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Viewpoint

Introduction to Engineering Biology: A Conceptual Framework for Teaching Synthetic Biology

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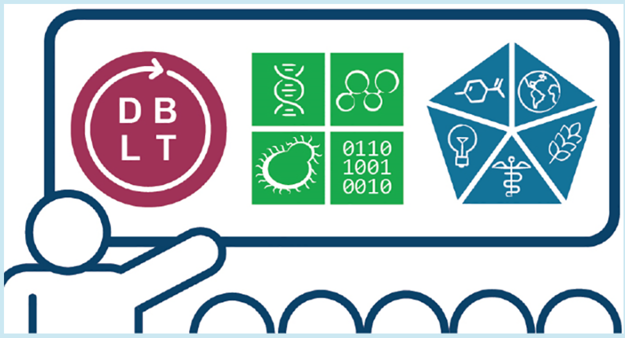

ABSTRACT: As the impacts of engineering biology grow, it is important to introduce the field early and in an accessible way. However, teaching engineering biology poses challenges, such as limited representation of the field in widely used scientific textbooks or curricula, and the interdisciplinary nature of the subject. We have created an adaptable curriculum module that can be used by anyone to teach the basic principles and applications of engineering biology. The module consists of a versatile, concept-based slide deck designed by experts across engineering biology to cover key topic areas. Starting with the design, build, test, and learn cycle, the slide deck covers the framework, core tools, and applications of the field at an undergraduate level. The module is available for free on a public website and can be used in a stand-alone fashion or incorporated into existing curricular materials. Our aim is that this modular, accessible slide deck will improve the ease of teaching current engineering biology topics and increase public engagement with the field.

KEYWORDS: *education, engineering biology, synthetic biology, curriculum*

■ INTRODUCTION

Engineering biology is a rapidly growing field with the potential for substantial impact across multiple aspects of society including medicine, climate change, and manufacturing. Globally, there is acknowledgment from governments that engineering biology will play a major role in future technological and economic advances (*e.g.*, recent legislation and policy for investments in biomanufacturing in the US[1−3] and internationally[4−8]). Accordingly, it is important to promote literacy in, or at least familiarity with, engineering biology for both the general public and future science leaders.

Promoting advancement, awareness, and participation in engineering biology necessitates teaching this new and impactful field to a broader population than just those that are already engaged in it. Obstacles to teaching engineering biology include limited representation of the field in widely used scientific textbooks or curricula and the inherently interdisciplinary nature of the subject that requires convergence of science and engineering rather than the more siloed approach in which these fields are frequently taught. It is also not always obvious where in a student's educational path engineering biology concepts are most appropriately and effectively integrated.

There are numerous opportunities to introduce core engineering biology concepts and applications to individuals during different stages of training and professional development. High school or college courses covering introductory biology, molecular biology, biochemistry, computer science, bioethics, and other topics all could provide opportunities to link to, at minimum, a high-level discussion of engineering biology principles or applications. Instructors of these courses may already have interest in introducing students to engineering biology, but may not have the time or expertise to create their own instructional materials that are accurate yet appropriately leveled for their students. For example, a high school instructor may want a few big-picture slides requiring little previous biological knowledge, while a university instructor might prefer an entire lecture or unit that goes into greater detail. Continuing education in industry provides yet another potential use case, where relevant introduction of core tools or applications could serve as an "onboarding" tool for people from nontechnical or unrelated backgrounds who

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will be expected to interface with engineering biology technologies or products.

As evidence of the obstacles and challenges to teaching engineering biology described above, the Engineering Biology Research Consortium (EBRC) Education & Engagement Working Group[9] has received multiple requests for freely available introductory engineering biology teaching resources for use in a variety of settings. To meet this need for an introductory resource compatible with diverse educational settings, we have developed a reusable and adaptable curriculum module that can be used by anyone to teach basic principles and applications of engineering biology. The module is freely available on the EBRC website at https://ebrc.org/curriculum-modules/. (This module accompanies another member-created curriculum module on Synthetic Biology and Machine Learning, also available at https://ebrc.org/curriculum-modules/.)

