LEAP
Synthetic Biology
Leadership Excellence Accelerator Program

Enhancing Undergraduate Education to Drive Responsible Growth of the Bioeconomy

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Synthetic Biology LeAP Strategic Action Plan

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Synopsis

The US bioeconomy generated an estimated $300 billion of revenue in 2011. Advances in foundational technologies, such as synthetic biology, are lowering barriers to biotechnology, enabling a growing number of people to participate. Technological advances and the democratization of biotechnology present opportunities for economic growth, particularly in areas like small-scale, distributed biomanufacturing. In addition to growth, technical advances springing from the bioeconomy also present great hope for reducing the severity of some of our nation's most pressing financial challenges, particularly those related to the increasing costs of healthcare delivery and energy. These opportunities challenge educational institutions to enhance training programs, foster innovation and entrepreneurship, and to promote the responsible/ethical use of biotechnology. We identify new opportunities for research universities to help drive growth in the bioeconomy, highlight existing efforts and propose new opportunities, and describe some of the associated "boots-on-the-ground" challenges that must be addressed before widespread implementation can succeed.

Sustaining responsible growth of the bioeconomy: Three goals/action items for research universities

The White House's Bioeconomy Blueprint estimates that the annual growth of the bioeconomy ranges between 15 and 20%[1, 3]. This includes activities in agriculture, biologics (pharma), and a broad range of activities classified as "white" or industrial biotechnology. Growth and in each of these sectors – but particularly industrial biotechnology –is projected to lead to sweeping changes in health care, bioenergy, green chemistry, bioremediation, and other important societal problems. Some industries already feel shortages of appropriately trained employees (e.g. in agriculture, plant breeders are scarce) while in other cases a glut of non-specialist (e.g. molecular biologists) may actually exist. Rapid changes and uncertainty, current and projected, in the type of activities that will underpin growth of bioeconomy make it reasonable to

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[1] This paper is a working version. Please contact the author at mtfacciotti@ucdavis.edu to provide feedback.
For the most recent version of this strategic action plan, visit http://synbioleap.org

suppose that increasingly severe imbalances in appropriately trained scientists, engineers, and entrepreneurs may slow the transition to a more robust bioeconomy and reduce our international competitiveness. Educational institutions play a key role in shaping the talent pool and must therefore be sensitive to the dynamics of the bioeconomic landscape. Unfortunately, sparse data reporting trends in the bioeconomy makes it difficult to define targeted enhancements to educational curriculums. Accordingly, we identify three broad thematic action items that research universities can pursue at the undergraduate level that will help smooth the path towards a robust bioeconomy. They are:

1. **Enhance technical training in response to bioeconomic need**

2. **Enhance innovation and entrepreneurial activity**

3. **Promote the responsible use of biotechnology**

We recognize that broad success in the educational sphere requires the harmonious orchestration of players from across the educational spectrum (K-12, Community Colleges, Undergraduate, Graduate and community groups). For the sake of this brief discussion we focus strictly on undergraduate education, since its unique role as hub of the educational system gives reforms in this area the potential to reach the broadest audience.

Enhance technical training

Fortunately, research universities tend to excel at content delivery; even in the face of profound pressures to significantly change the mode of delivery. Curriculums, whether lecture-based or on-line, supplemented with discussions and laboratory activities usually provide students with good technical training. The critical questions to ask are whether the "right" material is being taught and if not what mechanisms exist to adapt curricular materials to meet the needs of all constituents (e.g. employers, students, taxpayers). In the context of the bioeconomy identifying the current needs, let alone projecting what they will be the future, is complicated by a lack of industry data and narrow bands of communication between industry and academic centers. Federally directed efforts to assess and distribute data on the changes occurring in the bioeconomy would make a dramatic difference in the ability of universities to respond appropriately and are desperately needed. That said, even when need for curricular change is identified programmatic response to newly identified "needs" may be painfully slow. Corresponding cultural and structural changes at universities that would make them more responsive to economic data – if available – are also important.

Enhance innovation and entrepreneurial activity

If, as projected, growth of the bioeconomy will come courtesy of small-scale start-up entrepreneurial activity, universities can play a critical catalytic role by cultivating innovation and entrepreneurship in undergraduate biology and bioengineering education. While we cannot expect that all students will chose to pursue opportunities in entrepreneurial activities, the societal and economic opportunity costs are too high to ignore those with this inclination. We note that even students who may not be entrepreneurially inclined can benefit from additional entrepreneurial educational experiences that ask them to exercise their creative thinking skills within economic constraints. Fortunately, models for possible activities already exist in many business and engineering programs. Many of these programs have strong traditions of providing students opportunities to participate in formal business courses, business plan and design competitions, and design and innovation spaces. Unfortunately, most of these design and entrepreneurship programs target graduate or professional students and few focus specifically on biotechnology. The annual iGEM (http://www.igem.org) competition in synthetic biology is perhaps the most successful example of an undergraduate focused biotechnology innovation (and now recently entrepreneurship) program and its incredibly rapid growth reflects a huge pent up demand for innovation activities in the biotechnology space.

