Engineering Platforms for Synthetic Biology Research: Postprint

Authors: Cui Jinming, Zhang Bingzhao, Ma Yingfei, Fu Xiongfei, Wang Meng, Liu Chenli

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Abstract

In synthetic biology research, the massive volume of engineering trial-and-error experiments far exceeds the capacity of traditional labor-intensive research paradigms, thus necessitating a transformative engineering research platform. Engineering platforms introduce various types of intelligent equipment that meet production requirements, enabling innovation in large-scale personalized customization models and facilitating remote customization, geographically distributed design, and economies-of-scale production of living organisms. Such platforms can rapidly accumulate empirical knowledge, forming the scientific foundation for predictable synthesis of living organisms. This article introduces several engineering platforms for synthetic biology research, along with development cases, innovation mechanisms, and trends of their upstream and downstream institutions.

Full Text

Engineering Platforms for Synthetic Biology Research

CUI Jinming[1], **ZHANG Bingzhao**[1], **MA Yingfei**[1], **FU Xiongfei**[1], **WANG Meng**[2], **LIU Chenli**[1]*

[1]Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences, Shenzhen 518055, China
[2]Tianjin Institute of Industrial Biotechnology, Chinese Academy of Sciences, Tianjin 300308, China

Abstract

In synthetic biology research, the massive scale of engineering trial-and-error experiments far exceeds the capacity of traditional labor-intensive research paradigms, necessitating a transformative engineering research platform. By introducing various types of intelligent equipment required for production, engineering platforms enable large-scale personalized customization and paradigm innovation, achieving remote customization, offsite design, and economical scale production of living organisms. These platforms can rapidly accumulate experiential knowledge and serve as the scientific foundation for predictive synthesis of life. This article introduces several engineering platforms for synthetic biology research, along with development cases, innovation mechanisms, and trends in their upstream and downstream institutions.

Keywords: synthetic biology, biofoundry, engineering platform

The design and synthesis of predictable life forms represents not only the core scientific question in synthetic biology but also a prerequisite for applications across industry, agriculture, and medicine. Synthetic life forms are often highly complex, requiring massive engineering trial-and-error experiments—that is, the need to rapidly, cost-effectively, and iteratively complete the "design–build–test–learn" cycle to deeply understand the design principles of genetic circuits while accumulating a large collection of high-quality components. This will make genetic circuit design in synthetic biology more direct and predictable, thereby improving research efficiency [1,2].

For instance, an important direction in synthetic biology involves using molecular components to create genetic circuits that reprogram cells and endow them with new capabilities. However, artificially designed genetic circuits rarely work exactly as intended and often require weeks or months of iterative tuning, primarily due to limited understanding of core design principles and a current lack of diverse, well-characterized high-quality components. Clearly, massive engineering trial-and-error experiments will far exceed the capacity of traditional labor-intensive research paradigms, creating an urgent need for a transformative engineering research platform. Such platforms can rapidly accumulate experiential knowledge and serve as the scientific foundation for predictive synthesis of life. Upon this foundation, the standardization of biological components, genetic circuits, metabolic pathways, genomes, biological systems, and even multicellular systems can be gradually promoted, ultimately enabling rational design of life forms. This article will introduce several global engineering platforms for synthetic biology research, along with development cases, innovation mechanisms, and trends in their upstream and downstream institutions.

Development Cases of Engineering Platforms for Synthetic Biology Research

The large-scale engineering synthesis of life forms shares certain similarities with the manufacturing of discrete products such as household appliances and electronics in light industry. Consequently, concepts of intelligent manufacturing and smart factories from these fields have been introduced into synthetic biology research. In simple terms, this involves advancing the intelligence of production equipment and lines by introducing various types of intelligent equipment required for production (such as liquid handling platforms, PCR machines, microplate readers, automated incubators, and centrifuges) to establish workshop-level intelligent production units based on cyber-physical systems (such as those linked by robotic arms or conveyor belts), thereby improving precision and agile manufacturing capabilities. More profoundly, it involves introducing concepts of personalized customization and connected factories, using internet platforms to innovate large-scale personalized customization models that fully meet the diverse needs of researcher-users while achieving remote customization, offsite design, and economical scale production of life forms. Such automated facilities for synthetic biology research, also known as BioFoundries, constitute the core of engineering platforms [3].

