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| Perspective

Supporting the democratization of science during a pandemic: genomics Course-based Undergraduate Research Experiences (CUREs) as an effective remote learning strategy

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ABSTRACT The initial phase of the COVID-19 pandemic changed the nature of course delivery from largely in-person to exclusively remote, thus disrupting the well-established pedagogy of the Genomics Education Partnership (GEP; https://www.thegep.org). However, our web-based research adapted well to the remote learning environment. As usual, students who engaged in the GEP's Course-based Undergraduate Research Experience (CURE) received digital projects based on genetic information within assembled *Drosophila* genomes. Adaptations for remote implementation included moving new member faculty training and peer Teaching Assistant office hours from in-person to online. Surprisingly, our faculty membership significantly increased and, hence, the number of supported students. Furthermore, despite the mostly virtual instruction of the 2020–2021 academic year, there was no significant decline in student learning nor attitudes. Based on successfully expanding the GEP CURE within a virtual learning environment, we provide four strategic lessons we infer toward democratizing science education. First, it appears that increasing access to scientific research and professional development opportunities by supporting virtual, cost-free attendance at national conferences attracts more faculty members to educational initiatives. Second, we observed that transitioning new member training to an online platform removed geographical barriers, reducing time and travel demands, and increased access for diverse faculty to join. Third, developing a Virtual Teaching Assistant program increased the availability of peer support, thereby improving the opportunities for student success. Finally, increasing access to web-based technology is critical for providing equitable opportunities for marginalized students to fully participate in research courses. Online CUREs have great potential for democratizing science education.

KEYWORDS democratizing science education, Course-based Undergraduate Research Experience (CURE), genomics, online, web-based, virtual teaching assistants

How does one support the democratization of science education during a pandemic?

Democratizing science education increases the number of scientifically literate citizens who can knowledgeably participate in political decisions regarding scientific information (1). The need for a scientifically literate society was underscored by the COVID-19 pandemic, in which misconceptions, vivid anecdotes, and magical thinking vied with medical science and data-informed public health policies. How, then, do we train more citizens to think like scientists? In previous reports (e.g., 2), the Genomics Education Partnership (GEP; https://www.thegep.org) has argued that Course-based Undergraduate Research Experiences (CUREs) provide opportunities for

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students to grapple with scientific thinking and judgment. Here we recount how the GEP, a consortium devoted to incorporating research participation into the undergraduate science curriculum, succeeded in sustaining and enlarging its efforts to democratize science education, during the COVID-19 pandemic, by engaging undergraduates in genomics and bioinformatics research via CUREs. We acknowledge the limits imposed by inequitable access to computers and internet connectivity. However, we suggest that genomics- and bioinformatics-based CUREs promote the inclusion of faculty and students across a diversity of institutions in the scientific community.

Founded in 2006, the GEP provides opportunities for students to perform original research by applying bioinformatic analyses to generate high-quality gene annotation models. The models are then analyzed collectively to derive and publish novel insights into the evolution of genes and genomes. Students now also have the opportunity to publish their individual gene models in *microPublication Biology* (e.g., 3). To date, more than 1,100 students have co-authored (4, 5). As of September 2021, the GEP membership consisted of 213 faculty members from 181 institutions providing instruction to over 3,945 students annually. The growth of the GEP consortium by cumulative membership is shown in Fig. 1.

Efforts to democratize science during a pandemic

During the 2020–2021 academic year, the pandemic forced many institutions to halt in-person learning. Fully remote instruction caused concern throughout academia as educators worried about the loss of student learning and engagement. Silverberg expressed the concern most dramatically by entitling a report "The Pandemic Defeated My CURE (6)." Silverberg described the loss of in-person laboratory work and the substitution of a literature review project that could be completed remotely. Wang and colleagues (7) took advantage of an ongoing longitudinal observation of students who pivoted from in-person CUREs to online learning and reported a decline in situational interest (evoked by activities).

Since the curriculum of the GEP CURE is exclusively web-based, requiring no special software, it was ideal for virtual learning and allowed the program to easily transition to remote instruction. Details of the project workflow are recounted elsewhere (e.g., 8), but the key concept is that undergraduate students are provided with digitized projects, based on the genomes of *Drosophila* species, that require description and annotation of gene sequences. Bioinformatics and other computer-based research projects have several inherent advantages. There is a large repository of publicly accessible raw data and web-based tools; there are no lab safety issues, and the lab is open access 24/7.