Like many other activities at the undergraduate level instilling confidence in a students' own ability to use what they learn in school is as important as any vocational "book" knowledge they gain. Students must leave school believing that they can become the catalysts for a new bio-based industry. Instilling that confidence is no easy task, but is one that can be accomplished. One idea, championed by this author, is the creation of biotechnology innovation labs. This idea is borrowed unapologetically from similar efforts at the other educational levels including MIT InvenTeams (http://web.mit.edu/inventeams/) and efforts at the Bio-X institute at Stanford University (http://biox.stanford.edu). We also borrow from the ideas like the formation of undergraduate-focused core facility labs, like those at Texas A&M (http://biomed.tamu.edu/research/labs.php). Our aim is to blend core curricular activities with traditionally extracurricular innovation/entrepreneurship programs. This mixed approach accomplishes two important things. First, by providing physical resources (innovation/prototyping labs) it gives students a low cost-of-entry space and support to put their technical knowledge and imaginations to work bringing to life ideas that would otherwise never materialize. Second, giving students the opportunity to pursue their original ideas help breed the self-confidence they'll need to become transformational leaders. The formation of bioinnovation labs should also serve as nucleation points for interaction with industry, providing direct access to talent, exposing students to players in the bioeconomy, and shortening the "needs" feedback loop between educational institutions and industry.

In all cases programmatic support (both financial and in curricular flexibility) will be critical successful implementation of bioinnovation labs. Monies will be required to support projects and hire staff, while programs (including accreditation programs like ABET) will need to develop creative ways of substituting elective credit hours for work in facility. The latter requirement may be a challenge depending on the disposition of a program's faculty towards activities that fall outside the traditional. Finally, reasonable expectations must be set for the number of marketable products that emerge from an undergraduate innovation lab. The primary goal is not to turn these facilities into revenue streams for universities but rather to enhance technical training and embolden students to innovate. Nevertheless, we expect some students to develop innovations to the point at which a focus on entrepreneurial activity is warranted. If, in this respect, sufficient momentum is achieved, existing entrepreneurial centers like the Deshpande Center at MIT (http://deshpande.mit.edu/) may provide examples for how one can bring entrepreneurial expertise and funding to evaluate the commercial potential of early stage projects.

Promote the responsible use of biotechnology

The notion of responsible use has several components, including ethics, safety, and economic factors. Universities training students on the responsible use of biotechnology should strive to instill in students an awareness for the responsible use of biotechnology (students should be aware of the concept of responsible use), an understanding of the concepts underlying responsible use (students should be able to identify topics related to responsible use and think critically about the underlying arguments), and to develop the student's capacity to take actions that ensure responsible use and reduce the potential for misuse (students should feel empowered to act responsibly).

In the context of technology, the term "responsible use" can have several connotations. For instance, nearly all technologies come with dual-use potential and biotechnology is no exception. Distinguishing between "good" and "evil" uses of biotechnology obviously falls under the umbrella of understanding responsible use. The increasing likelihood that biotechnology will touch all corners of our daily lives also makes it reasonable to expect that future biotechnologists and entrepreneurs will encounter less obvious (but no less important) ethical questions in the course of their work. Having a grasp of and developing the sensitivity to ethical and moral boundaries that may be crossed during product conception and development also constitute responsible use. Finally, an even more subtle, but equally important element of responsible use is to recognize whether one is working on viable and safe technologies. Deciding how to allocate resources for projects that have real potential for good is critical and a key component of technology application. This notion of responsible use is harder to teach but nevertheless extremely important. Training students who ultimately become developers and vendors of new technologies to recognize and become sensitive to issues related to responsible use and to instill within them the capacity to act responsibly remains a critical goal of the educational system. This issue, however, extends beyond a technology-focused audience. The expansion of the bioeconomy will also create increasing opportunities for the public to interact with products of biotechnology. Enabling the consumers of biotechnology to participate in educated debates on responsible use may be equally, if not more, critical to the long-term success of biotechnology.

Surprisingly, while many universities offer courses on bioethics – and most engineering programs require students to complete an ethics course – few biology/biotechnology require this. A good, easy first step to promoting the responsible use of biotechnology would be to require that all biology and engineering students successfully complete a course in bioethics. As noted, this is a relatively easy requirement to implement since most universities already offer these courses as electives. That said, many existing courses in bioethics focus almost exclusively on medical ethics rather than issues pertaining more directly to biotechnology. For instance, a discussion about responsible resource allocation would need to be added to most existing courses.