To date, the U.S. government has supported the establishment of three major synthetic biology research centers, while the UK government has funded six large synthetic biology research centers. Germany, the Netherlands, Japan, Singapore, Australia, and other countries are also closely following suit. Most major research centers and academic institutions have built BioFoundries as their core facility. These automated facility platforms for synthetic biology serve to accelerate both academic research and industrial development (Table 1)[1]. Many companies have also built their own automated facility platforms, such as Amyris, Ginkgo Bioworks, Zymergen, and Transcriptic. The scale of these facilities varies, but their primary function is to help researchers automatically load specific genetic circuit designs into living cells with high-throughput testing support. Workflows are typically organized according to the "design–build–test–learn" cycle to achieve massive engineering trial-and-error.

Among these, the "Living Foundries" program funded by the U.S. Defense Advanced Research Projects Agency (DARPA) is one of the earliest and largest initiatives, with nearly $400 million deployed since its launch in May 2011. The Living Foundries program aims to use synthetic biology technology to construct a new bio-based manufacturing platform using natural or synthetic substances as feedstocks, transforming biological design, R&D, and manufacturing into engineering design problems. By manipulating natural organisms, the program seeks to obtain novel materials, devices, systems, and platforms, achieving "on-demand design and production" of high-value military materials and equipment. The ultimate goal is to compress the biological design, build, and test cycle time and costs, enable modular and standardized design of biological components and manufacturing platforms, drive qualitative breakthroughs in bio-manufacturing platforms, and create U.S. strategic and economic advantages in areas such as materials (e.g., fluoropolymers, lubricants, special coatings for harsh environments), sensing (e.g., self-healing and self-regenerating systems), and manufacturing (including biological production of known and novel molecules, semiconductor devices, etc.) [4].

Since its implementation, the Living Foundries program has made major progress: developing new bio-synthesis computer software systems that reduce design time from one month to one day with end-to-end monitoring; constructing large-scale genetic networks to preliminarily validate forward engineering capabilities for bio-manufacturing; establishing new large-scale DNA assembly methods that increase the number of accurately assembled DNA fragments from 10 to 20 with error rates reduced to one-quarter of previous levels; achieving a 7.5-fold acceleration in the design, engineering, and production of various novel biological products; and completing the design and preparation of acetaminophen synthesis pathways. Although the Living Foundries program has achieved several important advances and its feasibility has been preliminarily verified, numerous challenges remain for its engineering applications. The biggest technical challenges include difficulties in rapidly improving known molecular structures, inability to synthesize certain molecular structures, and challenges in designing novel molecular structures. Overall, the program remains at the frontier of exploration, but breakthroughs could significantly enhance existing manufacturing capabilities.

Existing BioFoundries in the UK and US still have certain limitations, including weak capabilities in complex circuit design, limited chassis organisms, high costs for large DNA fragment manufacturing, few high-throughput testing methods, and weak connections with downstream applications. Many R&D needs remain unmet, and the field's development still faces obstacles. In response to these limitations, China has made its own deployments.

