As somebody who has a master's in philosophy and spent a lot of time in bioethics, it is certainly a delight to have a philosopher in the room helping manage some of the bigger questions and implications as it pertains to biotechnology.

Dr. Hegg, according to Dr. Carlson's testimony, biotechnology already makes up at least 2 percent of the total U.S. GDP, and it is expected to surge in the coming years. And we recognize what we need to do with the NAICS codes, by the way.

Areas that have greatly benefited in terms of job creation areas, meaning our regions across the United States, tend to be on the coast, San Francisco Bay Area and Boston. And not surprisingly, much of the academic research also tends to be concentrated in these areas along with engineering biology student populations that become part of the bioeconomy workforce. However, the needs and opportunities and brain power are significant across our Nation. What role, Dr. Hegg, can the Federal Government play in facilitating the growth and expansion of research centers and industry to other areas across our country including the Midwest?

Dr. HEGG. Well, I think that as I noted in the testimony that one of the most important roles the Federal Government can play is to continue to support basic research at multiple levels. I specifically talked about the undergraduate level and the importance of this hands-on research that students can obtain and the real-world knowledge that that can impart and how that can then be transferred to not only a thriving workforce but also one that has the skills necessary to compete in today's global economy.

At the same time, I think that increased level of support for basic research can also greatly impact graduate students, graduate studies. These are the people that go on and ultimately start their own companies, perform their own research, and lead to the technologies which are the beginning of new economic sectors.

So in short, I would say simply continuing to support basic research and especially understanding the role that the undergraduate as well as the graduate students play.

Chairwoman STEVENS. Thank you. And Dr. Solomon sort of mentioned this as well in his remarks, but I'd love to hear from you, Dr. Hegg, on how well-suited is our training infrastructure is in the United States to prepare the workforce for a sustainable bioeconomy?

Dr. HEGG. I think that our infrastructure is actually pretty good. I think we have the infrastructure that we need. I think we have a faculty, people who want to teach and who can do what we need to do.

What perhaps is lacking sometimes is the funds to support their efforts. And for a relatively modest investment, we can have a huge influence on the students, both undergraduate and the graduate level. We heard about IGEM, which is a really important program

and has continued to grow. And I now believe it has teams from over 80 countries. That is just one example of students who want to get into this field and who want to solve real-world problems.

So I think we have the infrastructure. We just need to make sure that we continue to support it so that it can live up to its potential.

Chairwoman STEVENS. Thank you. I have one last question but I also have something that I wanted to say which is as someone who spent their career in manufacturing innovation, focused on the skills gap, you know, certainly very inspired by the programs and the work that you all are leading from, you know, an early stage and some of the continuity that we need to see and workforce training.

I think if there's, you know—the last question I might have would be just around some deep thinking around any gaps that we might have in educational programming or development? Anything we might be missing in terms of workforce training, particularly if there are jobs going unfilled. We're all quite familiar with the demand and oftentimes the dogfight for technology talent. And it's multi-disciplinary, which poses some challenges. So if you have anything else to add on that, I'd certainly—we'd love to hear that.

Dr. HEGG. I honestly cannot think of any obvious gaps that we have. I think certainly at the large research institutions that I've been involved in, we're very broad and importantly, the technologies and the research that we're doing often impacts multiple areas. And you can see that for instance in some of the crops that we're working on. They can be important not only as bioenergy crops but also important for forage crops as well.

And so you can see these multi-use research opportunities, and I think we do a pretty good job. Thank you.

Chairwoman STEVENS. Great. Thank you. I now recognize Mr. Baird for 5 minutes.

Mr. BAIRD. Thank you, Chairwoman. And again, I appreciate this. My difficulty's going to be trying not to delve too deep in some of the conversations that we've had but I'll try to avoid that.

Dr. Solomon, you mentioned several potential applications for your research in the gut microbiome of cattle and other livestock. Could you elaborate on that? Because I'd like to, the next step after you discuss the process, then I want to know what kind of challenges you foresee in translating your research into products and solutions.

Dr. SOLOMON. So just to recap, I work with microbes that we can find in cattle, sheep, and other ruminants and hindgut fermenters. What they do is they break down the ingested plant material and help other microbes digest that in a way that allows them to provide nutrition to the host animal.

They also produce a number of compounds that essentially control which microbes are present, and what they do and the specific identities of those microbes and how many of them there are lead to have an impact on how healthy an animal will be. And so my research tries to understand this and tries to understand how to control this.

Specific challenges that I see is that as we've discussed right now, the implications of that research, at least from that dimension are very clearly agricultural. However, the way that our funding

system is set up, for example, different agencies, they tend to prioritize technologies at different levels of readiness. And so fundamental basic science such as this can be difficult to fund in this environment.

And so trying to have a more coordinated framework that has an eye toward these more long-term outcomes I think would be very beneficial.

Mr. BAIRD. Thank you. Second question would relate to gene editing and the gene editing technology. This is for you, too, Dr. Solomon. I'm sorry about that but anyway. And it relates to cross-breeding and hybridization techniques that we've used for years in agriculture. So how does that relate to what we're doing with this gene editing technology in your view?

Dr. SOLOMON. So what I think gene editing allows us to do is that it allows us to do these things more effectively and more rapidly than we've ever been able to do before. I think in the past, biological research has enabled us to do these things in a controlled fashion. However, at the end of the day, you get what you get. With the techniques that we have available to us, we can actually custom print DNA sequences, and we can actually do this with such precision that these advances can happen in a matter of weeks, months, as opposed to years which is what has happened in the past.

Mr. BAIRD. So we're running close on time. So the one last question, if I may—

Chairwoman STEVENS. Certainly.

Mr. BAIRD. I might have each one of you respond briefly to the idea that the United States and Europe does have some differences in terms of their interpretation of regulations and policies relating to biotechnology. Could you just quickly give us a feel for that, how that might impact some of the products that we could produce from these processes?

Dr. CARLSON. Well, just to start, it will have an impact, and certainly some of the companies that we have invested in are seeing a more challenging regulatory environment in Europe than in the United States. And that's of course because the precautionary principle is built into the European Union's fundamental structure. And they have to be cautious. They have to move very slowly. And that will impact our ability to sell to them, but also it will slow them down. You know, there are companies leaving Europe simply because they can't get anything done and have no hope of selling what they make there.

Mr. BAIRD. Thank you. Dr. Solomon?

Dr. SOLOMON. I mean, I'm not sure I have much else to add beyond what Dr. Carlson said, other than—I think in this new and exciting space, I think that we have not agreed on what definitions are. And so for example, if we take GMO (genetically modified organism), what would be GMO and safe in the U.S. might not be GMO and safe in Europe and vice versa. And I think until we harmonize and agree on those definitions, there's always going to be some friction as to what can and cannot be sold.

Mr. BAIRD. Dr. Hegg?

Dr. HEGG. I think one of the most important things that we can do to help alleviate this problem across the globe is to continue to

provide the information that people need to make informed decisions. And I think that's where higher education can be critical. And so I think we need to continue to do it here in this country and I think it also probably needs to be done for instance in Europe as well. I think many of the decisions that are being made are sometimes made by people who are ill-informed about the subject matter at hand. So I think education will be critical across the globe.

Dr. SIMPSON. While there are clear differences in terms of opinion and legislation regarding genetically modified organisms between Europe and the U.S., the area that actually impacts us as a company commercializing biotechnologies, is for example regulations around what constitutes a renewable or low-carbon fuel. For example, in the U.S. the renewable fuel standard dictates what a biofuel may be produced from. It basically says that it has to be made from a plant material. In Europe, rather than dictating what a fuel should be made from, legislation now seeks to define what the outcome of the production of the fuel should reflect, i.e., a degree of carbon reduction or carbon emission reduction.

And so now in the U.S., legislation in this field is somewhat dictatorial in terms of defining what resources can be used, and in that sense, in my view, is somewhat anti-innovation because it takes away the power of innovators to develop new ideas with new resources to achieve the outcome that I think legislators had in their mind. Whereas in Europe, the legislation is somewhat more technology-agnostic and so is leaving the field more open for innovators to develop new ways to harness available, lost-cost resources for the production of renewable or low-carbon fuels. Thank you.

Dr. ZOLOTH. There are two reasons why it's a different climate in Europe. One of them is the precautionary principle that grew out of German romanticism and German idealism that says don't do anything unless you can prove that it won't make the world worse. And Americans don't like that principle. American philosophers are pragmatists, and we think that the way that things are now is also bad. And so making an improvement is just a matter of going forward, in either a world with improvement or a world without. So we use a risk-benefit analysis, a very different kind of philosophy.

But additionally, Europe is tremendously affected by the Shoah, the Holocaust, where the German scientists, who were in the lead especially in the chemical industry, saw their, despite their technological prowess, they were ethically bankrupt. And of course, that tragedy means people are very cautious, especially in the E.U. in general and German as leaders in particular.

Now, the U.K. in looking at this sees the E.U. environment as so potentially restrictive that the House of Lords had a committee hearing very much like the one you're having here today, that worried about this same question. How can the British scientists move forward when they're very close to a restrictive atmosphere in Europe? And the same conversation happens in the U.K. as it does in the United States relative to the much more restrictive environment in the E.U. And that's played out in terms of the use of

GMOs, GMO crops, which have been banned in many cases in the E.U. and their trading partners but not in the United States.

So that comes at a very different history, and I think that history is something we can build on.