Challenges to implementation

Understanding the "needs" of the bioeconomy

Tracking economic activity and the labor needs of the bioeconomy may be one of the most pressing issues facing bioeconomy-oriented policymakers and educators alike. Intelligent decisions are difficult to make in the dark. For universities the lack of market data makes it extraordinarily challenging be responsive to industry's needs. Interestingly, the "data hole" is not equally spread across all sectors of the bioeconomy. While detailed statistics on GMO crops and biologic production are available, the "white/industrial biotechnology" sector - where an expected large portion of bioeconomic growth is predicted – is woefully tracked. Some have suggested that a portion of this "data hole" can be tracked to the fact that few appropriate NAICS codes (http://www.census.gov/eos/www/naics/) are available to track activity in this new sector of the economy. Fixing this knowledge gap, starting perhaps with better NAICS codes, is critical and will help answer seemingly simple questions like: How many people should we train and what skills should they have?

Identifying the labor needs of the current bioeconomy is clearly important but is only the first step. Assuming that current trends in bioeconomic activity accurately forecast potential growth areas and the potential of the technologies to meet societal needs is shortsighted. Additional efforts to directly assess societal needs that can be met by advances in biotechnology are also critical. In the context of education's role in spurring the bioeconomy, a first good step along these lines may be to help students develop an appreciation for evaluating societal needs outside of those defined by current industrial trends. Enabling more students to identify solvable problems may ultimately prove to be one of the most economically and socially important activities that universities will engage in.

Breaking institutional traditions

Change, of any sort, typically comes slowly at large educational institutions. Even simple changes to core courses can be met with resistance from faculty. Allocating space for new educational/entrepreneurial activity may be even more controversial. Therefore, developing strategies for lowering institutional barriers of resistance and incentivizing curricular changes will be critical.

Incentivizing young faculty

Individual faculty often champions new initiatives. In the case of new disciplines (like synthetic biology), it is often junior faculty who find themselves promoting the "new ideas" sometimes against a current of opposition by established interests. Unfortunately, while the intrepid junior faulty often enthusiastically invest time and resource into new educational projects, they are also the least incentivized to do so by existing tenure, merit, and promotion criteria. Understanding how to reward junior faculty for creating new activities also remains a challenge. This challenge is not new and not unique to the discussion at hand. Unfortunately, to our knowledge, no obvious solutions have been satisfactorily implemented.

Funding

Some of the activities proposed above - particularly those involving laboratory resources - will require stable funding to be successful. Given current budgetary constraints, it is difficult to see how broad-scale adoption can take place. This needs serious attention - the opportunity cost is too large not to find a solution.

Suggestions for implementation

The specifics of how these action items discussed herein should be best implemented and broadly distributed is still a matter of discussion. It is clear that a "one size fits all" approach to implementation will not work and that implementation of specific plans will differ at every institution. However, we summarize some suggested principles for facilitating local implementation of productive ideas here:

1. Invest in our ability to better track activities in the bioeconomy, particularly in the "white"/industrial sector – this lets institutions set specific goals based on broad economic trends which may help buffer against gluts of generalists and shortages of specifically skilled individuals.

2. Organize and promote social and professional networks among individuals acting to foster responsible growth in biotechnology (e.g. LeAP) – this provides a network for idea creation,

refinement and dissemination among student, educator, government, and business constituents.

3. Create and maintain an on-line materials sharing resource for networked educators to share ideas/tools etc. – several good examples already exist or are being built across various disciplines. Support in these efforts should continue.

4. Develop support for curricular changes that help drive growth in the bioeconomy and responsible use by enabling well-informed advocates that can take a clear message directly to institutional leadership and reluctant faculty.

5. Provide funding dedicated to catalyzing innovative ideas that foster entrepreneurship in biotechnology - for example, funding for educational activities like the aforementioned bioinnovation labs or NSF's Lean Launchpad initiative (http://steveblank.com/category/lean-launchpad/) .

6. Promote incentives for faculty across the spectrum of seniority, but particularly junior faculty, to invest time and effort in reshaping curriculums while also experimenting with new delivery mechanisms. Incentives may be targeted at supporting faculty research initiatives rather than the educational work itself.

Assessing progress/success

Determining causal associations between changes in curriculum, particularly in highly multi-dimensional research universities, and specific external outcomes is incredibly difficult. We propose to measure several variables that may collectively serve as valuable indicators of successful implementation of programmatic change. The metrics we propose focus heavily on assessing the perceived value of the curricular enhancements for key constituents: students, faculty, and external partners. Individual institutions will need to determine for themselves what level of change in behavior and new activities constitutes success.

Proposed Metrics to Assess Success

1. Measure yearly trends in student participation in innovation/entrepreneurial activities. This is easily accomplished if dedicated classes and programs are offered.

2. Measure yearly interest of faculty to participate in biotechnology/synthetic biology related education related activities. For example, increased willingness to co-mentor activities in a bioinnovation lab would be viewed as progress and an indicator that faculty perceive value in these activities.