The "Major Science and Technology Infrastructure for Synthetic Biology Research" (hereinafter referred to as "the Facility") led by the Shenzhen Institutes of Advanced Technology (SIAT), Chinese Academy of Sciences (hereinafter referred to as "SIAT"), was included in the overall deployment of the "National Long-term Plan for Major Science and Technology Infrastructure Construction (2012–2030)" in 2013 and was approved by the Shenzhen Municipal Development and Reform Commission in January 2018. With a planned investment of 940 million RMB, the substantial scale-up will effectively address the limitations of smaller facilities, such as single chassis organisms and high costs for DNA and consumables, while better enabling large-scale personalized customization of life forms to serve the diverse needs of researchers both domestically and internationally, achieving remote customization, offsite design, and economical scale production. The Facility aims to provide critical scientific means for massive engineering trial-and-error in synthetic biology, driving China's life science and technology capabilities to achieve five strategic transformations: from understanding life phenomena to mastering the essence of complex life, from qualitative description to quantitative prediction, from single-dimensional to multi-dimensional biological function detection, from single-level to multi-level biological instrument development, and from basic research to medical translation applications. The scientific objective of the Facility is to address the key scientific question of how to design and synthesize predictable life forms by adhering to a modular philosophy, standardizing experimental objects, methods, and technologies, and enhancing rational design capabilities through continuous closed-loop engineering trial-and-error. The Facility utilizes intelligent, automated, and high-throughput equipment to build multiple automated synthesis and testing production lines for multi-dimensional artificial life including biological components, devices, complex networks, artificial organelles, artificial cells, and multicellular artificial systems. These production lines coordinate organically, and combined with in-depth R&D of design software and machine learning, establish a core platform that integrates rational design and engineering trial-and-error for synthetic biology. With this Facility's support, Chinese scientists can make breakthrough achievements, rapidly obtain large genomes and non-natural elements designed from scratch, improve technical methodology systems, enhance component standardization and universality, create an integrated innovation path from components to genetic circuits, biological devices, and artificial life based on demand, and form disruptive industrial technologies.

The synthetic biology science and education infrastructure led by the Tianjin Institute of Industrial Biotechnology (hereinafter referred to as "TIB"), Chinese Academy of Sciences, with the goal of CO_{2} biotransformation, has been approved by the National Development and Reform Commission for inclusion in the CAS "13th Five-Year" science and education infrastructure project library. The "Artificial Biological Creation and Key Technology R&D Platform" will form an engineering cycle of "learn-design–synthesis-assembly–test-analysis." Its core construction content is a synthetic biology automated workstation that will integrate various operation and analysis equipment centered on orbital robots and fixed-point robots to form an integrated automated device system. This system will complete standardized tasks such as sample processing, DNA synthesis and assembly, large-scale genome editing, screening, and evaluation with high throughput and automation. Automated logistics robots will enable high-throughput sample "flow" management and coordination; a "dual-track" system of robots and human labor will achieve synergy between artificial and human intelligence; and information technology will integrate different types of big data to provide a foundation for intelligent machine learning. After completion, the platform will use CO_{2} biotransformation as a model to rapidly and efficiently create synthetic organisms with target characteristics, achieving internationally advanced "synthetic organism" customization capabilities. It will support fundamental, forward-looking, and leading-edge innovations in synthetic biology key technologies, meet enterprise customization needs, provide innovation and entrepreneurship services, and support the cultivation and development of China's synthetic biology industry.

Upstream and Downstream Institutions and Innovation Mechanisms Around Engineering Platforms

To solve practical problems using synthetic biology means, synthetic biology research must be transformed from original mechanistic discoveries to small-scale trials and then expanded to mature large-scale production. This full-chain industrialization from R&D to market cannot be achieved by automated facilities alone. Using penicillin development as a historical example: penicillin was initially discovered by Alexander Fleming at St. Mary's Hospital in the UK, then developed for production, purification, animal experiments, and clinical trials by Howard Florey and Ernst Chain at the University of Oxford. The USDA's Northern Laboratory subsequently identified the highest-yielding Penicillium strain and optimal culture medium formula, and improved fermentation technology, ultimately enabling penicillin's industrialization in the United States—a process that took 12 years and spanned three institutions in two countries [5]. Fleming, Florey, and Chain were jointly awarded the 1945 Nobel Prize in Physiology or Medicine for penicillin, powerfully illustrating the importance of seamless cooperation between upstream and downstream institutions to complete continuous work. Similarly, the journey from synthetic biology R&D to industrialization requires not only engineering platforms but also the joint promotion of multiple institutions and elements around these platforms.