Mr. BAIRD. Thank you. I yield back.

Chairwoman STEVENS. The Chair now recognizes Mr. Foster for 5 minutes.

Mr. FOSTER. Thank you, Ms. Chairman, for having this hearing. There appear to be two major threads in bioengineered products. One of them is low-valued fuels which will rely importantly on things like a carbon tax, price on carbon emissions. The second one is unique, high-valued products. As an example of this, I think of Dr. Carlson's testimony. You were talking about a modified PMMA (polymethyl methacrylate) with better properties than normal Plexiglas that might uniquely be able to be produced through biochemical means.

And so my questions there is I guess first to Dr. Simpson. Assuming you have an optimal price on carbon emissions rather than one targeting specific crops, what is the range of the price on carbon to which the state-of-the-art in biotechnology would allow you to be commercially viable with a simple carbon price alone? How close are you right now?

Dr. SIMPSON. So right now, we are operating commercially in an environment where there is no price on carbon. So we produce fuel ethanol in China. There is no price on carbon in China, and we're able to operate entirely viably. The plant that we constructed has a 3-year payback period. So this allows us—because of the inputs we're able to leverage are themselves very low cost. Our advantage because they are low cost, they are non-commodity, and they're found in a single location. They're not food, and they're essentially industry waste with no other value other than to be burned as power. We're able to produce—

Mr. FOSTER. Oh, so they're not for example just pure carbon dioxide? They have a significant energy content in carbon monoxide or hydrogen or similar.

Dr. SIMPSON. Exactly.

Mr. FOSTER. OK. So that those are not going to be available on as wide a scale as carbon dioxide would be, for example?

Dr. SIMPSON. Carbon dioxide is certainly available in extraordinarily high volumes. But carbon dioxide can also be leveraged in the context of technologies like electrolysis which would allow you to produce hydrogen from, for example, sustainable power to leverage carbon dioxide. However, I would say that the resources that can be converted into carbon monoxide and hydrogen are broad and widely available.

Mr. FOSTER. Do you have an estimate of what fraction of carbon emissions could be—if you could capture 100 percent of energetically viable carbon emissions—

Dr. SIMPSON. Certainly. So if we—

Mr. FOSTER [continuing]. What fraction is that?

Dr. SIMPSON. If we were able to capture, for example, all the emissions from the steel industry, all the emissions from refineries and convert all available agricultural residues, we estimate that we could produce over 700 billion gallons of fuel annually.

Mr. FOSTER. And what—

Dr. SIMPSON. To put that into context, the current global production of fuel ethanol sits around 26 billion gallons. So this would allow us to displace something like 33 to 35 percent of global transport fuels using emissions or wastes from industry, society, and agriculture.

Mr. FOSTER. And so I guess Dr. Carlson, can you say a little bit about the outlook for specialty chemicals that are uniquely provided by biochemical means?

Dr. CARLSON. I can. It's spectacular. One thing that I didn't point out during the first part of my testimony is that roughly \$100 billion in biochemicals are already out there in the market. That's somewhere between 1/7 and maybe a quarter of the total chemical sales in the United States. So already biochemicals are a massive contributor to the chemicals industry, and we just don't know it because we don't measure it.

I'd really like to have a better understanding of what that number is because those are chemicals that are as best I can tell just already out-competing petrochemicals on price and performance. And then as we learn to better engineer materials—whether that's concatenating unique unichemical operations that enzymes can perform naturally to make new chemicals or as our company is doing now to design enzymes that have never existed before that create chemical operations that have never existed before to manufacture compounds in biology that have never existed before but that have been sought for quite some time—the world is going to start to look very different.

So the set of chemicals that we can make right now using synthetic chemistry is actually quite small compared to what we'd like to make, and the universe opens up as we learn to make those using biology.

Mr. FOSTER. Yes. And I guess one of the things that's opening that up is the whole CRISPR-Cas9, you know, revolution. I guess I'd like a shout-out to the—tomorrow we're going to have Jennifer Doudna, the inventor or the co-inventor of the CRISPR-Cas9 system here in Congress for an R&D caucus briefing to staff members. So any staff members interested, it's I think at 10:30 tomorrow, along with the Biophysical Society having that.

And if I could just close quickly, the whole issue with human genetic engineering is something that has been—I think we had our best-ever attended hearing of the Science Committee when we brought up—we had Jennifer here to talk about human genetic engineering. I think it was ironic that the National Academy study, the second one, was the venue at which the Chinese announced that they had genetically engineered a child. So this has gone from sort of fringe speculation to something that exists that we have to deal with.

So I guess, if I could ask you one question, is there any alternative to very intrusive international regulation to prevent the abuse of things like human genetic engineering or, you know, bio-weapons?

Dr. ZOLOTH. Genetic engineering for reproductive purposes and bioweapons are two different kinds of discussions. But I can just say that nearly everybody else on the planet, except for one rogue

scientist in China, was abiding by a very carefully constructed moratorium crafted by the National Academies of three countries. And that moratorium was honored but not fully understood, clearly by this man. And so we have yet to see those babies. So it's unclear how real the story is. But let's just say it is. He was promptly disciplined by and carefully disciplined by the scientific community of China and the ethical community of China.

So it did show that if you violate the moratorium, there would be significant repercussions. And people who gave him advice are also being reviewed very, very carefully and strong sanctions will be taken I think in those cases and certainly strong academic approbation will be directed to the people who gave him that terrible advice or didn't disclose what he was doing.

Is there anything to prevent this? Reproductive uses of CRISPR technology always needs a woman to agree to become pregnant to give birth to a child at tremendous risk. There's no way to do that safely. There's no way to construct a phase one clinical trial with safety. And so ethicists have long opposed this so safety standards could be demonstrated much more carefully. And that's a long way off.

For biotechnology for weaponry is a much more sobering discussion. I know Dr. Carlson has spent a lot of time thinking about that. We want scientists to be good not only technically, but morally. My job as an ethicist is to train them to know that you ought never do harm with your science and that every gesture of science is a profound moral gesture as well as an interesting scientific gesture. And it's my hope, my fond, optimistic hope, that if you train someone to be moral and ethical and responsible and responsible to his or her colleagues as well, they would never think about using their technologies for nefarious purposes. But these are powerful technologies, and they're self-sustaining. And careful consideration has to be put in place in addition to ethics training for the regulation of those technologies.

Mr. FOSTER. Yes. And unfortunately, I think one of the lessons I take away from computer viruses is that everything bad that can be done has been done with computer malware. And the fact that there's a very small footprint for these laboratories now and shrinking footprint is a cause for concern. You know, I urge all of my colleagues to have the classified briefing on the technology.

And I am past my time so if—all right.

Chairwoman STEVENS. You can do a second.

Mr. FOSTER. OK. So we're having a second round?

Chairwoman STEVENS. Yes.

Mr. FOSTER. Great. Wonderful. Yield back.

Chairwoman STEVENS. Yes, we'll go. We'll do it. The Chair now recognizes Mr. Gonzalez for 5 minutes.

Mr. GONZALEZ. Thank you, Madam Chair, and thank you everybody for being here today. I'll get to you, Dr. Carlson. I have a similar line of question. I saw your hand up.

So just thank you everybody for being here. The topic discussed today is of great importance to Northeast Ohio. I share Madam Chair's sentiment that we need more science and technology development in the Midwest where I'm proudly from. Research in the polymer sciences has allowed the University of Akron to become a

world-renowned institution in this field. From the invention of cheap spectrometers to measure the amount of nutrients responsible for algae growth in local water systems like Lake Erie to development of materials to preserve proteins in medicine, these are just two examples of the incredible research and development that the University is conducting but very important.

So when I think of these technologies, I kind of think of three things or three questions essentially. One, are we leading? Two, how quickly can we commercialize? And then three, how are we on security and maintaining standards across the world?

First, Dr. Simpson, before we get into the bioweaponry, carbon capture. Can you talk briefly about sort of what percent of carbon you are able to capture and repurpose? And then how your technology has developed over time, so kind of when I started it looked like this and now we are able to do the why if that makes sense.

Dr. SIMPSON. So when we started our company in 2005, at that time our technology literally existed in a test tube. And over the intervening years we've developed not only the biology but the engineering allowing gas fermentation and now offer as a commercial package, a full industrial process allowing the conversion of carbon monoxide, carbon monoxide-hydrogen, and carbon monoxide-hydrogen-carbon dioxide gas streams into fuels and chemicals. What does this mean physically? It's a facility that literally is like putting a brewery on the back end of—for example a steel mill comprising multiple reactors that stand around 100 feet high and several feet in diameter in which gases are converted microbially to, in the first instance, fuel ethanol, but subsequently we'll be able to produce chemicals in those same facilities.

In terms of percentage of carbon, it really depends on the input gas. The more hydrogen we have in our gas, the more carbon in that gas stream we fix. For example, we are now constructing a facility that converts a waste stream produced by an oil refinery in India. In that process, 50 percent of the carbon in the product comes from CO₂. At a steel mill, there is no hydrogen. Our process simply converts carbon monoxide into fuels and chemicals. And in that case, we convert carbon monoxide.

Mr. GONZALEZ. Got it. And then you mention carbon doesn't have a price in China. And quickly, if we did price carbon, what would that do to your business model?

Dr. SIMPSON. That would greatly accelerate our business model, I'll say that. I mean, just to be clear, one cannot raise money on legislation that doesn't exist.

Mr. GONZALEZ. Right.

