Symposium on Imagining the Future of Undergraduate STEM Education
National Academies of Sciences, Engineering and Medicine
November 2020

Revised stories from symposium participants

Ann Austin
Professor of Higher, Adult, and Lifelong Education
Michigan State University

Envisioning the Future Role of Faculty and Staff

Faculty in 2040 will be very diverse in many ways-- but all will be similar in a very important way. That is, those who become faculty will be motivated by their love of their field or discipline and their commitment to helping learners grow, develop, and meet their individual learning goals. Some faculty will be experts in their disciplines. Others will have started with a disciplinary focus but will have decided to emphasize and develop skills in facilitating interdisciplinary work. Faculty positions will be of all types—full-time and part-time, long-term and short-term—but they will all feel respected by the institutions employing them for the contributions they make.

In graduate school, future faculty will have opportunities to learn about how learning occurs and is fostered, how to use effective and evidence-based teaching practices, how to support the diverse array of learners, how to collaborate with partners, such as academic colleagues, industry, business, and nonprofits, and how to assess learning and provide feedback.

Once employed, faculty will be valued and rewarded for their effectiveness at fostering learning. Faculty will be committed to learner growth and development as their overarching teaching goal, and will know how to work with individuals and with groups. Commitment to diversity, equity, and inclusion, and teaching informed by anti-racist perspectives, will be a core value and ongoing aspiration for each faculty member. This will be a commitment to which they devote individual professional learning time, while also engaging with other faculty, staff, and students to consider ways to integrate the advancement of diversity, equity, and inclusion more fully within their work, and seeking to have their daily interactions reflect their values.

Part of their work will be to encourage students to identify problems of interest, and to talk with groups outside the academy to identify possible collaborative relationships around those problems. Faculty will then support and scaffold learners as they work, collaboratively and with multi-disciplinary perspectives, to address those problems.

Faculty will often co-facilitate learning experiences, working with colleagues from other fields to bring multi-disciplinary perspectives to the problems that learner groups are addressing.

Faculty will also be supported throughout their careers to engage in ongoing learning about effective practices for teachers/facilitators. They will engage in holistic self-evaluation, in which they periodically self-reflect and establish learning goals for themselves to improve as teachers, invite peers to assess all aspects of their teaching and observe and exchange ideas, and welcome avenues for students to provide feedback.

Melissa K. Demetrikopoulos
Chair Division of Program Development and Assessment
Institute for Biomedical Philosophy

Transforming the Student Learning Experience

Whatever we do we should not lose sight of the idea that there are universal truths. While it is important, and even critical to consider perspective, it is also important to consider that there are shared and even universal truths. For example, most scientists would likely agree that there are forces between large objects such as planets that are separated by vast distances and forces between small objects such as electrons and protons that are separated by minuscule distances. The types and magnitudes of these forces are also largely agreed upon as universal truths. While we should remember that while the existence of these forces is nearly universally accepted as truth, perspective would be important for the understanding of these forces, to the experience with these forces, to the importance of these forces, and to values related to the forces. When we remove the idea that there are universal truths, we eliminate the structure and language necessary to communicate between disciplines, communities, and individuals because we have eliminated anything that can be understood using commonalities. Shared language provides a mechanism for communication and sharing of learning and facilitates breaking of silos between disciplines. There should be a balance between shared and individual meaning. Providing clear operational definitions and shared vocabulary that can be translated across languages allows for more inclusion and broadening participation. Within an expanded shared structure, there is room for perspective and individual meaning which will bring a richness of experiences to any endeavor. For example, recall the old analogy of the six blind people and the elephant. There is something that is actually an elephant. The first person feels its side and describes it as broad and flat like a wall, the second feels its tail and describes it as rope like, the third its ear and so on. They each bring their experience with the elephant (that shapes their perception of what an elephant is) to their explanation/report of the elephant. Nothing about this process changes what an elephant is. The underlying reality of the elephant is the same. They could choose to argue about what an elephant is due to their different individual experiences or they could understand that there is an underlying truth of the elephant and choose to work together and bring their individual experiences to bear in discovering this underlying truth. I hope that as we come to understand and value perspective and differential experiences that we do not eliminate the idea that we as a scientific community are searching for universal truths. By bringing more ideas/perspectives (more blind people in this case) to the table we have the possibility of getting incrementally closer to the underlying universal truth. This is the strength that we find in interdisciplinary and multidisciplinary research; each field brings its expertise and perspective to the collective in a way that expands the knowledge base of each discipline in a synergistic manner. The whole becomes greater than the parts because the whole is able to reveal more of the underlying truth. Therefore, it is critical to bring together various perspectives and diversity of thought when trying to discern the truth. In addition to the more commonly considered areas of diversity of thought that focus more on demographic factors, it is also important to consider diversity of thought that address alternative avenues of gaining knowledge outside of formal learning pathways. Self-taught learners, informal learning environments, community-based learning, citizen science, authentic learning in place, and authentic learning at work are some of the avenues for gaining knowledge that should be acknowledged in order to enrich our understanding.