Reflecting on synthetic biology's development to date, the most representative industrialization achievement is the production of the antimalarial drug artemisinin using engineered yeast. This project was conducted through the engineering platform funded by DARPA's Living Foundries program. Professor Jay Keasling of the University of California, Berkeley, was the central figure throughout the R&D and industrialization process, successfully organizing a group of upstream and downstream institutions around the synthetic biology engineering platform to form an innovation chain for developing artemisinin products and promoting their industrialization. The mature production capacity ultimately reached a level where 100 cubic meters of industrial fermentation tanks could replace 50,000 acres of agricultural cultivation, significantly reducing artemisinin production costs. Within this innovation chain, three key links can be identified.

(1) Upstream original discovery at Lawrence Berkeley National Laboratory. This national laboratory is operated by the University of California, Berkeley, with Professor Jay Keasling serving as its Deputy Director. The laboratory comprises 18 academic divisions and research centers, including the Biosciences Division, with 3,304 employees and a fiscal 2015 budget exceeding $800 million. Research platform construction funding comes almost entirely from U.S. Congressional appropriations based on Department of Energy R&D plans. The Lawrence Berkeley National Laboratory focuses on highly interdisciplinary, strongly original frontier research and stipulates that visiting personnel must outnumber permanent staff, maintaining at least a 1:1 or even 2:1 ratio. It often allocates 50% or more of project funding to external organizations, particularly universities, institutionally strengthening close cooperation between the national laboratory and universities—highly beneficial for talent cultivation. In the innovation chain, the Lawrence Berkeley National Laboratory primarily serves as the 主体 for high-risk exploratory research and the source of original basic research outcomes. The laboratory also possesses major infrastructure such as the Advanced Light Source, National Electron Microscopy Center, and National Energy Research Scientific Computing Center, which create synergistic effects with the BioFoundry's automated facilities. Meanwhile, UC Berkeley provides academic support and talent in molecular biology, cell biology, molecular genetics, proteomics, and environmental science for synthetic biology innovation.

(2) Midstream technology development at the Joint BioEnergy Institute (JBEI). JBEI is a research institution funded by the U.S. Department of Energy (2007–2017), led by Lawrence Berkeley National Laboratory, and jointly established by four national laboratories and three universities, with Professor Jay Keasling as its CEO. JBEI's key research areas include new plant design for bioenergy production, enhanced biomass degradation, new synthetic biology routes for biofuel production, and automated experimental facilities and software technology R&D. JBEI emphasizes the development of platform and enabling technologies, such as high-throughput nanostructure-initiator mass spectrometry (HT-NIMS) that can rapidly and accurately measure the composition of thousands of samples on a small silicon chip—100 times faster than traditional methods and applicable for rapid screening of biomass-degrading enzymes. JBEI has also developed techno-economic models to simulate how factors such as crop modification, biomass pretreatment, enzyme types and dosages, and biofuel varieties affect final product competitiveness and profitability. JBEI places great emphasis on interaction with industry and industrialization, with advisory committees composed of industry advisors from bioenergy, agriculture, and biotechnology sectors who provide timely information on industry standards, challenges, and opportunities. The Director of Commercialization oversees patent licensing across all JBEI partner institutions. In recent years, JBEI has collaborated with 29 companies and incubated three startups. JBEI also partners with Lawrence Berkeley National Laboratory's Advanced Biofuels Process Demonstration Unit (ABPDU) to conduct demonstration applications of ionic liquid pretreatment and microbial synthesis of bisabolene.