Dr. SIMPSON. So as a company, we are commercializing a process to build commercial, commercially viable plants today in the current legislative environment, and we are without reliance on a carbon tax. A carbon tax would be a wonderful thing for this entire industry, but we cannot raise money on that and we are not commercializing our process on the basis of its existence.

Mr. GONZALEZ. Got it. And then switching to Dr. Carlson, so it looked like you had your hand up on the bioweaponry. I just want to turn you loose. So what were you going to say? Go for it.

Dr. CARLSON. Well, I was going to observe that science is a human enterprise full of humans, and humans are going to do ev-

everything they have in science that they've done throughout history. And they're going to make bad decisions. They're going to misuse the technology.

My read on what happened in China is that the approbation was not uniform. There was some celebration by parts of the government before other parts of the government shouted them down. And I think what I want to observe there is that whatever standards we think we hold ourselves to are not the same standards, not the same decisionmaking processes that other countries have. And they're going to go off on their own because they can.

Mr. GONZALEZ. Yes. Thank you. I tend to agree. When it comes to these sorts of technologies, I share that sentiment. Sure, there were some who later on maybe said, hey, we shouldn't have done this. Frankly, I don't believe that's something we can trust and put our faith in going forward. So I yield back. Thank you.

Chairwoman STEVENS. It's clear the Science Committee is the best-kept secret in Congress.

Mr. GONZALEZ. It's true.

Chairwoman STEVENS. And with that, the Chair would like to recognize Mr. Tonko for 5 minutes.

Mr. TONKO. Thank you, Chairwoman Stevens and Ranking Member Baird, for hosting this discussion. I think it's so very important. Congratulations to you, Chairwoman Stevens, on assuming this leadership of a Subcommittee that bears great relevance to the strength and future of this country. And to the panel, what a great group of individuals who are sharing great intellect. So thank you for joining us today.

Bioscience and biotechnology are exciting fields that offer the promise of life-changing applications across many fields. The Federal Government is uniquely positioned to lead the way in investing in high-impact research and partnering with universities and industry to innovate. These fields are moving forward in exciting ways in my district. For example, the NSF funded a research experience for undergraduates at Rensselaer Polytechnic Institute, RPI to most of us. That allowed RPI to engage a diverse cohort of students in bioengineering and biomanufacturing research projects with an intellectual focus on engineering, biological systems, and biomanufacturing related to biomedical, chemical, and/or biological engineering. This integrated training experience guided undergraduate students recruited from underrepresented groups from non-research-intensive schools through a research project while also helping them understand how they could pursue an engineering career. I'm also proud to have RPI part of the National Institute for Innovation in manufacturing biopharmaceuticals, a public/private partnership to advance U.S. leadership in biopharmaceuticals. This partnership, led by the University of Delaware, is advancing U.S. leadership in the biopharmaceutical industry fostering economic development, improving medical treatments, and ensuring a qualified workforce by collaborating with educational institutions to develop new training programs matched to specific biopharma skill needs.

The Federal Government should continue these critical investments that strengthen our future workforce while also funding important research in these fields. We must not let the U.S. fall be-

hind in our commitment to lead in scientific exploration and technology development or risk taking a back seat to nations which do make such innovation a top priority.

So to any and all on the panel, one synthetic biology breakthrough that got a lot of attention 2 years ago is synthetic spider silk, which researchers at the University of Cambridge created to mimic the strength, stretchiness, and energy-absorbing capacity of real spider silk. The same year a California-based startup called Bolt Threads debuted its own bioengineered spider silk men's tie. They now sell an entire clothing line. They started, by the way, with SBIR (Small Business Innovation Research) funding from the National Science Foundation.

What's the most unexpected or most weird application of engineering biology that any of you has encountered?

Dr. CARLSON. Well, there are many of them, actually. And I could, you know, go on for hours. I don't think you want me to do that here but—

Mr. TONKO. Yes, just a sampling, if you could quickly.

Dr. CARLSON. I'd like to just shout out to the Microsoft digital DNA information storage project that I am fortunate to work on as a consultant. So rather than storing information on magnetic tapes or CDs or in flash drives, that will soon become impractical given the amount of information that we're generating on a daily basis and need to store, whether it's photographs or government records or, you know, your Facebook profile, whatever that may be. And we need something else. And it turns out that biology has provided us with a beautiful and perfect storage media, that is, DNA. We can now read and write DNA. When they asked me to join this project, because I had been around for a while and I know some things about reading and writing DNA, and the economics and the pace of that, I thought it was a bit of lark. I thought, sure. It's a nice consulting gig and you know, I'll learn some things. I can hang out with some smart students. A couple of years later, it's going incredibly well. It's moving very rapidly, and I'm convinced that we not only will do this, we must do it. We will be changing our entire data storage industry over to look something like biology because it works. And you know, an entire data center storing a good fraction of the internet can be the size of a sugar cube of DNA. And that is opening my mind to all kinds of new applications because we can also now compute directly on that DNA using other molecules which has been a goal, sort of a science fiction story for a long time. But it's now a reality in that group. And I'm having trouble, you know, even just conceiving of the limits of that once we get it going.

Mr. TONKO. Madam Chairwoman, can I just ask that the other four just give us an example, please? I'm out of time, but I would love to hear from them, please.

Dr. SOLOMON. OK. So an example that I think is really fascinating, as of now I'm not aware if it's actually been commercialized yet, but there's been some talk about using plants as sentinels in public spaces. And so for example, we're increasingly faced by a number of threats, both biological and explosive. However, plants have an ability to naturally breathe and respire. And so they can sample—they beautify public spaces. They can sample the

air, and they can sample these particles. And in some cases, they can actually tell us if a threat is possible.

I think it's amazing to imagine that you could walk in the airport and rather than going through the very elaborate TSA screening that you go through right now, you just walk by a tree. It makes the space look beautiful, and if there's something wrong, it will alert you.

That's one of the more wacky things that I think I've come across.

Dr. HEGG. I don't know if I would—it's certainly not wacky but it certainly impresses me a lot and that is trees, again, keeping on that theme. These are trees where lignin, which is a structural polymer of the tree, has been engineered to break down very easily when under certain conditions. And so it still holds its structure and the tree is still happy and healthy. Except when we put it under certain conditions, then this complex polymer can break down easily into its components which can then be—not only then does that release the sugars and allow us to make fuels but also the lining itself can be used to make various polymers or fuels as well. And this has applications not only in obviously the biofuels but also in the pulp and paper industry.

Dr. SIMPSON. One area that I've always been fascinated by is the ability of biology to accumulate the things that it requires for life as it goes through environments and how we can use that to recover and recycle material. So there are now companies that use the ability of microbes to adhere or absorb specific high-value elements, like platinum or gold or others to actually recover the precious metals from electronic waste. So going forward, when one discards a phone, those printed circuit boards will be ground up and the precious metals contained therein will be recovered by microbes that have the specific ability to I guess attract those metals so that we can recover them and recycle them and reuse them.

Dr. ZOLOTH. So one serious and one amusing example. So the serious one is that the most rapidly growing disease is dengue fever. And malaria, for instance, that we had been able to address malaria and change the death rate from 1 million a year to 1/2 million a year has stalled. And the reason these diseases are hard to fight is because we're using 19th century tools, right? So there's nothing—bed nets are failing a little bit. The vaccines were hard to do. But genetically engineering mosquitos so that the population changes holds enormous potential for very intractable diseases. These are called gene drives. And I'm very interested in them because they have tremendous, interesting ethical issues. But also they could really transform how these intractable diseases can be addressed.

And why this is important for Americans is because the climate's changing. In a city like Los Angeles, my hometown, Los Angeles, or all of Florida has a lot of mosquitoes and has anopheles mosquitoes which do carry malaria, right? So malaria used to be one of the leading causes of death in this country, and we managed to eliminate it with 19th century tools, 18th century tools. Now we're going to need 21st century tools, and these genetically engineered mosquitoes represent that kind of impulse.

And the funny example is about cotton. You know how bread mold makes a gray, furry sort of mat on your—but if you could transform the yeast as the French have done and put in a little genetic cassette that makes the fibers cotton instead of furry gray stuff, you can make sheets of cotton. Cotton's a very difficult crop to grow. It's a big plant, small, little tufts, and it uses 50 percent of all the water used in agriculture. But if you could make cotton in sheets by yeast instead of in plants, you could save enormous amounts of water. It would be better for the environment. And they make very pretty clothes, I must say.

Mr. TONKO. Thank you, Madam Chairwoman. I guess what appears silly or far-fetched at times can bear great relevance. With that, I yield back.

Chairwoman STEVENS. Absolutely. Thank you. The Chair would now like to recognize Mr. Marshall for 5 minutes.

Mr. MARSHALL. Thank you so much, Chairwoman. You know, as a biochemistry major from the Big 12 basketball champion, Kansas State University, this biotechnology is always quite intriguing to me. And perhaps nothing has been more impacted than the ethanol and biofuels industry. So it's certainly something I've kept a close eye on.

I'm amazed what we can do today. We can grow a bushel of corn with 40 percent less land and 50 percent less water than we used to. And I'm impressed the impact that ethanol has made on the United States. We've decreased greenhouse emissions by about 43 percent. We have the potential to decrease it by 76 percent. Cellulosic fuel has the potential to decrease greenhouse gas emissions by 100 percent. I've been told that it's the equivalent of removing 124 million cars from the road. So I'm pretty proud of what the ethanol and the biofuels industry has done.