Sarah C R Elgin (with Laura K Reed and Sam Donovan)
Viktor Hamburger Professor Emerita of Arts & Sciences (Biology)
Washington University in St Louis

Redesigning Pathways for Undergraduate STEM Education

Teach science by engaging students in doing science: Fully realizing the current opportunities.

The overarching goal of science education is for students to experience the nature of science and scientific reasoning, independent of the specific field that they study. The power of learning by doing has long been recognized as the most effective approach toward that end (see Dewey, J. Experience and Education [1938]. New York: First Touchstone Edition; Vision & Change https://visionandchange.org/finalreport/, and follow-on publications). Thus we propose a future in which science is taught primarily by engaging undergraduate students in doing science.

All science courses will be centered around a course-based undergraduate research experience – commonly referred to as a CURE. For STEM majors immersion in doing science will be pervasive, beginning the first semester freshman year and continuing through to graduation. Equally important, all science courses, including those targeted to non-science majors, will be taught in this fashion. By 2040 this approach will be available through all colleges and universities, whether two-year or four-year schools, regardless of institutional resources – regardless of whether there is a science graduate program on campus, regardless of endowment and/or other resources.

Further, the core research experiences will be designed to be accessible to all students, including part-time students, returning students, those with various home commitments, etc. While many students will participate in a given research course on their home campus, guided by resident faculty, others may participate outside of a degree structure, as part of a work-sponsored or certification program that provides mentoring. The goal is to democratize science education, maximizing opportunities for our changing population of students, and providing access to the full spectrum of science/technology jobs/careers.

Within a college/university structure, the first semester research experience is critical. For example, imagine that when Valentia enrolls in her first science course at the regional community college she is immediately introduced to a challenging scientific problem. There were several options to choose from, and she is excited to join an investigation that concerns a local environmental problem which has been a concern of her community for some time. She spends the first several weeks working collaboratively with her peers to learn some of the lab techniques and background on the investigation they will join, contributing data to a national research effort on such sites. The bulk of the semester is spent interpreting scientific literature, designing/carrying out experiments, collecting data, and communicating her research group’s results. While her time on campus and in the field is limited, all of the resources and much of the work are accessible online, allowing her to participate fully while still meeting her family’s needs. While the work does not always go smoothly, the online TAs are helpful, and the guiding faculty member is supportive. Time is allotted to reconsider, redesign and repeat data collection, experiments, etc. as needed. While her whole team wishes they could have done more, they are satisfied that they made real progress on the problem, and learned much more about the topic than they perhaps expected. Valentia is excited to share what she has learned with her family, and is thinking that the effort to pursue a science-based career may be worth it.

The key innovation that will make this possible will be to establish a continuing series of national research projects that can facilitate engagement of large numbers of students. NSF and other funding agencies will generate appropriate calls for proposals to identify and support these projects, working up to a level that meets national demand. Both projects that invite faculty to join a centralized project, and those that provide support for a series of local projects, will be appropriate. Support for a pedagogically successful project should be renewable until the scientific goals are accomplished. A competitive proposal will engage students in generating, collecting or retrieving data; analyzing data; and defending their conclusions, reporting out to local and/or national audiences. It is essential that the conclusions be of interest to the larger community, either the scientific community or society in general, either locally or nationally.