3. Assess the degree of integration of the ideas and associated principles outlined above into the formal curriculum by the faculty at large.

4. Measure the number of new partnerships with industry and non-profit institutions that results from an added emphasis on bioinnovation.

5. Measure the number of new educational partnerships (i.e. those with K-12 and/or community colleges) that derive from a greater emphasis on bioinnovation and responsible use of technology.

6. Survey alumni to assess the relative importance that the curricular changes have had on their career trajectory and outlook on responsible use of technology.

7. Count the number of companies spun-off directly from bioinnovation labs and related activities.

At a national level it will also be informative to:

8. Assess whether collective activity of at research institution is helping to drive growth in the bioeconomy. This can be achieved by surveying data collected by universities in point seven above.

9. Assess the rate of new private investment in biotechnology.

10. Assess how often the concept of "responsible use" appears in institutional mission statements, web sites, and other company media.

Concluding Remarks

We conclude by noting that in the seeming rush to alter curriculums, particularly in response to economically-driven arguments, we must be careful not to abandon the tenets of a liberal-arts education that have served nearly all undergraduate institutions so well for so long. This core bedrock of undergraduate education at research institutions remains inviolable and the realization of the goals stipulated above must continue to be consistent with these principles. Our efforts to enhance technical training or entrepreneurship should never focus too much on meeting specific industrial goals - where specific "application-driven" skills/knowledge can quickly become outdated. Rather we should ensure that education remains focused on developing a student's ability to explore their world without concern for vocational utility. We cannot trade short-term goals for long-term flexibility and competitiveness. That said, we should still strive to shape the context in which a student's thinking develops to reflect changing societal challenges and economic opportunity.

References Cited:

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ADDENDUM

The author's personal post-LeAP action plan and preliminary "results"

Given the preceding discussion, the author constructed a specific action plan to implement over the following months. Some of the activity is described below.

Enhancing technical training

While no specific action plan was proposed by the author to meet this goal, over the last two years, the author has developed an upper division elective lecture course in synthetic biology that covers a broad set of issues associated with this field and enhances the technical know-how of our graduates in an area of relevance to the bioeconomy. The course has been popular among students. One LeAP derived proposed course modification would be to collaborate with Dr. David Kong on the development of laboratory modules. The course is next offered at beginning April 2013 and will likely see a first draft of this idea incorporated in the form of rapid microfluidic design prototyping and construction. An on-line version of the course could be created as a way to expand content delivery beyond the confines of the university. Another option being considered by the author is the creation of a "flipped" course, in which content is, delivered on-line with the traditional lecture hours being used for project and problem-based activities.

Enhancing innovation and entrepreneurial activity

The author's set forth two action items at LeAP that attempt to meet this goal. The first action item was to create a lecture outlining broad challenges that might be solved with biotechnology and to deliver this lecture to a large enrollment (520 students) introductory biology course. This lecture attempts to introduce students to the potential of biotechnology and satisfies the requirements of reaching students early and across a broad range of disciplines. A first draft of this objective was recently completed, though the lecture was created and delivered by Dr. Denneal Jamison-McClung, an education specialist in the UC Davis Biotechnology Program.

Informal feedback from students indicates that this lecture was extremely popular and effective at getting them to see themselves involved in biotechnology.

The second action item was to begin advocating for the construction of a small undergraduate innovation laboratory for synthetic biology. Since LeAP, the author has also successfully advocated for creation of such a laboratory. The Department of Biomedical Engineering at UC Davis will dedicate space and resources to catalyze this idea. Once complete, the laboratory space will be a fully functional wet laboratory adjacent to the departmental machine shop and physical prototyping lab (e.g. 3D printing, PCB mills, laser cutting). We expect to provide a creative outlet for students with innovative ideas in synthetic biology with some activities even spanning across each of the prototyping labs. Funding permitting, students will receive technical training, some seed funding for their projects, guidance on responsible use of biotechnology, and exposure to entrepreneurial activities. We anticipate that most projects will be completely student driven. However, we also hope that the space will serve as a magnet for industrial partnerships in which companies may sponsor student or student team activities. While Departmental funds will be used to bootstrap this project funding for projects and staff advisors still need to be found.

Promote the responsible use of biotechnology

Another of the author's post-LeAP action items was to create and deliver an introductory lecture on the ethical use of biotechnology. Again, this lecture would be delivered to the large enrollment introductory biology class, immediately following the lecture on biotechnology and at this stage is meant to instill an awareness of the issue of responsible use of technology. With guidance from Dr. Laurie Zoloth, the author prepared and delivered this lecture/discussion. Again, informal feedback suggests that the students also appreciated this lecture. Collectively, the two lectures address two simple questions, respectively: What can we do with biotechnology? What should we do with biotechnology?