But despite this, there seems to be barriers for ethanol coming to the market. And I'm just wondering if anybody on the panel can speak to that? Dr. Solomon, you have any comments on why we have access problems for the biofuels?

Dr. SOLOMON. So I can only speak to the technical challenges. I think one of the barriers for cellulosic biofuels is just the cost of breaking down raw plant material into sugars that we can then ferment into ethanol. And I think as the price of oil has dropped, that has become even less competitive than has been in the past, which is why you're seeing a slow-down in uptake. And that is part of what my research tries to address. I mean, the same microbes that provide nutrition to animals, they are also the same type of organisms that actually break down these materials. And they provide the enzymes to do so.

And so for my part, what we're looking at is trying to understand how these unique microbes that we have, how they do it better than the current existing technologies do. And we're developing approaches to actually manipulate them. So rather than complex bioprocessing, where we have a cost associated with breaking down lignin cellulose and then the cost with upgrading it, can we get some efficiency by combining those two steps in a single organism? Can we engineer the one organism—

Mr. MARSHALL. Sure.

Dr. SOLOMON [continuing]. To go directly from grass to fuel rather than having to essentially take out the middle man?

Mr. MARSHALL. Dr. Carlson, any thoughts on some of the barriers to market?

Dr. CARLSON. Well, I think there are several. One is ethanol is a complicated molecule to dump into an engine. And so even though lots of engines today are supposedly flex fuel and can handle ethanol, it's the wrong kind of solvent is the right way to say that, I guess. And if you look at Brazil's experience, you know, they are people who like to drive 100 percent ethanol cars and people who like to drive 100 percent gas cars. But it's hard to mix those two very effectively on a day-to-day basis. So that's nothing to do with ethanol manufacture. It has everything to do with the way cars work. So that's one thought.

And then another, again, back to the oil price, is that there are certainly months now, if you look at the month-to-month fluctuations in the cost of corn and the cost of ethanol, the price of oil where it costs more to buy the corn to make ethanol than you can sell the ethanol for, which is a problem we can't solve by making better ethanol from corn just because corn costs so much. But I would observe that what I hope happens in the future is we shift from making ethanol to higher-value compounds. So we use something like 30 percent of our corn crop in the United States for industrial use, one way or another. A lot of that's ethanol which sells for give or take a buck a gallon, a buck a liter maybe, somewhere in that range. Wouldn't it be nice if we had technology that could upgrade that to something that's sold for \$10 a liter or \$100 a liter? So that's getting more toward that \$100 billion in biochemicals that those are higher-end chemicals rather than competing at the low end of the barrel, as ethanol does with fuel. So my recommendation would be, you know, as part of the bill to really think about how to facilitate the use of crops that right now are commodities. We're great at growing those in the States as you say. But rather than aim the product at, you know, something that's a commodity, low end of the barrel, aim it at something that's much more useful for higher-value products.

Mr. MARSHALL. OK. I've got 20 seconds left. I guess I'll yield back the end of my time. Thank you.

Chairwoman STEVENS. Thank you. We're now going to move into a second round of questions. So the Chair is going to recognize herself again. And the question is for Dr. Carlson and Dr. Simpson. To sustain job creation and U.S. leadership in the bioeconomy and our innovative biotechnologies, we must look to protect against forced technology transfer, industrial espionage, and theft. And as Dr. Carlson and others have noted, a number of other nations have launched sustained and effective efforts to build their own bioeconomies and biotechnology transfer activities.

In the meantime, tensions have flared between the U.S. and China in particular regarding trade policies and intellectual property protections. The U.S. has benefited historically from scientific collaboration, even with some of our adversaries. And there remains legitimate concerns that an overly protectionist approach might also hinder innovation.

So what should the U.S. Government look to do to strike the right balance between protecting the fruits of our innovation while also supporting the growth of industry?

Dr. CARLSON. Well, I'd like to answer that question two ways. The first is to look back to a report on how the internet developed and how the funding for the internet developed called Funding a Revolution. That was a National Research Council study many years ago. And it broke down where the money came from to build products that wound up in the world. And there were roughly three buckets' worth of funding. One is research, one is development, and we'll call the other one productizing. And research, fundamental research, is about 1 percent of the contribution of the final cost or the final total investment. The development showing that it can become a product is about 10 percent. The other 90 percent is the hard work of basically putting it in a box and turning it into something that somebody wants to buy and use.

I'm a great fan of looking back in history to understand the future of biotechnology. And that 1/10/90 rule seems to hold true for many of the industries that have developed in the U.S. The U.S. Government provided not just a large chunk of that 10 percent in development, it provides almost all of the 1 percent. So that also is largely true for biotechnologies. The U.S. Government taxpayers are funding a huge amount of the basic research that eventually results in products, even if companies are funding a lot of the development down the road.

And so I think we should pay a lot more attention to what happens to the products of those research, when they become starvers, when they become big companies, in effect. If you look at the way China, for example, has dealt with its own research agenda, it doesn't spend that much on basic research. Instead, it appears to be a farming mat task-out to the United States.

So there's a great deal of acquisition or had been. Thankfully this is now coming to a sudden halt. A great deal of acquisition by Chinese companies, many of which appear to have close relationships with the Chinese government to acquire U.S. taxpayer-funded technology and deliver it to the biotech industry in China. And so the CIFIUS trial period, I mean, I don't know exactly how to talk about that at the moment. But those new regulations are having an impact. We are seeing that even in our own companies. They're having some more trouble finding capital that was evidently flowing freely from China. And even though that is impacting me personally and impacting them personally, I'm totally fine with that. It should be harder for foreign companies to come in, foreign governments to come in and acquire that technology.

Chairwoman STEVENS. Dr. Simpson, did you want to jump in here?

Dr. SIMPSON. Yes. So I mean, I think for commercial companies, inherently protecting intellectual property developed domestically is part of our lifeblood. So internally, we invested enormous amount of effort and energy into not only solidifying our patent portfolio but protecting technology as trade secrets, ensuring that all information that we develop is harnessed behind firewalls, et cetera, et cetera. So data protection, invention protection, intellectual property protection is an inherent part of our business.

But we're also seeking to commercialize technologies internationally. And I think it is appropriate that technologies advanced here domestically, the domestic companies have the opportunity to commercialize that throughout the world and therefore generate revenues that flow back to the United States. And not hindering that commercialization is something that I think that the panel should consider very strongly because in order to maintain leadership, the opportunity for a local innovations to commercialize elsewhere, is something that should be encouraged because that encourages further investment in this technological area.

Chairwoman STEVENS. Great. Thank you. And the Chair would now like to recognize Mr. Foster for 5 minutes.

Mr. FOSTER. Thank you. I'd like to bring up the interesting subject of artificial meat, which is another interesting horserace that's happening. I remember after I had been defeated in the Tea Party wave about a decade ago, I was trying to figure out what to do with my life next and was fascinated by a set of papers coming out of I think the Netherlands on cell-based artificial meat which seemed like the promising thing, you know, avenue at that time. But I was struck, last weekend I stopped at a White Castle and treated myself to an Impossible slider, which is a 100 percent plant-based artificial hamburger, and to my mind to my taste buds a quite credible substitute.

And so I was wondering, there's also a recent article I think in Science magazine questioning the carbon footprint of cell-based meat, that it might actually not be a big win compared to just harvesting a crop and stuffing it through an animal and eating the animal. And in that case, the plant-based approach might be much better from a carbon footprint point of view. I was wondering if any of you have, you know, comments on how you view that horserace.

Dr. SIMPSON. I mean, I think the first thing to say is I think it is a fascinating development because for many of the people who would inherently be interested in consuming, for example, and Impossible burger, they may also be interested in organic food. They may also be interested in non-genetically engineered food. And the Impossible burger represents a highly inorganic, highly genetically engineered meat substitute. So from this perspective, and as a scientist, it represents an incredible way of educating the public as to what is possible but what one needs to think about when consuming the possible or impossible.

Dr. ZOLOTH. I just want to say one thing about the Impossible burger is that it was developed by an HHMI (Howard Hughes Medical Institute) scientist, one of America's leading scientists from Stanford University, who gave up tenure and HHMI funding because he was devoted to trying to solve climate change in any way he could, as Professor Patrick Brown. And this development, he's committed to doing this, making sure it's not just a hippy alternative but it's in White Castle and it's widely available. And that is a transformative technology, of course, America leading the way in this. This use of the most innovative and interesting science to deconstruct the hamburger, it really shows the power of this kind of technology and the way it should be supported.

Mr. FOSTER. Yes.

Dr. ZOLOTH. And it's very good, too. It's tasty.

Dr. CARLSON. I do have one observation here which is that it's very early. So whatever the assertions are today about the economics, about the environment cost of production, they will change. And the window that I have into this is not via meat, necessarily, but it's human cell culture for therapy. So one of our companies is manufacturing stem cell therapies, and they have driven the cost down by orders of magnitude just in the last few years. There's another couple of orders of magnitude to go, and they are reducing the footprint of the materials they use, the environmental footprint of the materials they use as well as the cost.

So I have a strong suspicion that whatever the analysis suggests today about the environmental and/or economic cost of meatless meat, it's going to change so much that, you know, it's going to be fine in effect.