The Internet will enable students to work together across the country. It also provides access to many freely available databases, from DNA sequence repositories, to environmental data, to star maps, and more. Modern cyberinfrastructure and open science practices are already enabling students to access data that previously would have been inaccessible: students can now work with professional tools and data resources at low cost. Providing students with experience working as part of a distributed team using modern tools will take us a long way toward workforce development.

While this effort will require considerable coordination, there are many effective examples in place at present that can provide prototypes, and help us reflect on lessons learned. Student contributions to science have been facilitated by various types of citizen science (e.g., Cornell Lab Bird Count, https://gbbc.birdcount.org ; Foldit https://fold.it), by programs organized by laboratories with a national reach (e.g. DNA Subway applications, Dolan DNA Learning Center, CSHL, https://dnasubway.cyverse.org), and by groups of faculty with shared interests (e.g. GCAT-SEEK, Genomics Education Partnership, Ciliate Genomics Consortium – see https://qubeshub.org/community/groups/gea). Some of these efforts invite faculty and their students to join a specific research project, while others provide tools that can be used in a local research project. A competitive proposal will need to develop/post curriculum, provide faculty training, facilitate quality control for student results, facilitate student presentation/publication, and facilitate assessment of student performance and success in reaching pedagogical goals.
The benefits of a central organization can be seen in the HHMI-funded SEA-PHAGES program, which engages a large number of freshmen nation-wide in isolating and characterizing novel phage, greatly enlarging our knowledge of phage evolution and furthering the possibility of using phage as a targeted antibiotic treatment, while providing thousands of students with an introduction to research (https://seaphages.org).

It might well prove cost-effective to have a central resource to help faculty/departments identify the available projects best suited to their school/program. Conversely, an NSF-sponsored website that provides examples and suggestions of how to situate a research problem in a context that will resonate with students; how to incorporate practice in communication skills, improve digital literacy, heighten ethical awareness etc. (see “Developing the Future Substance of STEM Education: A Concept Paper” by P Mishra, A Anbar, B Scragg, L Ragan https://d32ogoqmya1dw8.cloudfront.net/files/stemfutures/substance-of-stem-education-concept-paper-2.pdf); and how to manage assessment, would be of great help to scientists/educators who wish to design a large project or a single-campus CURE based on their own research, or develop a large collaborative effort Such resources would help scientists be confident that their proposed CURE is sound, not only in its science, but also in its pedagogy, assessment, and potential societal outcomes.

While the examples cited above are drawn from biology, we believe that there are a range of possibilities across STEM. Many of the big research questions critical to our time will require an interdisciplinary approach, in particular engaging students in investigations of our on-going climate change, and the impacts of this on all aspects of our society. Harnessing the power of our undergraduate students to investigate, analyze, and publicize a full range of scientific questions will have enormous benefits for all involved.

Madhura Kulkarni
Director, Center for Integrative Natural Science and Mathematics
Northern Kentucky University

Systemic Change in Higher Education

Yuval Noah Harari discusses 2 transitions in his book, 21 Lessons for the 21st Century. As the world industrialized, "jobs of the hands" were mostly replaced by machines and "jobs of the mind" took over. As artificial intelligence improves and becomes ever more ubiquitous, "jobs of the mind" will be increasingly taken over by "jobs of the heart", which can't be supplanted by an algorithm or machine learning. Higher education helped individuals and society transition to our current economy. Will we be able to do so again for this next transition? I hope so. Here's a vision for how that happens.

First, teaching and learning in the future will embody a sense of responsibility to our past, current and future communities, both local and global. Our educators and learners will embed the learning experience in these contexts, not just know about them. To make this happen, STEM will be connected with other disciplines in a transdisciplinary way from cradle to career such that being a "STEM person" doesn't connote someone centered on a computer or lab and detached from the "real" issues of the wider world. Everyone will be a "STEM person" to some extent, understanding the links among disciplines that already exist their everyday lives because that is how they have always learned to see the world, from preschool onward.