The module consists of a versatile, concept-based slide deck designed with input from experts across engineering biology sectors to cover key topic areas in an accessible way. In addition to the slide deck, which can be downloaded in PowerPoint, Google Slides, or PDF format, the module webpage also includes the expected level of background knowledge needed for students and related learning goals to enable instructors to appropriately place the content in their materials. Herein we describe the module content and topics, how this adaptable module could either be used in a stand-alone fashion or incorporated into existing curricular materials, and ongoing efforts to understand the utility and impact of this and other curriculum modules for engineering biology.

■ MODULE CONTENT

To define the scope and content of the introductory module, the Education & Engagement Working Group identified the major concepts and learning objectives most important for the future engineering biology workforce. These collected topics aligned well with the major themes of the 2019 EBRC technical roadmap, *Engineering Biology*.[12] The roadmap was created by leading members of the engineering biology research community and has since influenced research, policy, and industry at national and international levels. This roadmap addresses challenges and milestones across the field of engineering biology, focusing on four technical themes (engineering DNA, biomolecular engineering, host engineering, data science) and five application sectors (industrial biotechnology, health and medicine, food and agriculture, environmental biotechnology, and energy) (Figure 1).

These key themes were incorporated into the module, which has four Learning Objectives:

1. Understand how engineering biology interacts with and is distinct from similar fields.
2. Identify how the Design, Build, Test, and Learn (DBTL) cycle shapes research in the field.
3. Gain a high-level understanding of the technologies that make up the Core Tools of engineering biology, including how they work and how they are applied in the DBTL cycle.
4. Recognize how engineering biology impacts topics the target audience cares about or their area of expertise, and how it can impact society as a whole.

Existing educational materials incorporating these themes include videos on specific topics (iBiology[13] and see https://ebrc.org/youtube) and Massive Open Online Courses (MOOCs) that have had successful worldwide engagement to introduce fundamentals in the design of DNA, RNA, and protein circuits as well as in biomolecular modeling.[14,15] As a single modular slide deck, the teaching aid we have developed is meant to bridge the gap between single topic-focused videos and full courses like the MOOC. The modular nature of this slide deck is vital, providing a framework that allows any section to be updated or replaced. This allows the deck to keep pace with technology development and research advancement in the field without requiring a complete overhaul of the lecture. To support the material with currently relevant content, we collected existing open access figures or created our own as needed to illustrate key points.

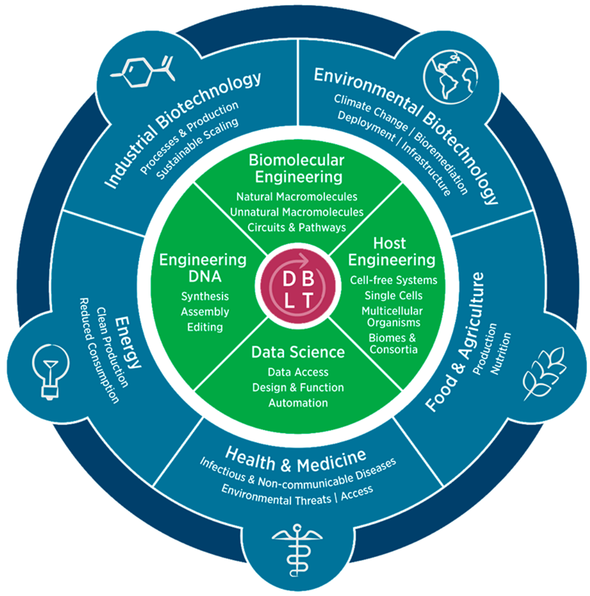

Figure 1. Technical roadmap for *Engineering Biology*, developed by EBRC. This roadmap provides the intellectual framework for our learning module. Figure reproduced with permission from EBRC.[12] Copyright (2019) Engineering Biology Research Consortium.