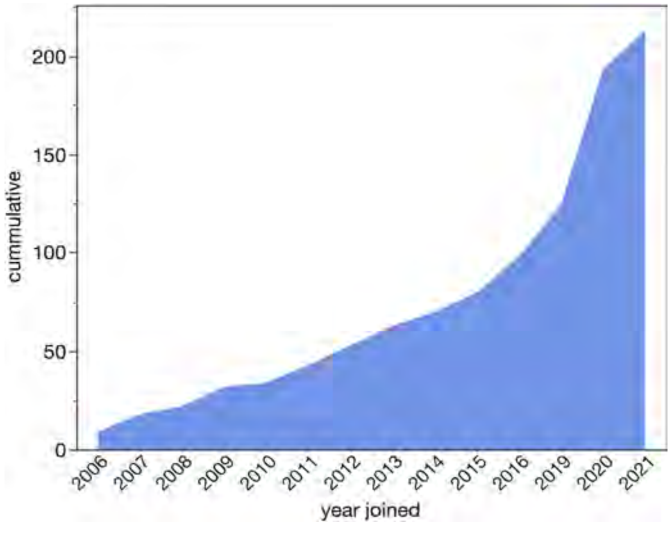

FIG 1 Cumulative GEP growth from inception to December 2021.

Consequently, the material lends itself to peer instruction, a huge plus that provides a program multiplier. Equally important, student mistakes are inexpensive in both time and money, giving students more freedom to try things possible in an actual wet lab or field study. We suggest that many more research projects could be designed for undergraduates, whether the setting for learning is in-person or online, making use of the online resources that are so abundant in the current age.

Democratizing science: lessons learned

Since its founding in 2006, the majority of new GEP faculty members were trained in-person at Washington University in St. Louis. After training at the central location, faculty led their courses at their home institutions with undergraduate Teaching Assistants (TAs) as a regular feature. These TAs were also trained in person. Students, in turn, generally experienced the GEP curriculum in person. In fact, despite the web-based nature of the GEP CURE, it established itself as a strong research experience in the in-person modality. The program has been shown to improve comprehension of genomics concepts and increased engagement in science over a diverse group of undergraduate institutions (9, 10).

During the Spring 2020 semester and the 2020–2021 academic year, continuing members of the GEP converted to online instruction. If the students had access to basic computers and internet connections, then the core web-based genomics CURE continued successfully. Instruction changed from in-person to remote, and the GEP introduced an innovative "Virtual TA" (VTA) option. VTAs were available via Zoom video conferencing for all GEP students, ameliorating the loss of in-person teaching assistants.

Anticipating a need for faculty eager to provide their students with genuine research experiences despite social isolation, the GEP trained additional faculty between May 2020 and August 2021 online. The GEP also established other innovations in response to the pandemic, including transitioning the annual week-long professional development workshop for GEP faculty to a virtual platform, and broadening the associate educational resources to include 30+ additional videos on the GEP website leading to the development of the GEP YouTube channel which was launched in January 2021 (https://www.youtube.com/c/genomicseducationpartnership).

In the context of the pandemic, the accessibility of the GEP program may be measured by observing its growth. Figure 2 illustrates a growing interest based on the number of faculty contacting the GEP for training during 2020. A noticeable increase in interest developed in May 2020 (Fig. 2A) following the online presentation at the virtual TAGC (The Allied Genetics Conference) in April of that year. The GEP made a concerted effort to enhance visibility at the conference, including multiple presentations given by the GEP community, a featured talk by the Program Director, and a virtual exhibitor booth. We hypothesized that since the conference was virtual and free, awareness of the program at Minority-Serving Institutions (MSIs) and Community Colleges (CCs) would be enhanced relative to what a paid, in-person conference may have achieved. During a time of online instruction, the membership increase suggests that genomics- or bioinformatics-based CUREs are a feasible alternative to in-person, hands-on research experiences for a broad group of institutions. The trend lines suggest that the numbers of both faculty and students actively engaged in the curriculum increased (Fig. 2B and C). Notably, between January 2020 and June 2021 the composition of GEP changed as participation increased from "current" to "new" faculty, respectively, among many affiliations—including MSI (23–29%), Hispanic-Serving Institutions (HSIs) (15–17%), and CCs (9–13%)—suggesting that multiple demographics are attracted to the GEP CURE in the online format.