Students will enter higher education without the wide disparities between the advantaged and disadvantaged because society will have done a better job of advancing equity from before birth to adulthood. This change will be possible in large part because education as a whole will move back away from its trajectory of privatization of a public good. Higher education won't rely on wealthy private industry and individuals to directly fund their pet projects and programs. They will, instead, fund education by paying fairer taxes that recognize the full breadth of the education (and other public) systems in developing the society and workforce that they depend on. High quality universal pre-school will be publicly funded and school district funding will no longer be tied to the wealth of the community, but rather equally supported across neighborhood divisions in wealth.

As these better and more evenly equipped students enter more student-ready post-secondary institutions, they will--like their predecessors--be exposed to people and ideas that are different from those they grew up with. But in 2040, higher education will be much more immersive. Students will learn in "pods" with students from different disciplines, tackling real-world problems collaboratively. For example a group of students becoming oriented to college and their various disciplines, would be tasked with first researching, defining, then re-defining (because the first try isn't usually good enough!) a problem on campus that affects student lives. Then, as the year progresses, they would draw on their unique backgrounds, disciplinary knowledge, collaboration skills, and creativity to design, test, and redesign (because again, the first try isn't usually good enough!) a solution. Each year, the problem space expands, from campus, to local community to global community, with the scale of the final year project chosen by the students. Students will collaborate with partners around the world (e.g. undergrads in Tokyo or farmers in rural El Salvador) using immersive virtual reality, the new Zoom. Professors build content knowledge and disciplinary skills into and alongside these group learning experiences and mentor students through both. With this model, students will find a sense of belonging and community with their campus, locality, and their fellow citizens of planet earth.

As we make these changes, education--especially undergraduate STEM education--will become both more foundational and more applicable to careers of the future. The class of 2024 will graduate with portfolios of work products that demonstrate their knowledge, skills and even "virtues" or "dispositions" as well as networks of professionals with whom they have already collaborated.

I realize that this is very ambitious for a 20 year window, but I'm optimistically envisioning a powerful response to the growing public consciousness on lack of equity, accelerated change due to the pandemic, heightened urgency to address climate change, and growing dissatisfaction with rising socioeconomic inequality.

Diego Navarro
Emeritus Professor & Founder / PI
Cabrillo College & Academy for College Excellence

Transforming the Student Learning Experience

Though this vision of a STEM education in 2040 fits within a spiral of ever deepening use and application of STEM and 21st century professional competencies while a STEM student is in college, I will focus on the first semester, a critical semester if we are to succeed in creating a robust pipeline of racially minoritized STEM students and professionals in 2040.

At the core of this vision is:
I. nurturing of college students from disadvantaged neighborhoods and substandard high school educational experiences to become the diverse STEM workforce the U.S. needs to maintain technological competitiveness,
II. transforming the trajectory of many families for generations to come by having their first family member succeed in becoming a successful STEM professional; as a STEM professional they will become an example to family and friends that shows a

way out of poverty that is a guiding light to their children, nieces, nephews, grandchildren, aunts and uncles, and friends
III. addressing difficult societal problems with perspectives that are informed from their lived experience not just from reading.

To make sure that these students can make the transition effectively to college-level performance we must address the first semester of college, sometimes the first three weeks of college the most critical three weeks of a racially minoritized student's college life [(1.a) – see bibliography for references below].