(3) Downstream application at Amyris, Inc. Downstream industrial transformation is primarily driven by enterprises, representing the final link in the innovation chain. Amyris was co-founded by Professor Jay Keasling with Vincent Martin, Jack Newman, Neil Renninger, and Kinkead Reiling to produce artemisinin and other terpenoid compounds, becoming the first NASDAQ-listed company in synthetic biology with annual sales of $143 million. At its inception, Amyris received $42.6 million from the Bill & Melinda Gates Foundation. Through designing and constructing artificial yeast cells for artemisinin production, its technical production capacity reached a level where 100 cubic meters of industrial fermentation tanks could replace 50,000 acres of agricultural cultivation. The cost reduction gave Amyris an important position in the supply chain of scarce medicines. Subsequently, Amyris has grown into an influential producer of farnesene and long-chain hydrocarbons for the chemicals and fuels industries. For example, using engineered yeast to produce squalene has replaced extraction routes from shark liver oil and high-grade olive oil. Amyris's automated strain engineering platform is currently one of the largest engineering platforms in the corporate world, with functions including DNA design, DNA assembly, DNA quality control, strain transformation, colony picking, strain quality control, phenotypic testing, high-throughput screening, strain preservation, data analysis, and scale-up experiments. To obtain farnesene-producing strains, Amyris researchers added 112,074 bases, deleted 41,174 bases, introduced 30 chromosomal integrations, and made 500 single-nucleotide mutations in the chassis cells, screening an average of 350 strains per week—an enormous workload made possible by the automated platform. Despite ongoing challenges in product structure and production capacity improvement speed, Amyris's technology platform potential remains remarkable, with applications in fuels, lubricants, rubber, plastic additives, cosmetics, fragrances, and pharmaceuticals.

2.1.2 Imperial College London's SynBICITE Research Center In the UK, SynBICITE (Synthetic Biology Innovation, Commercial and Industrial Translation Engine)—one of six major synthetic biology centers funded by the UK government—was established with Imperial College London at its core. SynBICITE receives £10 million from the UK government and £14 million from partner companies, led by Professors Richard Kitney and Paul Freemont. In addition to Imperial College, SynBICITE's partners include 17 universities and research institutes, plus 13 companies including Microsoft, Shell, and GlaxoSmithKline.

SynBICITE is more than just an engineering research platform; it positions itself as an innovation and knowledge center that promotes synthetic biology for industrial use, drives platform technology transformation, incubates companies, and bridges basic research to industrial translation. SynBICITE's services cover both upstream product R&D and downstream commercialization, including: BioFoundry for automated design, construction, and verification of large DNA fragments based on robotic equipment; Laboratory facilities supported by an experienced technical team to help external R&D teams complete the process from concept to product; In-lab training through workshops sharing new methods and results in synthetic biology; Commercialization training courses offering a 4-day MBA-style "Lean LaunchPad" program for synthetic biology startups and teams; and Funding opportunities through awards for proof-of-concept and prototype development, assisting winning teams in securing financing. Currently, SynBICITE has incubated startups such as Bento Bioworks (DIY genetic testing devices), Team Cellibero (educational kits for science 启蒙), and Nanocage Technologies (protein nanocages for drug delivery).

Innovation Mechanisms of Chinese Engineering Platforms

Compared with foreign academic institution platforms, Chinese platforms such as SIAT's "Major Science and Technology Infrastructure for Synthetic Biology Research" and TIB's BioDesign Center also have distinctive features and innovations.

2.2.1 Innovation Mechanisms of SIAT's "Major Science and Technology Infrastructure for Synthetic Biology Research" To fully leverage the Facility's strategic, integrated, and leading role, SIAT has implemented four innovative mechanisms based on international experience:

(1) Institutional mechanism innovation for large-scale facilities. Rather than forming a consortium of multiple units or a virtual laboratory as in previous models, SIAT is applying to establish the "Shenzhen Synthetic Biology Innovation Research Institute" to coordinate and manage facility operations uniformly. This will help clarify relationships between national, local, departmental, and host organizations, break institutional constraints, effectively coordinate local resources to support national large-scale facility construction, and represent a beneficial exploration of institutional mechanisms for CAS-local collaborative construction of major science and technology infrastructure. When preparing to build the Shenzhen Synthetic Biology Innovation Research Institute, SIAT plans to establish a new operational mechanism—including institute evaluation, personnel management, open sharing, project management, financial management, public affairs management, intellectual property management, industry-academia-research collaboration, and technology-finance innovation—by drawing on the construction methods, management systems, and operational mechanisms of world-class foreign research institutions while incorporating China's experience in establishing new-type research institutions and Shenzhen's local characteristics.