Mr. FOSTER. All right. And another sort of big-picture question. Do we have enough farmland? You know, if all your dreams come true, are we going to have, for the number of people—just assume that we keep the population constant in the United States and look at the rate at which we consume transportation, fuels, all the other. When you get all the efficiencies working here, are we going to find ourselves having surplus farmland and turn large fractions of the country back into national parks or what's your view of how all this will end up, you know, 100 years from now?

Dr. CARLSON. Over the long term, yes, we could return substantial fractions I think of the land now under cultivation to other use, to natural, you know—I mean there's this old phrase, the gardenification of nature. It turns out that significant fractions of this country were not so natural, even when European settlers arrived. They were altered significantly by the native population.

So back to that observation that we use about 30 percent of our corn crop for industrial use already, in that sense, we produce more than enough food in this country to use those raw materials for other purposes. And I think it's also important to recognize there are other technical trends coming that impact that. So I keep a close eye on electric cars and solar and wind and basically how the electricity grid is changing.

And well before 100 years from now, we're going to have shifted transportation use to nearly 100 percent electric vehicles. And that means that, you know, if you plan on selling ethanol as a fuel, that market isn't actually going to be around very much longer. It would be surprising to me if that were a 10-year market even. So we're going to wind up using those crops to make chemicals much sooner than maybe everyone is anticipating. I mean, Exxon for example is investing now very heavily in petrochemicals. I'm not sure that's a wise choice of their investment.

Dr. SIMPSON. I think one thing I would mention is that electric vehicles will affect the market for ethanol, there are fuel markets in which we cannot electrify. I for one am not getting on an electrically powered plane any time in the next 50 years. That is almost certainly not going to happen anytime soon.

And so one has to develop low-carbon fuel solutions for sectors where battery technologies simply won't provide the solutions required. I mean, within our company, we've developed the technology to convert ethanol actually into jet fuel, ethanol into diesel.

And so using a molecule that we can produce en masse from agriculture and from waste streams and ultimately from CO₂ as a platform for the production of high-density air transport, sea transport, and road transport fuels as well as a platform for a variety of commodity chemicals makes absolute sense from both an industrial security, energy security, and national security perspective.

Dr. CARLSON. I just want to throw my 2 cents in there, too. I didn't mean to say that we won't have any liquid fuels or that, you know, there won't be any use for that kind of technology. But I think the world is going to change remarkably over the next 10 years. And if you look at China just in the last 6 months, internal combustion automobile sales have been crashing and electric vehicle sales have been going through the roof. And it's going to really alter the way we, very soon I think, think about the way we use our petroleum resources and our biological resources.

Mr. FOSTER. Thank you. I guess I made the mistake a couple years back of going to one of these websites where you calculate your personal carbon footprint and found as a Member of Congress it was completely dominated by the fact that I fly back to Illinois each weekend to say hello to those who elected me.

Anyway, I want to thank the panel. This has been really good. And the Chair for having this hearing.

Chairwoman STEVENS. Before we bring the hearing to a close, we obviously want to thank our witnesses, our expert witnesses, for testifying before the Committee here today. We find ourselves in the Research and Technology Subcommittee at a tipping point where there is no vision, the people will perish and where we find ourselves dipping into the future. And so the remarks of my colleague, Mr. Tonko, about the importance and honor of being a part of this Committee are quite significant. And we remain very pleased to have such strong, Midwestern leadership at the table and with us here today, particularly given the important role that industry, government, academia, philosophy play in having these dialogs and as we look to put forward the *Engineering Biology Research and Development Act*. No doubt today was significant. So our record will remain open for 2 weeks for additional statements from Members and for any additional questions that the Committee may ask. The witnesses are excused and the hearing is now adjourned.

[Whereupon, at 11:45 a.m., the Subcommittee was adjourned.]

Appendix I

ANSWERS TO POST-HEARING QUESTIONS

ANSWERS TO POST-HEARING QUESTIONS

Responses by Dr. Rob Carlson**Robert Carlson, PhD****Responses to "Questions for the Record" Submitted by Chairwoman Haley Stevens.****Questions:**

"Biotechnology is democratizing, enabling the spread of the "garage biology" you discussed in your testimony. While this promotes innovation, it also increases the risks. You were very clear that we should err on the side of openness. However, we still must have systems and processes to manage the risks. What is the role of the US government in managing the risks of synthetic biology? How can we better incentivize venture capitalists who fund synthetic biology entrepreneurs, citizen scientists, universities, and private industry to address risks in this sector? How does your own venture capital firm take into account security risks when making your investment decisions?"

Responses:

Madame Chairwoman,

Thank you for the opportunity to comment on the critical intersection of innovation, economics, and security in regards to the future of biotechnology. Below I address each of your questions in detail. Given the critical role of biotechnology in our physical and economic security, that is, in US national security, my responses are extensive.

To begin, I would like to reiterate that synthetic biology is an approach to engineering biological systems, and that it comprises not just an expanding body of knowledge but also a growing set of tools. I suggest that in public policy conversations we should clearly differentiate between the tools themselves and the use of those tools by particular people for particular ends.

We must be concerned about security, and about risk, because those various ends might be beneficial or they might be nefarious. But a conversation putatively about risk from technologies is instead really about risk from human behavior, and about the choices humans make in using technologies. Consequently, the use of biotechnological tools by humans to cause harm is no more relevant to a specific harm than is the use of screwdrivers by humans to cause a specific harm. The comparison of biotechnology and screwdrivers is here not incidental, and I will employ it throughout my responses.

Notably, so far as I am aware, the use of screwdrivers to cause harm, either directly through use as a sharp object or indirectly through the construction of devices that kill or maim, vastly exceeds any harm caused by the human use of biotechnology. And deaths attributed to the use of screwdrivers are very clearly caused by humans who chose to behave in way that caused those deaths.

We do not typically fear new screwdrivers, nor do we speak of a proliferation of new screwdrivers as increasing any particular risk, whether they are employed in garages or elsewhere. Instead our culture usually sees new tools as providing new opportunities. It is generally assumed that one learns how to use a screwdriver at a young age, and also learns to use it responsibly. The same should be true of biotechnology. And yet public conversations about synthetic biology consistently elevate fear above opportunity. This may be because, unlike screwdrivers, we do not yet gain experience with the capabilities and limitations of biotechnology at a young age. But that time will come, and with it we should ensure that knowledge of responsible use becomes ingrained along with skill in using the tool itself.

Q: What is the role of the US government in managing the risks of synthetic biology?

The short answer to this question is that, at a minimum, the US government should continue its policy of encouraging all those who wish to learn to use biotechnology to also become familiar with safe and secure use of that technology, i.e., the government should encourage training in the responsible use of biotechnology. It is probably infeasible to *require* training in responsible use, in part because biotechnological skills can be acquired in venues beyond any plausible jurisdiction of the US government. In other words, the US government should continue the policy of engagement and normative education now implemented by the FBI and other agencies. The long answer is that, both in principle and in practice, the US government may be able to do no more than the short answer.

There are (at least) two foundational questions here in regards to biosecurity: 1) What does the Constitution allow the US government to do in principle with legislation or with rules? 2) What policies will in practice increase security?

Without delving overly into detail, the notional basis of the US government to take legislative action to control the use of biotechnology is likely to be found in its obligations as a State Party to the Biological Weapons Convention (BWC). The BWC is a non-self-executing treaty, and the US has obligations under Article IV to, "in accordance with its constitutional processes, take any necessary measures to prohibit and prevent the development, production, stockpiling, acquisition or retention of the agents, toxins, weapons, equipment and means of delivery specified in Article I of the Convention, within the territory of such State, under its jurisdiction or under its control anywhere."¹

The BWC is similar in structure to the International Chemical Weapons Treaty, and specific legislative action to enforce the BWC may need to follow along similar lines as the International Chemical Weapons Treaty Implementation Act ("the Act"). However, there is some question about whether the Act is constitutional. Briefly, it is disputed by many that enacting legislation at the federal level to implement treaty obligations is among the powers enumerated by the Constitution, and, to the contrary, it is further asserted that the federal government cannot use international treaties to introduce, via legislation, restrictions on the actions of states or individuals². According to these arguments, neither the Commerce Clause nor the Necessary and Proper Clause can be used to justify federal legislation that domestically enforces treaties. This might begin to sound like a rehash of a 10th grade civics lesson, except that these matters have recently come before the Supreme Court, and have yet to be settled. In the recent *Bond v US* decision, which in principle hinged on the constitutionality of the Act, the Court explicitly opted not to settle the constitutional matter and ruled instead on a narrower basis³.

In the face of this uncertainty, there are two obvious alternatives to pursue. First, each of the fifty states could enact legislation aimed at implementing the BWC. Second, as was the case with Prohibition, the Constitution itself might be amended to specifically proscribe certain substances or technology and to enable federal legislation to enforce that proscription.

¹ The Biological Weapons Convention: An Introduction, The United Nations, June 2017.
[https://www.unog.ch/80256EDD006B8954/\(httpAssets\)/6D16C7B1933F0937C125815D00349763/\\$file/BWS%20brochure.pdf](https://www.unog.ch/80256EDD006B8954/(httpAssets)/6D16C7B1933F0937C125815D00349763/$file/BWS%20brochure.pdf)
² See, for example, Cruz, Ted, "Limits on the Treaty Power", *Harvard Law Review*, 2014.
<https://harvardlawreview.org/2014/01/limits-on-the-treaty-power/>
³ <https://www.law.cornell.edu/supct/html/09-1227.ZO.html>

It is not my intention here to take a position on these matters. Rather, I merely wish to observe that what might appear as an obvious course to enacting domestic policy may, in practice, run aground on questions that have occupied us since the founding of the country. It may be that other national governments have an easier time managing such questions, in that their authority is clearer or more absolute. But then the Founders were well aware that they were not choosing the easy path.