In this vision of the first semester each student has the experience of:
1. Participating in an academic culture of dignity where they feel emotionally and psychologically safe.
1.1. We need to move beyond culling students the very first semester to supporting them to become the STEM professionals that they strive to become. We need to develop an educational pedagogy that helps these students transition their strengths in persistence and survival to the academic environment [(1.b) – see bibliography for references below].
1.2. There are several longitudinal academic and salary outcome studies (funded by the NSF, Gates Foundation, Hewlett Foundation, James Irvine Foundation and Joyce Foundation) that point the way, indicating that a high percentage of racially minoritized students from poverty can make this transition effectively if they are supported in a culture of dignity and where they feel psychological and emotional safety. These studies show that underprepared minority students from poverty can step up to the challenge of accelerated learning [(1.c) – see bibliography for references below].
1.3. The culture of dignity and belonging can be created rather quickly in 5 to 8 days with an immersion approach [(1.d) – see bibliography for references below]. This approach was first developed in 2003 and implemented with NSF ATE funding - NSF Award #0302913. We have a study of 769 students from six colleges which indicates that students improved in seven of eight psychological factors (e.g., academic self-efficacy, college identity, mindfulness, etc.) associated with academic success at a $p<.001$ level of significance after a 8-day immersion course. With the exception of two factors, the change remains consistent or improved four months later at the end of the semester [(1.c) – see bibliography for references below].

2. Students become fully engaged in a STEM learning environment when their life experiences are utilized, their STEM learning is contextualized, and their need for relevance are met by working in teams to address social justice issues that have affected their families, neighborhoods and communities.
2.1. Racially minoritized students from poverty have PhDs in social injustice. Their life experiences equip them with inherent knowledge to effectively formulate research questions and apply research methods when given proper guidance by STEM faculty. The following description was instantiated in an NSF-funded project, i.e., NSF Award #0802581.

2.2. Using a scientific method-oriented pedagogical process model in the first semester, students experienced intensive preparation in science and math, centered around a Project-Based Course which contextualizes and allows the student's to apply what they are learning in a just-in-time curriculum model. In the central Project-Based Course, students worked in self-managed teams to study and report on a significant current community issue (a theme) that requires substantial scientific and math literacy. One proposed theme, for example, is diabetes, which is present at high levels in Watsonville, CA; another possibility is saline intrusions of the local aquifer that supports the valley's agriculture. The Math and Science feeder courses, using a "just in time" method, provide the students with the math and science background needed to advance their progress toward understanding the content and methods of the project theme. (To understand the methodology used to develop this integrated just-in-time model see the American Association of Community College Pathways Webinar – A FRAMEWORK FOR PATHWAY COHERENCE: Meta-Major Design & Levels of Integration at https://www.pathwaysresources.org/webinars-events/)

2.3. The lecture and laboratory portions of these courses are thoroughly integrated into a system called "studio teaching". In order to maximize student attention and engagement, breaking each day's work into alternating segments of lecture and demonstration, followed by active hands-on lab exercises or computer simulations. These lab exercises may last from 15 to 50 minutes and are then followed by discussion of the results measured or observed by the class. Their results are then related to a scientific theory or law which explains how their data correspond to the model's prediction and puts these results in a larger context.

3. Students learn 21st century professional competencies in teams where they experience belonging and which supports their application of these competencies.

3.1. In an immersion course at the beginning of the first semester plus another class over the rest of that semester students learn 21st century professional competencies. They apply these competencies as they work in their Project-Based social justice research team. Students develop skills, build a sense of belonging and confidence to trust one another, and learn to communicate and become dependable because their team mate's need them for their success. The competencies described below in #3.2 are provided just-in-time to support the success of the social justice student research teams. This approach has been applied in the development of computer support specialists instantiated in NSF Award #0302913.

3.2. As background, in my 7 years of social science research in Hewlett Packard Labs where I studied professionals in a number of industries for which Hewlett Packard built products, I've found that on average 20% of professional competencies where highly technical, the other 80% encompass collaboration and other professional competencies. We've found in this NSF funded project the following 21st century professional competencies to be critical to project-based team success:

3.2.1. self-managing team methods;

3.2.2. communicating findings and solutions to relevant stakeholders;

3.2.3. collaborative leadership (listening, interacting, dealing with conflict);

3.2.4. self-discipline and professional hygiene (meeting deadlines, aligning action with commitments, prioritizing work, etc.)