(2) Emphasis on biological design capabilities. Analogous to industrial automation, most existing synthetic biology automated facilities are at the 3.0 era, having achieved most automation and gradually moving toward the 4.0 era with enhanced data and information capabilities [6]. Shenzhen's Facility aims to fully enter the 4.0 era by systematically and substantially improving biological design capabilities using bioinformatics, mathematical models, and artificial intelligence. By developing experimental workflows that integrate automated machines with high-throughput analysis, and by rapidly iterating through thousands of potential circuits to test and validate the most valuable candidates, the platform will promote widespread application of complex synthetic genetic circuits. Moreover, biological design software will be primarily self-developed.

(3) Independent R&D of key technical equipment. High equipment purchase and maintenance costs, along with the difficulty of upgrading purchased production lines, pose another challenge for automated facilities. Shenzhen's Facility addresses this by building localized automated modules as flexible "functional islands" that perform specific functions and can be combined into various production lines for DNA, phages, bacteria, fungi, etc. Functional island modules offer flexibility, scalability, and strong specificity, effectively addressing continuous technological updates in synthetic biology while leveraging system integration advantages by combining various equipment features. Key technical equipment development follows a "red-blue team approach," balancing independent innovation with absorption of foreign advanced technology to promote domestic production of high-end automation equipment.

(4) Medical translation research capabilities. To strengthen connections with downstream applications and build on Shenzhen's research foundation, the Facility specifically includes a medical translation research sub-platform. This platform uses artificially designed genetic circuits to modify cells, bacteria, or viruses to intervene in human physiological and pathological processes, creating breakthrough biological therapies and improving diagnosis, treatment, and prevention of cancer and metabolic diseases. It includes clinical resource systems, clinical testing systems, biologics R&D and preparation systems, and clinical translation scale-up systems. The focus on medical synthetic biology represents a major feature of the Shenzhen Facility.

2.2.2 Innovation Mechanisms of TIB's BioDesign Center Leveraging strong top-level design and strategic vision, TIB established the BioDesign Center in 2012 and independently designed China's first robotic automation equipment for synthetic biology. Hardware introduction is only the first and simplest step in applying automation equipment to synthetic biology. The core of an efficient and widely applicable synthetic biology engineering platform lies in automation technology development based on hardware, biological experimental process development, 上位 biological design software development, and interface technology between biological design software and automation equipment.

Based on TIB's solid technical foundation in industrial biotechnology and good cooperation with relevant enterprises, TIB's synthetic biology automation platform focuses on deeply developing capabilities for creating synthetic biology relevant to bio-manufacturing, building the most professional and industry-suitable open engineering platform in the industrial biotechnology field. The existing platform has actively developed numerous automated experimental processes and methods, significantly improving automated system service capabilities. For example, it has initially achieved automated single-gene cloning with a throughput of 300–600 clones per day. Complex plasmid multi-modular assembly has reached 100 constructs per day with >90% accuracy, and automated genetic operations have been implemented for various model organisms (e.g., *E. coli*, *Corynebacterium glutamicum*, *Saccharomyces cerevisiae*, *Bacillus subtilis*), with some model organisms achieving high-throughput automated genome editing capabilities of 300 edits per day. The center is also collaborating with the BioDesign Center to develop 上位 biological design software and its interface with automation equipment, providing strong platform technology support for high-throughput automated creation of synthetic biology at the institute.

Future Prospects for Synthetic Biology Engineering Platforms

Like synthetic chemistry's rapid development in the 19th century, synthetic biology technology is an engineering technology and scientific fusion capable of creating a new era of wealth generation. Its impact on traditional industry will be revolutionary, and it has already become the forefront and strategic high ground of life sciences. The construction of synthetic biology engineering platform facilities may provide novel solutions to major human challenges in healthcare, energy, and environment, fundamentally transforming human production and lifestyles.