It is worth considering the text of the BWC in a bit more depth. Article I makes explicit that the Convention is targeted at intent, specifically using language that States Parties pledge never to acquire or retain materials "of types and in quantities that have no justification for prophylactic, protective or other peaceful purposes." All of biology is dual use, and it is only through the intent of the wielder that a molecule or an organism can be unambiguously identified as a weapon.

The architects of the BWC were both wise and clever. They recognized that biological technologies would be a force for good in the world, and also recognized that they could not predict how biological technologies would develop. The document that they created was intended to facilitate the ability of States Parties to put their feet down and stamp out biological weapons while encouraging innovation and peaceful use.

Articles I and IV are together very clear: States Parties must renounce the use of biological weapons and must also work to eradicate them as allowed and enabled by their constitutions.

In my travels through domestic and international biosecurity over the last two decades, I have found that most discussions of biological weapons end at the content of Article IV, and are primarily focussed on implementing laws and regulations to contain and control the use of biological technologies. However, the Convention itself does not end at Article IV. Rarely do biosecurity conversations encompass Article X, which "requires States Parties to "facilitate, and have the right to participate in, the fullest possible exchange of equipment, materials and scientific and technological information" for the use of biological agents and toxins for peaceful purposes".⁴

Article X continues:

Parties to the Convention in a position to do so shall also cooperate in contributing individually or together with other States or international organisations to the further development and application of scientific discoveries in the field of biology for the prevention of disease, or for other peaceful purposes.

This Convention shall be implemented in a manner designed to avoid hampering the economic or technological development of States Parties to the Convention or international cooperation in the field of peaceful biological activities, including the international exchange of biological agents and toxins and equipment for the processing, use or production of biological agents and toxins for peaceful purposes in accordance with the provisions of the Convention.

Article X is crafted specifically with the goal that States Parties "shall" not only endeavor to avoid hampering peaceful biological research and development, but also "shall" cooperate to further peaceful development of biological technologies. Consequently, national policies that embrace Article I at the expense, or even the exclusion, of Article X, might be viewed as counterproductive to the larger aims of

⁴ The United Nations, 2017.

the Convention. Neither does simple proscription in any context appear to be consistent with the aims of Article X. The tricky part of implementing obligations under the BWC is, therefore, managing the balance between nefarious and beneficial use of tools, which brings us back to the challenge of judging intent. This will always be a messy, labor intensive problem, as judging intent is always contextual, and also contingent upon inferring a state of mind. In the US, these matters are argued before, and settled by, juries who have the task of weighing all the evidence put before them. I do not presume to have suggestions for improving our system of judging intent.

Despite the uncertainty cataloged above, I do have concrete recommendations regarding security policy. And so I return to the second question I asked above: What policies will in practice increase security? To which I now add: what policies will in practice decrease security?

As I stated in my prior testimony, there is already massive economic demand for the fruits of biotechnology, and the technology itself is broadly democratized. The US government has experience with trying to control technologies in similar situations with the aim of improving security, and the results are not encouraging. The following paragraphs are adapted from a forthcoming article of mine on this subject, to appear in *Nature Biotechnology* later this year⁵.

Presumably, we can agree on the simple idea that improving safety and security should be our primary goal. With that established, we can then explore how we might pursue that goal. We can start with the following testable hypothesis: Does restricting access to democratized technologies improve safety and security? There is copious data available to test this hypothesis, and the hypothesis does not fare well. Its failure, and in particular the manner in which it fails, suggests that restricting access to raw materials and markets in attempts to reduce the production, distribution, and consumption of illegal substances often creates insecurity and is thereby counterproductive.

In the case of alcohol, Prohibition in the U.S. was repealed not only because it did not prevent access to alcohol — Anheuser-Busch did a brisk business at the time selling copper kettles, yeast, and other ingredients for beer — but it also incentivized the creation of illicit production and distribution networks that were extremely violent and costly to society⁶. Quantitative data on behavior during the period is hard to come by, but anecdotally it is clear that “the law that was meant to stop Americans from drinking was instead turning many of them into experts on how to make it, and in many parts of the United States more people were drinking, and people were drinking more.”⁷

In the case of methamphetamines, the U.S. Drug Enforcement Administration’s own reporting reveals that the suppression of “mom-and-pop” production beginning in 2001 resulted in the creation of foreign manufacturing that within two years surpassed the domestic production it replaced^{8, 9}. Moreover, these professionalized, international drug trafficking organizations, formed to satisfy U.S. domestic demand, are also harder to surveil and disrupt than their predecessors; increased proscription thereby created bigger, blacker markets than existed previously.

⁵ Robert Carlson, *Nature Biotechnology*. In preparation, 2019.

⁶ Knoedelseder, William. *Bitter Brew: The Rise and Fall of Anheuser-Busch and America’s Kings of Beer*. 1st ed. New York: New York: HarperBusiness, 2012.

⁷ Lerner, Michael, in the online material for *Prohibition*, Ken Burns and Lynn Novick, Dirs., Florentine Films, 2011. <http://www.pbs.org/kenburns/prohibition/unintended-consequences/>.

⁸ Carlson, R., *Biology is Technology: The Promise, Peril, and New Business of Engineering Life*, Harvard University Press, Cambridge, MA, 2010.

⁹ Carlson, R., “The Pace and Proliferation of Biological Technologies”, *Biosecurity and Bioterrorism*, 2003, 1(3).

The resulting concentration of economic resources enables investment in innovation that is specifically aimed at circumventing proscriptions, as demonstrated by experience with cocaine trafficking. Restricting access to U.S. markets has led drug cartels to build semi- and fully-submersible vessels that can carry illicit cargo worth hundreds of times the cost of the vessel itself^{10, 11}. The relative value of vessel and cargo means that these smugglerines constitute disposable infrastructure, which utility is itself another techno-economic innovation incentivized by proscription, and which has security implications far beyond drug trafficking¹². The cartels have recently demonstrated further innovation by deploying advanced surface vessel hull designs that were previously only available to race competitors and special forces¹³. All three types of vessels have proven very difficult to locate at sea, and it is unclear what fraction are ever intercepted¹⁴. Unfortunately, many decades of significant spending on hard security measures in the U.S. – e.g., prohibitions on the sale or possession of precursor chemicals, and crackdowns on domestic production laboratories – have not had a lasting impact on illicit drug markets. The primary effect of implementing these measures is apparently to shift use between illicit drugs over time, without significantly affecting aggregate demand^{15, 16}. (Note that this is a distinctly different problem than the misuse of legal pharmacologicals, which is argued to be the cause of widespread harm from opioid use.)

More directly relevant to the use of biotechnology in garages is the outcome of attempts to restrict the use of synthetic chemistry to produce so called “legal highs”. Also referred to as “bath salts” and “synthetic cannabinoids”, among other street names, these chemicals can be produced just about anywhere, using modest technology, and are often drawn from academic literature describing the synthesis of psychoactive compounds¹⁷. These compounds are explicitly legal in many countries until their specific chemical structure is outlawed. A 2010 news report described “a wave of laboratory-adept European entrepreneurs who see gold in the gray zone between legal and illegal drugs”¹⁸. The article focussed on the story of an out-of-work carpenter who turned to synthesizing these drugs to make ends meet, a sure sign that a technology has been thoroughly democratized. This laboratory-adept entrepreneur averred that he was always ready to move onto the next compound when authorities banned whatever he was selling, staying just ahead of the law, thereby illustrating an international phenomenon. In the U.S., the Synthetic Drug Abuse Prevention Act of 2012, which added fifteen specific chemical structures to schedule 1 of the Controlled Substances Act, was reportedly circumvented within days by entrepreneurial chemists who were ready to commercialize compounds with structures different to those proscribed by the Act¹⁹. Here, again, regulation created perverse incentives to innovate in the very market that regulation was supposed to eliminate.

10 “To Smuggle More Drugs, Traffickers Go Under the Sea”, Micheal Schmidt and Thom Shanker, *The New York Times*, 9 September, 2012.

11 “Watch the US Coast Guard seize a narco sub laden with more than 5,600 pounds of cocaine”, Christopher Woody, *Business Insider*, 31 October, 2016.

12 Lichtenwald, Terrance G., Mara H. Steinhour, and Frank S. Perri, “A Maritime Threat Assessment of Sea Based Criminal Organizations and Terrorist Operations,” *Homeland Security Affairs*, 8, Article 13, August, 2012.

13 “Colombian Drug Smugglers Built This Stealthy, Special Forces-Inspired Boat”, Kyle Mizokami, *Popular Mechanics*, 13 June, 2017.

14 *ibid.*

15 “Meth, the Forgotten Killer, Is Back. And It’s Everywhere”, Frances Robles, *The New York Times*, 13 February, 2018.

16 *2018 National Drug Threat Assessment*, Drug Enforcement Administration, U.S. Department of Justice, 2018.

17 David Nichols, “Legal Highs: The Dark Side of Medicinal Chemistry,” *Nature* 469, no. 7328 (2011): 7.

18 “In Quest for ‘Legal High,’ Chemists Outfox Law”, Jeanne Whalen, *The Wall Street Journal*, 30 October, 2010.