3.2.5. marshalling action (project management, strategic planning, budgeting, product needs assessment, etc.)
3.2.6. product development approaches (requirements definition, user needs analysis, etc.), and
3.2.7. developing flexibility and dealing with increasing degrees of freedom and ambiguity.
3.3. In our sixteen years of teaching in this manner with 80% of the students from racially minoritized populations from colleges situated in urban, rural and suburban locations we've established evidence that these 21st century competencies can be taught effectively. We have longitudinal academic and salary outcome studies that indicate that these competencies can be effectively taught to underprepared racially minoritized students from poverty. We also have evidence which indicates that faculty can be taught to teach other faculty to effectively teach these competencies to students and get the same outcome effect as the original cohort of students [(1.e) – see bibliography for references below].
3.4. At the end of the semester research teams present their research and solutions in a public forum. Government officials attend these presentations because our students are gathering data from communities that UC Santa Cruz cannot obtain. For example, one team studied why youth join gangs; the team members were either former gang members or had family members in a gang; 75% of the survey respondents were gang members since these students went to gang parties to collect the data; since they were a part of the gang community they were accepted there. UC Santa Cruz does not have access to these communities. The public presentation becomes a rites of passage into the community of scholars and they receive recognition from their home community as college students too. Examples of presentations can be accessed at https://drive.google.com/drive/folders/1iuATL9hhYxXubtaWD7sj5NoOD1s0rdrM?usp=sharing.

Of course there are other things needed in the first semester as well as throughout the student's college experience. Student's will need proper guidance, curriculum modules that are engaging, assessment methods that take into consideration their life learning, an electronic portfolio to document their abilities and what they've learned, exposure to future career possibilities, work-based learning opportunities, etc.

1. BIBLIOGRAPHY (For ease, these referenced materials can be found at https://drive.google.com/drive/folders/187fI05rUMXWe41yz85Io2sZTeWDZviF-?usp=sharing):
a. Rethinking Entry to College – Rose Asera paper
b. Students of the Future, Change article
c. Summary of Evidence for Academy for College Excellence
d. Case Study of Academy for College Excellence.Research and Planning Group for the California Community Colleges
e. Faculty Training Evaluations, University of California Center for Justice, Tolerance & Equity

Wendi J. W. Williams
Geosciences Faculty / Department of Physical Sciences and Engineering
South Texas College

Envisioning the Future Role of Faculty and Staff

In the future, a story we will tell about education is that it is now holistically seamless due to sustained efforts of diverse groups of change agents. No longer will we need to design rigid steps through grade progressions starting from the traditional kindergarten to whatever grade or age throughout a human lifespan. Gone will be explicit and ingrained implicit biases because we have evolved beyond personal judgement of others…because education and broadly defined family structures with cultivate more awareness about biases and how they manifest. How? Implementing lessons in pre-kindergarten all along the continuum for students, as well as faculty and staff facilitators. Intellectual and socio-emotionally age appropriate and most definitely not a punctuated one-time training.

The interface between human capital (students and their families, faculty, and staff) and intersectional resources to historically known content and unknowns “to achieve and know” (no longer like today’s silos of STEAM) should be threaded between real in-person to virtual haptic experiences conveying information (visual, audio, touch, temperature, emotional) regardless of whether or not the lifelong student, faculty or staff has “some perceived socio-economic status,” or differs from year 2020 norms regarding sight, hearing, anatomy, mobility, or social acumen due to neuro diversity.

In the future, faculty and staff will be more equitably supported and rewarded professionally to team more deliberately with other academic entities (K – 12, 2YC and 4YCU/ other continued growth programs) that require incorporation of family cultural structures in partnerships with currently termed “informal” (but vital) learning hubs, businesses, and government / non-government sectors. Faculty as expert facilitators and mentors will help better foster student intrinsic motivation and incubate ideas leading to interdisciplinary understanding followed by actions to make a better baseline for living on Earth and elsewhere. And my vision is that faculty and staff will more broadly acknowledge and celebrate how inclusion moves humanity positively and productively forward. That vision may be more than two decades forward from now, but I hope not for all our sakes.