Regarding platform self-development. In June 2018, representatives from 15 academic institutions worldwide attended the "Global BioFoundry Meeting" in London[2]. Participants identified common challenges facing BioFoundries, including expensive infrastructure maintenance and operational personnel costs, lack of common facility hardware/software standards and intellectual property sharing mechanisms, difficulty in sharing biological component materials across countries, and potential users' lack of understanding of automated facilities. Therefore, future trends for synthetic biology engineering platforms include: forming alliances to develop common operating systems, automation protocols, and standards to drive overall industry development; improving legal tools such as cross-national and cross-institutional material transfer agreements and intellectual property sharing agreements to reduce costs for sharing experimental materials and avoid redundant R&D; providing cloud services around automated facilities to expand user groups, particularly small and medium-sized enterprises; and strengthening collaboration among international automated facilities, such as jointly undertaking international big science program research tasks, sharing allocation tasks, and negotiating pricing with consumables suppliers.

Regarding institutional innovation around engineering platforms. Recommendations include: clarifying the positioning of engineering platforms and their host institutions, focusing on major scientific tasks and national large-scale science and technology infrastructure as the main line, and conducting strategic, forward-looking, foundational, systematic, and integrated technological innovation through interdisciplinary collaboration and intensive support to address major national long-term goals and needs, break through world-leading major scientific questions, and master disruptive technologies that create first-mover advantages and lead future development; establishing a high-level unified coordination and management agency to ensure efficient platform system operation; granting host institutions high degrees of autonomy, with government responsible for managing platform establishment, budgets, and evaluation while delegating sufficient autonomy in specific research, personnel, and financial management to ensure academic and operational independence and flexibility; establishing sound scientific evaluation and supervision mechanisms with regular evaluations at different levels and forms, including board evaluations, third-party peer reviews, internal academic committee evaluations, and research group self-evaluations to ensure research direction, level, and quality; improving the innovation chain, with different entities responsible for new discovery, development, and industrialization to create a clear path from basic research to industrial translation; and fully leveraging the CAS Group Army advantages in synthetic biology in Tianjin, Shanghai, Shenzhen, and other locations to further establish core aggregation and open collaboration innovation mechanisms, organize frontier-leading technologies and key common technology innovations in industry, strengthen technology diffusion and transfer transformation, and form a more complete industrial innovation ecosystem.

In the future, as synthetic biology engineering platforms mature, biological design, manufacturing, and testing cycles and costs will be substantially compressed. Researchers are expected to ultimately master genetic circuit design principles, transforming biological design, R&D, and manufacturing into engineering design problems. Through manipulation of organisms, humanity will be able to obtain new knowledge and manufacture novel materials, devices, systems, and life forms.

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CUI Jinming is an Associate Investigator at the Shenzhen Institutes of Advanced Technology, Chinese Academy of Sciences (CAS), and a member of the Youth Innovation Promotion Association, CAS. He received his Ph.D. in biochemistry from Purdue University, followed by postdoctoral research at the School of Medicine, Johns Hopkins University. His research interests include directed evolution of membrane protein components, applied microbiology, and policy and ethics studies of synthetic biology development. As a project leader, he has presided over two national funds and four regional funds. E-mail: jm.cui@giat.ac.cn

LIU Chenli is a Principal Investigator and Director of the Institute of Synthetic Biology, Shenzhen Institutes of Advanced Technology, CAS, and Director of the Center for Quantitative Synthetic Biology. His research interests include exploring fundamental biological principles with synthetic gene circuits, tumor therapy, and development of directed evolution methods. He leads the preparation of the "Shenzhen Major Science and Technology Infrastructure for

Synthetic Biology Research" as Chief Scientist. He is an awardee of the national "Thousand Youth Talents Program" and the CAS "Hundred Talents Program." He received the Hong Kong Young Scientist Award and Li Ka-shing Award in 2012, and the Zhongyuan Concord Biomedicine Innovation Breakthrough Award in 2017. He serves as an Editor of *ACS Synthetic Biology*, Deputy Director and Secretary-General of the Chinese Bioengineering Society, and President of the Shenzhen Synthetic Biology Association. E-mail: cl.liu@siat.ac.cn

Note: Figure translations are in progress. See original paper for figures.