The slide deck itself is grouped into five concepts, outlined in Table 1. These concepts cover first fundamentals, followed by technical topics, and finally applications and impacts, as described by the *Engineering Biology* roadmap.

Concept 1−1, "What is synthetic biology?" gives an overview of the field of engineering biology ("synthetic biology" and "engineering biology" are often considered synonyms for the field; "synthetic biology" may be more broadly recognizable though is narrower than the scope our module aims to cover). This section directly addresses the first

Table 1. Topics and Organization of Introduction to Engineering Biology Curriculum Module

Concept	Topic	Slides
1−1	What Is Synthetic Biology?	4−23
1−2	Engineering Biology Roadmap and the "Design, Build, Test, and Learn" Cycle	24−28
1−3	Core Tools for Engineering Biology	29−48
	Part 1: Engineering DNA and Biomolecules	
1−4	Core Tools for Engineering Biology	49−73
	Part 2: Engineering Hosts and Data Science	
1−5	Impacts and Applications of Engineering Biology	74−85

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Table 2. Use Case Examples for the Intro to Engineering Biology Module and Specific Concepts

Setting	Goal	Concepts Used
Community college: Biology 101 course	Show approach, applications, and careers. Teach DBTL thinking.	Complete lecture, with DBTL project.
Graduate school course on molecular biology	Introduce students to the field, use slides as framework to incorporate current material.	1–2 DBTL early in course. 1–3/1–4 Core Tools slides expanded to full lectures.
Company in engineering biology industry onboarding new employees	Introduce new employees to a conceptual overview of engineering biology as a field using slides as a point of departure.	1–1 and relevant application of 1–5, coupled with slides on the company's own technology.
High school club/extracurricular on synthetic biology	Expand on existing coursework (such as that from BioBuilder, https://biobuilder.org), show technologies used and careers in the field.	Full lecture (have different group members present a section of slides to the group), including further resources.

Learning Objective of the module and acts as a broad primer for audiences new to the field. For experts in related fields, this Concept could also help them identify where their current work and expertise aligns to the broader efforts of engineering biology. The Concept closes with two relevant examples (insulin bioproduction and gene drives) to introduce some of the technology used in the field and engage users with applications of engineering biology. These examples also begin to address the fourth Learning Objective and were chosen for their global impacts. This Concept is likely to be most effective for students who are considering entering the field or are not familiar with engineering biology, inspiring them and showing how the technologies it enables can have real world impacts.

Concept 1–2, "Engineering Biology Roadmap and The 'Design, Build, Test, and Learn' Cycle" introduces the DBTL cycle and uses the examples from the first Concept to contextualize how the cycle works in practice. This Concept addresses the second Learning Objective by directly explaining the DBTL process. We also use this section to introduce a project-based element that educators can use as an in-class group activity or a take-home addition to the lecture. For high school and undergraduate students, exploring how they could engineer biotechnology to improve society—and how the DBTL cycle can help this happen—can be a particularly impactful way for them to engage with the content more deeply. This Concept could also be used in a stand-alone fashion in a variety of biology courses to introduce the engineering mindset. Moreover, it does not focus on specific technologies that are likely to change in the near future, likely giving it significant longevity without frequent updates.

Concepts 1–3 and 1–4 cover the "Core Tools for Engineering Biology". Although these Concepts are the most likely to require changes as the field progresses, their organization around key aspects of biology and engineering (genetic code, biomolecules, organisms, and data science) will allow specific elements to be changed out without disrupting the module as a whole. These Concepts are vital to creating understanding of the use and development of biotechnologies, which is the third Learning Objective. For each technology, the slides give enough detail to understand how it might be used without becoming a tedious lecture on any specific topic. For advanced courses, the slides and linked resources could be expanded into separate lectures for each topic. Concept 1–3 covers the first two "Core Tools," which are "Engineering DNA" and "Engineering Biomolecules." "Engineering DNA" explains how DNA is synthesized, assembled, and edited, as well as how DNA elements can be abstracted into "parts" and how these are depicted in gene circuit diagrams. "Engineering Biomolecules" goes over how natural and unnatural macromolecules are designed and engineered, as well as how they can be assembled into circuits and pathways within a cell. Concept 1–4 contains the final two "Core Tools," which are "Engineering Hosts" and "Data Science." "Engineering Hosts" discusses how different organisms and cell types are used in engineering biology, the advantages and disadvantages of different model systems, and the scales at which engineering of hosts is done (e.g., cell → tissue → organism, microbe → consortia → ecosystem). "Data Science" highlights the huge amount of biological data being created and the databases that collate those data, along with the modeling, automation, and robotics tools used to make these large-scale experiments possible.