19 “New Federal Ban On Synthetic Drugs Already Obsolete”, Brandon Keim, *Wired*, 12 July, 2012.

Based on the above data, it appears that the hypothesis that restricting access to democratized technologies always improves public safety and security is false. Instead, even in the face of significant sanctions for the production, distribution, and use of illicit drugs, regulation can be ineffective or deleterious. The points of failure of drug proscription are relatively easy to diagnose: broad demand supports the use of tools and skills that cannot be readily constrained. It seems plausible that the history of responses to drug prohibitions by manufacturers, traffickers, and customers represents a general phenomenon. In the absence of practical means to physically prevent access to democratized technologies, increased regulation creates perverse incentives for innovation while evidently having minimal impact on demand. This experience suggests that any security strategy based on proscription of democratized technologies is doomed not merely to failure, but is doomed to exacerbate insecurity by incentivizing individuals to hide their activities.

The consistent outcomes of drug and alcohol proscription point to a consistently misformulated strategy to control tools and skills in a market in which 1) those tools and skills are already widely available, 2) those tools and skills are required broadly across the economy, and 3) consumers are willing to pay prices that support the illicit use of those tools and skills.

Similarly, biotechnological skills are already broadly available. Biotechnological skills already support a significant fraction of the economy in many developed countries, demonstrating the existence of significant demand. Indeed, public and private investment around the world is directed at increasing the prevalence and utility of those skills in order to generate skilled jobs and economic growth. Taken together, these characteristics suggest that attempts to control the use of biotechnological skills will fare no better than prior attempts to control synthetic chemistry.

Indeed, FBI officials explicitly acknowledge the implausibility of top down efforts to physically prevent access to widely accessible tools and ideas, particularly in the context of large and rapidly growing international demand²⁰. Yet that does not mean no action can be taken. The US government does have in place "systems and processes to manage the risks" of synthetic biology and garage biology, and they comprise the engagement activities described in my prior testimony. I reiterate my earlier recommendation, which is that the US government "should devote resources to continuing engagement activities that are, in my experience, the best single step that the U.S. government has taken to improve security." The US government arrived at this policy after discovering that attempting to constrain the use of biological technologies in the name of improved security was not merely ineffective, but counterproductive.

In the years after 2001, the U.S. government investigated, arrested, and sought to prosecute several scientists and biohackers under terrorism charges without sufficient legal basis or evidence. In at least one case, public accusations were revealed to be errant even before charges were brought, resulting in financial penalties for the U.S. government²¹. In another case, an indictment was eventually dismissed by a federal judge as "insufficient on its face"²². One defendant pled guilty to a reduced charge to end his legal ordeal due to health concerns, a charge that arguably would have been dismissed along with the rest had that case gone to trial. This underreported and poorly understood historical episode had a chilling

²⁰ "A Way to Brew Morphine Raises Concerns Over Regulation", Donald G. McNeil Jr., *The New York Times*, 18 May, 2015.

²¹ "The Wrong Man", David Freed, *The Atlantic*, May, 2010.

²² "Charge Dropped Against Artist in Terror Case", The Associated Press, 22 April, 2008.

impact on the willingness of garage biohackers to disclose or discuss their activities. Here I write from personal experience.

By 2004, I was regularly briefing security and law enforcement organizations in Washington DC on global trends in biotechnology while maintaining a lab in my own garage, the existence of which did not enter into my briefings precisely because I was concerned about overenthusiastic law enforcement. Only much later did I speak freely about my garage lab, which I built to support a start-up company, and only then because US security policy was restructured according to the 2009 National Strategy for Countering Biological Threats²³. To this day, I am aware of individuals who have chosen to keep their garage labs secret precisely because they fear that a future political reversal of the two most recent National Strategies, presumably accompanied by new legislation and law enforcement priorities, could land those maintaining garage labs in legal peril. The FBI's public statements about its shift in strategy and its embrace of engagement and transparency, now acknowledging that "We've learned that the top-down approach doesn't work," have not been sufficient to overcome distrust²⁴. Consequently, it is not now possible to assess how many garage labs are in operation in the U.S. precisely because of the fear of sanction instilled by prior government actions. The ongoing lack of even rudimentary information about how many garage labs are in operation, let alone what practitioners are up to in those labs, counts as a safety and security own-goal that could have been avoided, and that must not be repeated.

This paucity of data is a global problem and is a characteristic of the challenges inherent in economic and security assessments of democratized technologies. In the absence of voluntary information sharing, not only do we not know how many garage labs are active in the US, but we *cannot know* without some combination of pervasive surveillance and invasive physical searches, a strategy that is logistically implausible and also generally incompatible with the laws and values of this country.

How can we construct a biosecurity and biosafety policy conversation that 1) respects demonstrated public interest in participating in the biotechnology revolution, while at the same time 2) also respects the need to monitor potential threats, but 3) simultaneously avoids casual calls for restricting access to biotechnology as a magical route to improved safety and security? Given the difficulty of physically controlling access to biotechnology, maximizing transparency and information is the only plausible course available to improve security. This statement should be treated as a policy hypothesis as well, though one consistent with recent experience across multiple law enforcement and security jurisdictions. This hypothesis is also consistent with the 2009 U.S. National Strategy for Countering Biological Threats, which does not advocate for controlling access to biological technologies, nor for surveilling those who use biotechnology, and – to the contrary – explicitly states the security benefits of transparency and broad, open access²⁵.

Finally, this transparency and open access must be accompanied by personal responsibility. That sense responsibility can be fostered through education and engagement. As I stated in my prior testimony:

The U.S. government would do well to develop a network of community laboratories that would provide access to infrastructure, increase communication between innovators, and facilitate

²³ Ledford, H., "Garage biotech: Life hackers", 6 October 2010, Nature 467, 650-652.

²⁴ McNeil, 2015.

²⁵ "National Strategy for Countering Biological Threats", National Security Council, 2009.
https://obamawhitehouse.archives.gov/sites/default/files/National_Strategy_for_Countering_BioThreats.pdf



engagement with the U.S. government in regards to national security and national technology development goals²⁶. In addition to providing venues for education and public conversations, this strategy would facilitate economic development via start up formation, thereby accelerate job creation, and would dovetail nicely with the aforementioned existing FBI outreach activities.

Q: How can we better incentivize venture capitalists who fund synthetic biology entrepreneurs, citizen scientists, universities, and private industry to address risks in this sector?

There are two broad areas of risk to consider here. The first, which I have extensively discussed above, is a physical risk from human behavior that can only be addressed through encouraging safe and beneficial use of biotechnology. I firmly believe that more education, and more exposure to positive norms, is the best route to ameliorating this risk. The US government can incentivize participation in open networks and normative conversations by providing venues for education and engagement, as described at the end of the previous answer.

The second broad area of risk boils down to international competition. This is a different definition of risk than used above, and has more to do with physical and economic security. I will here refer back to my prior testimony, although I would be happy to take this up again if desired by the Committee.

Q: How does your own venture capital firm take into account security risks when making your investment decisions?

We carefully evaluate the combination of team and technology to ensure that our investments are aligned with both public and private interests. To that end, we vet not only the entrepreneurs who might receive an investment but also other participating investors, along with customers and suppliers. In this we take an expansive view of "security" and "risk" that includes both the potential end use of a technology and the potential end user. Ultimately, these are matters of judgement that reduce to intent, both ours and the entrepreneurs.

²⁶ Carlson, R. "Building a 21st Century Bioeconomy: Fostering Economic and Physical Security Through Public-Private Partnerships and a National Network of Community Labs", Biodesic, 2011.

Responses by Dr. Kevin Solomon

Kevin Solomon, Ph.D.
Assistant Professor of Agricultural & Biological Engineering
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How can the Engineering Biology R&D Act better address either or both national security and public health and environmental risks in the context of an R&D program?

R&D programs supported from federal sources must comply with existing regulations surrounding the public interests in national security, public health, and environmental risks. These laws are implemented at the institutional level through research review boards/councils that evaluate the risk of all research and its perceived impact. Biological research may only be initiated after a review of the scope of work and implementation of appropriate safeguards to minimize environmental risks and harm to public health. Similar infrastructure exists for human and animal work, restricted chemicals and other elements of concern for national security and public health and environmental risks. Thus, existing laws may be sufficient to protect societal interests in the short term. However, as the field advances and new challenges arise, the Engineering Biology R&D Act provides an excellent framework to further minimize harm by supporting research in the social sciences and allied fields that inform about the potential societal impact of engineering biology, and that develop solutions that protect society.

Responses by Dr. Eric Hegg

**House Committee on Science, Space, and Technology
Subcommittee on Research and Technology
Hearing on “Engineering Our Way to a Sustainable Bioeconomy”**

Question for the Record to:

Dr. Eric L. Hegg

Professor of Biochemistry & Molecular Biology, Michigan State University
Michigan State University Subcontract Lead, Great Lakes Bioenergy Research Center

Submitted by Chairwoman Haley Stevens

1. **How can the Engineering Biology Research and Development Act of 2019 better address either or both national security and public health and environmental risks in the context of an R&D program?**

There are both risks and benefits associated with any new technology, and in this respect synthetic biology (or engineering biology) is no different. What is perhaps a bit unusual in the field of synthetic biology is the magnitude of both the benefits and the potential risks. Having the ability to re-engineer organisms (something that nature is constantly doing through evolution) to perform a particular task such as (a) producing chemicals, biofuels, and medicinal drugs, (b) improving the yield, robustness, or nutritional value of plants, (c) degrading unwanted chemicals and products, or (d) eliminating disease vectors provides us with the opportunity to greatly improve human well-being. On the flip side, it also provides us with the opportunity to do harm, either unintentionally (e.g., via accidental release of unfavorable traits into the environment) or intentionally via the engineering of organisms with destructive capabilities.