In addition to faculty interest and student participation, normal operation of the GEP can be measured by counting the number of research projects completed and submitted by students to the central GEP data collection server during remote learning. The introduction of a new "Pathways" Project to the ongoing "F-element" Project contributed

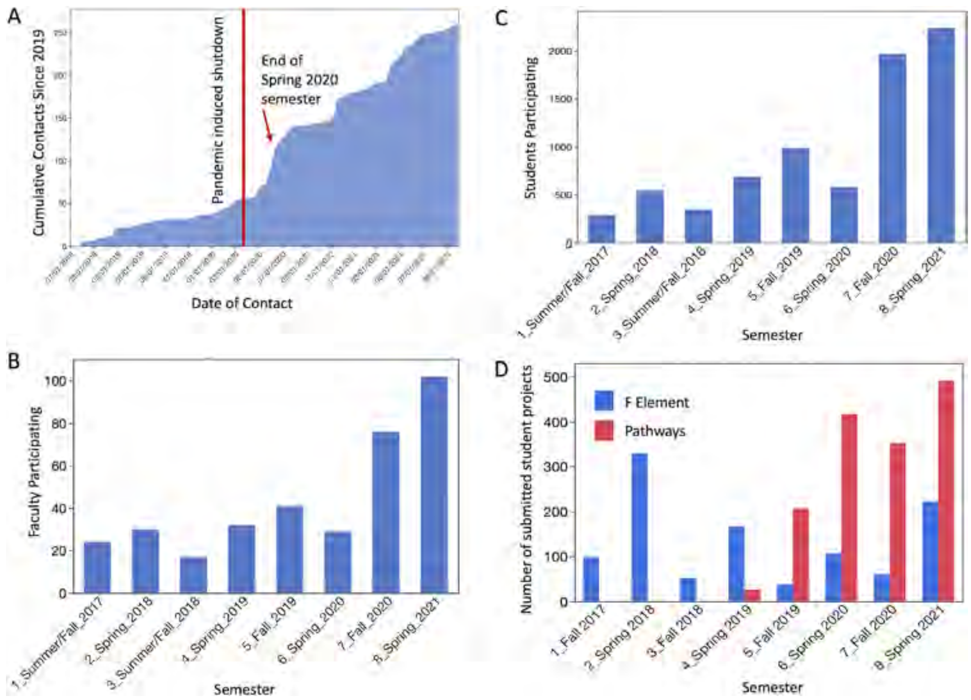

FIG 2 Growth of the GEP. (A) The number of faculty contacting GEP to inquire about training increased at the time of COVID-19 lockdown. (B) The number of faculty members actively implementing GEP projects and (C) the number of students participating per semester have increased starting in Fall 2020. (D) The number of student research projects submitted per semester remained high during the pandemic. It shows the number of projects submitted for two investigations within the CURE, the F-element Project that analyzes the role of chromatin structure on gene expression and evolution in *Drosophila* (4, 5), and the Pathways Project that studies regulatory evolution of metabolic and signaling pathway genes (e.g., insulin signaling) across the *Drosophila* genus (11).

to a growth of submitted student projects in Spring 2020 (Fig. 2D), and the number of projects continued to grow throughout the 2020–2021 academic year.

Taken together, the increase in faculty interest, the persistence of faculty/student participation, and the consistency in the number of research projects submitted per time-period all support the assertion that genomics-based CUREs are as robust online as they are in person. The implication is that a remote research experience can successfully increase accessibility to science learning for students at distributed geographical locations (Fig. 3).

The GEP has a history of measuring student learning with a multi-operational approach that includes a direct measure of gene-structure annotation knowledge and self-reported measures of perceived benefits and attitudes. GEP students who participated from 2020 to 2021 provided data on these measures that was comparable to data provided by a pre-pandemic student cohort. The results of a 20-item quiz based on the annotation experience are shown in Fig. 4. In addition to the quiz, students were asked to evaluate five items concerning personal agency for doing science (positive attitude) and six items concerning the epistemology of science (negative attitude) on a scale of 1 (strongly disagree) to 5 (strongly agree). Examples of positive and negative attitude statements that students evaluated follow, respectively, "I can do well in science courses" versus "Creativity does not play a role in science." Previous work had established that each set of items could be summed to give the student one positive attitude score and one negative attitude score (12). To examine if the online delivery affected these student attitudes, the post-experience attitude scales were compared for students from the 2017–2018 academic year (in-person instruction) and the 2020–2021 academic year (online instruction). The comparison is shown in Fig. 5. Despite the difference

FIG 3 Map showing the geographic distribution of GEP institutions. Color code shows the year that faculty member joined the GEP.

in delivery methods, the data reflect no remarkable differences in either positive or negative attitudes.