Finally, **Concept 1–5, "Impacts and Applications of Engineering Biology"**, gives examples of current and future technologies with real-world impacts across the major sectors connected to engineering biology. It also highlights career sectors and paths open to those interested in the field, with examples showcasing diverse educational and scientific trajectories. This Concept completes the fourth Learning Objective, encouraging students to visualize both the broad impacts of the field and how they can contribute to those efforts. The format also outlines how educators could add application examples highlighting their own research, and it allows space for new applications to be added or swapped as the field progresses.

■ USAGE AND SHARING

To highlight the variety of ways the slides can be utilized for different audiences and goals, we outline potential use cases in Table 2. Across diverse possible educational settings and instructional goals related to engineering biology, the modular nature of the deck is intended to work in a plug-and-play fashion with an existing curriculum while providing exposure to current engineering biology concepts and techniques. This removes the burden of instructional resource development for teachers looking to incorporate engineering biology into their courses while also providing a standalone resource to students looking for a quick introduction to the field. The use cases describe the potential educational setting, the goal of incorporating engineering biology into that setting, and which Concepts from the curriculum module can be leveraged to achieve that goal.

The module is intended to be usable by biology teachers and learners across educational settings and levels. The slide deck has been released under a Creative Commons CC BY-NC-SA 2.0 license to allow free classroom and individual usage and remove barriers to access.[16] This license also allows derivatives, which is vital for educators seeking to use and adapt the material for their own needs. Open educational resources like this are critical in helping broaden the scope of professionals and students who have the ability to gain knowledge about engineering biology,[17] as well as for developing an equitable, diverse, and innovative bioeconomy.[18]

CONCLUSION: FUTURE OF THE SLIDES

EBRC continues to work on developing curriculum modules across various topics in engineering biology as a resource and educational tool to enable greater engagement with the field. This set of slides represents the first "Design" and "Build" iteration of this curriculum module. They are intended to be updated over time and refined through the crowdsourced "Test" of actual use and "Learn" through community feedback. We encourage the engineering biology community to explore this material and would value feedback on their content and on individual use experiences (feedback can be provided to education@ebrc.org). We hope that the modularity and framing of the content will help keep each section usable longer, even as the specific details of the technologies and applications described change as the field progresses. Although concepts like "Engineering DNA" are core to the field, the tools we use to implement these concepts will evolve over time. This modular structure further enables the addition of new modules by EBRC or others, including potential modules on bioethics, technologies like CRISPR, or deep dives on specific applications. Overall, our hope is that as a free and customizable introductory educational resource, this slide deck will further access to engineering biology education for all.

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Notes

The authors declare no competing financial interest.

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(9) The EBRC Education & Engagement Working Group is a collection of academic and industry experts in engineering biology with extensive experience and commitment to increasing understanding of engineering biology and participation in the field,

primarily through education. Past Working Group efforts have included a compilation of Synthetic Biology videos available on YouTube and described in Dy et al.[10] and a family oriented podcast series in partnership with Tumble Media.[11] EBRC (https://ebrc.org) is a nonprofit public-private, member-driven organization dedicated to advancing engineering biology across academic, industrial, and government sectors. Within EBRC, the Education & Engagement Working Group focuses on promoting awareness of and increasing participation in research and the bioeconomy.

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