When assessing risks versus benefits, there are two critical points we must keep in mind. The first is the cost of doing nothing. Many of the problems synthetic biology is addressing are serious societal concerns, and not addressing them will have very real consequences. The second important point to remember is that the technology to engineer organisms already exists, and other nations will use it. In my opinion, it is better for us to be involved in the process so that we have the expertise to identify, evaluate, and if needed, resolve any environmental or health risks, or any other deleterious unintended consequences.

What specific changes can be made to the Engineering Biology Research and Development Act to help mitigate the risks while not stifling innovation and progress? Most importantly, we need to ensure that sufficient resources are available to identify and study potential unintended consequences as well as develop possible solutions, and this should be a specific part of the Act’s mission. For example, can we develop a way to ensure that genes inserted into organisms cannot be accidentally transferred to other species via horizontal gene transfer? Can we develop effective “kill switches” such that organisms accidentally released into the environment could be made non-viable? Developing innovative approaches to minimize the chance of unintended consequences will significantly mitigate both the

potential environmental risks and the potential health risks, but these approaches will require resources to discover and develop.

Additionally, this Subcommittee could work with the other major Federal funders of synthetic biology (*e.g.*, NIH, DOD, and USDA) to develop improved guidelines for basic science researchers working with recombinant DNA. Currently some of the regulations, at least as far as they are interpreted and enacted at some universities, encourages a "one-size-fits-all" approach that does not appropriately prioritize regulation based on risk. My concern with this approach is that large amounts of time can be invested in areas where the risk is low, thereby taking resources away from monitoring research that really does require more intense scrutiny. One possible solution to this problem is improved coordination between granting agencies to establish risk-based reporting requirements and provide guidance to universities about best practices for implementation.

Finally, I would like to take this opportunity to reiterate a point I made in my previous testimony. It is imperative that any new initiatives be supported with a commensurate level of new funding. In times of tight fiscal budgets, it is essential that funding for broad, investigator-initiated research not be reduced by redirecting existing research funding to engineering biology. Broad, investigator-initiated research encourages the creativity that has been the hallmark of U.S. innovation leadership and can lead to profound and unexpected breakthroughs. More targeted funding (*e.g.*, to engineering biology) provides synergies with similar benefits. It is important to maintain a healthy balance between these two distinct funding models.

Responses by Dr. Laurie Zoloth

Response to question.

When Chinese researcher Dr. He Jiankui began to correspond and then visit US researchers to describe his work and ask for advice on what was clearly a project of editing human embryos, the response from the scientists he consulted ought to have been immediate: they should have all told him to stop such work immediately.

Further, they all ought to have informed the National Academies of Sciences, of which nearly all of the consulted faculty were members, and should have contacted faculty colleagues at their institution who were well educated, creditable, and credentialed scholars of bioethics. Yet, after the experiment was made public via YouTube (for real scientific evidence, including independent DNA sequencing of the actual infants, is still not forthcoming,) several of America's leading researchers told the press that "they did not know who to tell" about the work, despite its obvious important and problematic ethical violation of long established norms.

The moratorium on "germ-line" gene editing of human embryos has been a longstanding "bright line" not to be crossed for three decades. Numerous publications, a 1999 AAAS Report on the Topic (*Designing our Descendants*) as well as the entire history of the Recombinant DNA Advisory Committee, a federal committee established in 1976 to oversee all genetic intervention proposals established a careful practice to avoid any chance of germ-line contamination by somatic cell therapeutic intervention. "The Recombinant DNA Advisory Committee is a federal advisory committee that provides recommendations to the NIH Director related to basic and clinical research involving recombinant or synthetic nucleic acid molecules. RAC proceedings and reports are posted to the OSP Web site to enhance their accessibility to the scientific and lay public." The RAC discussions, including discussions about the impermissibility of germ line research on humans, and the names and contact information of the 21 members of the Committee are fully public and accessible.

The long-standing principle was then re-confirmed with the invention of CRISPR-Cas 9 technology in a well published national public meeting of the US National Academies of Sciences, the British Royal Society, and the Chinese National Academy of Sciences. A clear, firmly promised, international, and definitive moratorium prohibiting the use of CRISPR and other new techniques for altering the human germ line has been in place since that meeting. Several of the US scientists who were contacted by Dr. He attended that meeting, and all must have been aware of its importance and consensus.

Further, both Stanford University, Rice University, and Arizona State University, all contacted by or working with Dr. He are places with well-regarded Bioethics Centers, in two case, with a RAC member or former RAC members as a faculty. Neither the adjunct faculty medical doctor who has taught a course in bioethics, his son, who is a medical historian, nor the scientists who were consulted by Dr. He apparently thought to contact the faculty at these Centers for

advice on “who to tell,” nor did they set up a process in which the question could be carefully considered. Many of the other scientists were in similar positions, working at universities with bioethics centers, or local RAC advisory committees, or had worked closely with bioethicists, including bioethicists in the National Academy and Howard Hughes Medical Institute. And certainly, all of the scientists had taken the mandatory bioethics class required to receive an NIH grant. In short, all of our systems failed to prevent this experiment from taking place.

In response, I wish to make two points, for we must do better.

First, the National Academies, or the RAC, or national bioethics academic associations often make statements of support or prohibition, without any mechanism for strong and continuous enforcement of the norms, either *a priori* or *ex post facto*. This is because we assume, as scholars, that scientist wish to do good, moral work and thus, simply informing them of the norms and rules will keep them from breaking them. Confronted with genuinely unethical behavior, the scientists in this case, even at elite institutions, seemed surprised and unable to respond effectively.

Clearly, bioethics training must begin in the very earliest stages of scientific training and understanding ethics must be seen as just as critical as understanding molecular biology. If we as a field have failed to teach scientist precisely to whom to turn when they encounter unethical behavior, that must be corrected. Consultations should never be done (as it was in this case) as a sort of “curbside consult” with one person, but questions or information of the sort that Dr. He presented should be discussed within a careful process with an ethics committee of faculty, specifically trained in bioethics. This education, reporting and enforcement mechanism—all three parts—must be put in any normative statement by the National Academies. It is important to note that the Chinese National Academy and his institution has now forcefully punished Dr. He Jiankui. No sanction of any kind have, of this writing been place on the American faculty members who did not report this research or who helped in its creation. It is my opinion that some mechanism must be put in place to avoid this happening again. (At the very least, the strong reporting requirements used for example in the NASA System where the IACUC (Institutional Animal Care and Use Committee) has placed permanent bronze sign urging *anyone* in the lab to call the veterinarian’s personal phone if he or she thinks there is an ethical problem, should be put in place.) There must be powerful disincentives for rogue activity and for people whose silence works to protect it.

Second, even with a strong enforcement system, rogue scientists and bad actors will emerge—for example, every society has strong norms and laws, and the police power of the State, and yet, people still murder, and witnesses still protect murderers. No system of prevention will be perfect. However, we ought to reflect on the culture of science that allowed this problem to emerge and seek ways to change it. Scientific accolades reward primacy. Huge prizes and acclaim go to the person who can first articulate an idea. Dr. He himself believed his work would be “worthy of a Nobel Prize.” Further, because of the strong influence of the market, scientific research is often conducted in secret, to protect patents in many cases, and in others, as a part of the fiercely competitive nature of modern science. Dr. He’s request for secrecy may

not have seemed alarming given that culture. Thus, there must be powerful incentives for science to be ethical, collaborative and transparent.

Third, this case represents the way that research scientists in large universities may be isolated even from their colleagues on the faculties of the humanities, philosophy, law, and religion, where ethics is the core organizing subject of the discipline. Training of America's next generation of doctoral students in science must include not only a strong course in ethics but needs to support ongoing, lifelong relationships of mutual trust and respect. And the training of the professoriate in classical ethics must include awareness and careful attention to emerging science and of course, to the norms within the disciplines of bioethics so that no scholar of any discipline can be unaware of moratoria so critical to our national civic discourse.

As engineering biology finds its first principles and practices, it will be capable of extraordinary power and that power will be tempting—rule hacking, blue sky innovation, and DIY labs are all also part of the culture of synthetic and engineering biology. Dr. He worked within an elite academic system and went to consult with others who were members of elite academic system, which is why we know about his breach, albeit far too late. But the next rogue may emerge well outside of professional settings, and the person he or she tells about the work may also be confused about how to report back to a community to which he or she is an outsider. While science and engineering do have a series of internal norms that can allow for very strong self-regulation, it will surely not be sufficient to address such situations, in part because the stakes for harm are so high, and in part because of the lessons we should learn from the Dr. He case.

A discussion at the federal regulatory level must be organized to make the lessons and the norms learned from them perfectly clear. Reporting an ethical violation must be made obvious and imperative in all the places that engineering biology is performed: universities, medical schools, corporate labs, start-ups, and DIY communities. Ethics education standards must be organized across the life-span of any scientist, and any humanist, philosopher, or theologian who calls him or herself a bioethicist must have a similar education in science. Finally, the discussants must have a serious and rigorous plan for enforcement when the standards are breached.