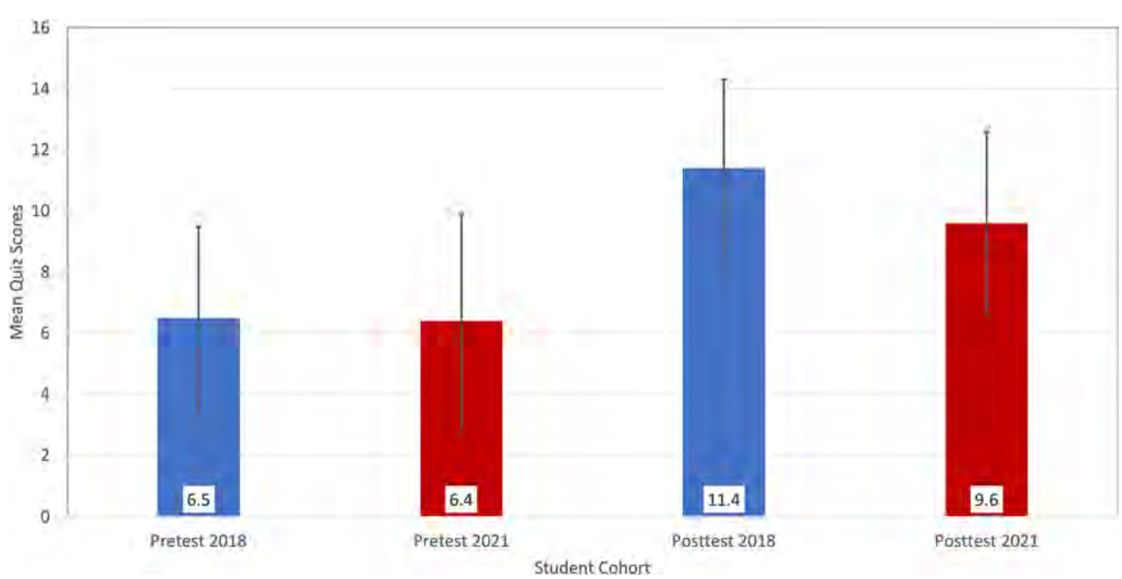

FIG 4 Mean scores for pretest and posttest annotation quizzes for a pre-pandemic, in-person instruction year (2017–2018, blue; $N = 401$) and a pandemic, remote learning year (2020–2021, red; $N = 621$). The error bars represent one standard deviation above and below the means. The 2018 posttest mean (11.4) is slightly higher than the 2021 posttest mean (9.6); however, the difference is not meaningful (i.e., less than two quiz points). Analysis using the TOST (two one-sided test) procedure found that the 2021 means were within the equivalence margin of the 2018 means.

To compensate for the loss of in-person TAs during the pandemic, the GEP organized a novel Virtual Teaching Assistant (VTA) program in which peer, undergraduate mentors were employed and available approximately 60 h per week via Zoom video conferencing to all GEP students across the country. To assess the effectiveness of the VTAs, GEP students were asked on the post-experience survey if they had employed the VTAs, and, if so, to evaluate their experience. While 259 students were aware of the resource but did not use it, 137 students reported using the virtual TA resource. The former group reported that they did not use the VTA resource because they did not feel they needed the assistance ($N = 168$), the meeting times were not convenient ($N = 38$), or they did not feel comfortable talking to a student TA they had not met in person ($N = 21$). Usage of the resource was most frequently 2–4 times during the term ($N = 75$). The students who did use the VTA resource were asked to evaluate their experience on nine items rated on a scale of 1 (strongly disagree) to 5 (strongly agree). These items and the mean and median responses are shown in Table 1. Overall, students responded favorably to the VTA initiative. Based on these reports, we conclude that the VTA program increases student comfort and supports student success in our genomics CURE.

The means reported in Table 1 support the proposition that VTAs are a valuable resource. Our data suggests that online delivery of the novel VTA program allowed the GEP CURE to remain effective through the transition from onsite to online: the GEP CURE is resilient. This resilience aids in the democratization of science education by making research experiences available to all (13); however, achieving the full potential for Virtual TA programs relies on the assumption that the appropriate web access is available to every student.

