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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. (1997). 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. The goal is to democratize science education, maximizing opportunities for our changing population of students, fixing the leaky pipeline, and providing access to the full spectrum of science/technology jobs/careers.

For example, imagine that when Valentia enrolls in her first science course at the community college she is immediately introduced to a challenging scientific problem. She spends the first several weeks working collaboratively with her peers to learn some of the lab techniques and background on the model organism they will use to contribute data to a national research effort. 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 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 experiments/investigations 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.

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. 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 data bases, 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.

It might prove cost-effective to have a central resource to help faculty/departments identify the available projects best suited to their school/program, and to coordinate common functions among the national experiments such as assessment. 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 (https://seaphages.org ).

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.