Strategies for the democratization of science

The SARS-CoV-2 virus continues to infect students and faculty. Should another deadly viral variant evolve, our data indicate that a genomics- or bioinformatics-based CURE can provide research training where other options are not available: especially for remote learners and other non-traditional students. For institutions transitioning from remote back to in-person instruction, we observe that several pedagogic tactics cultivated

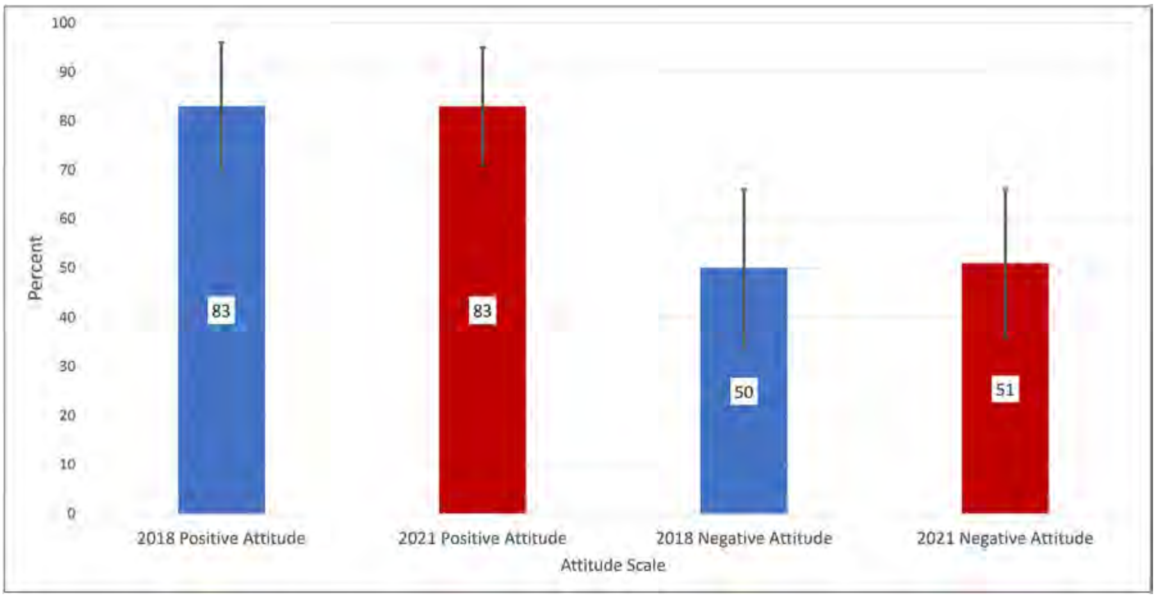

FIG 5 Positive and negative attitudes toward science are compared for a pre-pandemic, in-person instruction year (2017–2018, blue; $N = 809$ and a pandemic, remote learning year (2020–2021,red, $N = 1035$). The mean scores are presented as percentages of the maximum possible score because the positive attitude included five items while the negative attitude included six items. The error bars represent one standard deviation above and below the mean percentages. There is no significant difference in student attitudes between pre-pandemic in-person instruction and during-pandemic online instruction. Analysis using the TOST procedure found that the 2021 percentages were with the equivalence margin of the 2018 percentages.

from remote learning continue to be employed by instructors in combination with in-person learning, including (i) enhancing communication on genome annotation via screen-sharing, (ii) recorded lectures and help sessions on common challenges allowing more instructional time for discussion, (iii) an increase in "flipped classroom" teaching, and (iv) hybrid delivery of help sessions featuring both in-person and virtual teaching assistants, thus, allowing coverage of late-night hours.

In addition to these pedagogical tactics, our experience suggests four broader strategies that show promise for the democratization of science education.

First, the increased accessibility of online professional conferences appears to increase faculty participation and dissemination of teaching opportunities. As shown in Fig. 2, shortly after the pandemic triggered remote learning and a free, virtual TAGC Conference, an organization that took 13 years to grow to 100 members, began a steady increase in numbers. Within 1 year, we had grown from 125 members to more than 200. We suspect faculty who would not have otherwise been able to attend due to financial limitations (e.g., registration fee, travel costs) were able to access the event and learn about the advanced, web-based, genomics CURE, in part due to this free event. Indeed, as the pandemic has stretched over multiple years, many faculty and students have attended conferences that switched from onsite to online or hybrid venues with fee reductions and no travel costs. Maintaining this trend to include at least some cost-free, virtual participation for STEM education conferences going forward may facilitate STEM democratization efforts.

Second, we should continue to exploit virtual training sessions for faculty and students. Prior to the pandemic, GEP members were clustered in geographic subgroups—Regional Nodes—that reduced travel barriers to training opportunities. Development of Regional Nodes reflected our conception that onsite/in-person training was essential to learning the genome browser skills necessary for faculty to run the GEP CURE in classrooms. Similarly, we were convinced students needed to be in person for their training and research experiences. COVID-19 upended our conceptions forcing us to train fully remotely, irrespective of Regional Node placement. Removing many logistical barriers, including travel, allowed for accelerated growth in GEP membership, which broadened student access to genomics instruction and research experiences despite the pandemic. GEP students continued submitting authentic research projects (Fig. 2D) while also making learning and attitudinal gains (Fig. 4 and 5), thus demonstrating that research continued. With the plethora of bioinformatic databases available in the twenty-first century, building more web-based CUREs, that only require access to a web browser (no special software) could be a valid method to increase faculty and student accessibility to CUREs in remote and/or under-resourced locations. The wealth of data available to investigate is staggering.

TABLE 1 Student responses to propositions about the Virtual Teaching Assistants[a]

Item	Mean	Median
I felt comfortable asking the virtual TA questions	4.3	5
I felt more comfortable asking the virtual TA questions than my instructor	3.65	4
The virtual TA was knowledgeable about the GEP content material	4.3	4
The virtual GEP TA provided clear and understandable explanations	4.25	4
A virtual TA was available and responsive when I needed help	4.3	4
The virtual TA enabled me to successfully complete my GEP project	4.23	4
I would recommend other students completing GEP projects to utilize the virtual TAs	4.38	5
The virtual TAs are an important part of the GEP program and should be continued	4.43	5
I think all courses (and students) would benefit from having a nationwide set of virtual TAs associated with them	4.4	5

[a]Items were evaluated on a scale of 1 (strongly disagree) to 5 (strongly agree). *N* = 137.

Third, the pandemic inspired the innovative implementation of the Virtual Teaching Assistant (VTA) program. To compensate for the loss of in-person TAs during the 2020–2021 academic year of remote learning, the GEP initiated its national VTA program to provide increased assistance to students: supplementing the work of course instructors. While only a subset of students took advantage of the VTAs during their inaugural season, student feedback suggests that this is a welcome addition to the GEP program. As many students work jobs and have classes that clash with in-person faculty office hours or TA work sessions, it may be that VTAs could be successfully employed for other Undergraduate Research Experiences or national education programs. Having bi- or multi-lingual virtual peers with availability on evenings and weekends could also dramatically increase student's access to STEM education through advanced CURE initiatives.

Fourth, we recognize that broader participation in undergraduate research experiences may affect democratization of science education when measured by demographic characteristics of faculty and students. The benefit of remote research experiences may be constrained by unequal access to the appropriate technology. While we observed a 2–6% increase in participation amongst Minority-Serving Institutions (MSIs), Hispanic-Serving Institutions (HSIs), and Community Colleges (CCs) (legend describing Fig. 2), we queried the students about access. In response to a survey question, most GEP students (84%) reported adequate connectivity with the internet to participate fully in course instruction; however, the 16% who did not have adequate connectivity is troubling. Erickson and colleagues (14) reported that many students at remote sites were concerned about "technological issues" during the early stage of the COVID-19 pandemic when attempting to participate in the online Research Experience for Undergraduate (REU) programs (14). As broadband infrastructure reaches remote areas, the extension of high-quality, advanced research education provided by web-based CUREs could reach an increasing number of students, increasing the percentage of scientifically literate citizens.

At least 3,945 undergraduates participated in the GEP program during the 2020–2021 academic year. While we do not expect that all GEP students will continue in paths toward STEM careers, we are optimistic that the experience of conducting a research project, including in many cases defending their work in a report and possibly co-authoring in a publication, imprints students with the understanding that scientific habits of mind and judgment are broadly applicable. It also develops a necessary perspective for understanding our world of science. In general, genomics-/bioinformatics-based CUREs have the potential to democratize access to science education.

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