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# Research Group-Led Undergraduate Research Program: Analyzing and Improving a Versatile Springboard for First-Year Undergraduates

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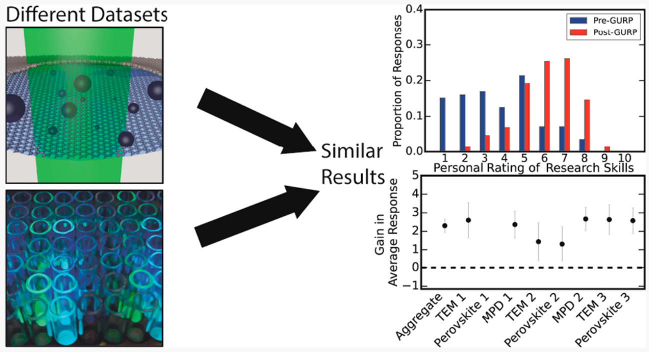


**ABSTRACT:** Increasing access to undergraduate research is critical in efforts to retain students pursuing careers in STEM. Alternatives to traditional research positions, such as course based undergraduate research experiences (CUREs), have played important roles in engaging more undergraduates in research. However, these opportunities are only a subset of possible nontraditional research experiences which can enrich the undergraduate experience. In this study, we critically examined and improved the research-group-led undergraduate research program (GURP) to better meet the needs of undergraduates seeking research. Specifically, we investigated if the program was successful with a greater diversity of data sets, if assessments of learning were consistent across different data sets and teaching environments, and if the program promoted student engagement in research. We have found that this model is scalable, robust, and adaptable to different implementations while producing consistent and positive learning outcomes for students. Especially remarkable are students' increased self-identification as scientists and statistically significant gains in self-perceived competency across multiple domains of knowledge. This program model has shown promising results as a partially and fully online research experience for undergraduates and has benefited program alumni in their research careers. To assist research groups starting similar programs, we have created public data sets and instructional resources. We believe that GURP programs can work in a variety of situations and hope that they can become a tool to increase interest and build communities for young researchers.

**KEYWORDS:** *First-Year Undergraduate/General, Interdisciplinary/Multidisciplinary, Collaborative/Cooperative Learning, Distance Learning/Self Instruction, Inquiry-Based/Discovery Learning, Materials Science, Nanotechnology*

## ■ INTRODUCTION

Research is an essential undergraduate opportunity, particularly in technical subjects such as chemistry which require hands-on experience.[1] Active participation in undergraduate research has been shown to improve learning outcomes in coursework, increase student retention in STEM fields, and help students develop their creativity and problem-solving skills.[2,3] Research can also motivate undergraduate students to continue their education through graduate programs, many of which expect prospective applicants to have prior research experience.[4,5]

While undergraduate research can have positive learning outcomes for students,[6] there are barriers that inhibit student access to traditional undergraduate research opportunities.[7] Obtaining traditional undergraduate research experiences (UREs) can be highly competitive and daunting to students, especially for students who worry that they lack knowledge or experience.[8,9] UREs also require effort for training on behalf of both the mentor and mentee, which may prevent students from applying and limit mentors from offering more positions. Equalizing and increasing access to research opportunities has tremendous impacts for aspiring students and could help promote their careers in science, particularly for students who remain underrepresented in their field of study.[10−14] With this in mind, several universities have implemented course based undergraduate research experiences (CUREs) where, as part of a university course, students research a topic of their choosing by conducting laboratory experiments. These programs scale access to research opportunities and help students receive

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many of the positive learning outcomes of research while keeping costs lower than traditional UREs.[15−22] Despite this, some professors are hesitant to implement these programs due to additional logistics, financial constraints, and uncertainty involved in student projects.[23]

To add to the range of research experiences available to students, we previously developed a hybrid approach, attempting to combine the best aspects of the URE and CURE models. Similar research-group-led research experiences have previously been attempted but were generally smaller in size.[24] In our model, an on-campus research group directs a group-led undergraduate research program (GURP) for a cohort of roughly 20 first-year undergraduates. Undergraduates work in small teams to investigate a large data set collected by a research group member, who helps guide students through the research process. This approach gives many students access to active fields of research early in their undergraduate experience and bypasses a significant investment of time to train students in experimental procedures and safety concerns, giving students a fast on-ramp into intellectual participation in research. Over a semester, student teams use exploratory data analysis to develop hypotheses that they subsequently attempt to answer through greater analysis of the data set. This program model has led to positive learning outcomes among students, including familiarity with scientific programing, increased scientific literacy, research collaboration, and scientific communication. While similar to a CURE in many aspects, we believe that the GURP model provides a different experience where students have reported that they are “tangentially joining a research group”, and this may help students get a better understanding of how a traditional URE may feel. In a previous work, we described in detail the structure of the course, our implementation, and the outcomes of the first cohort of 20 students from our course in 2018.[25]

In this work, we critically examined and improved the GURP model to better serve the needs of students and instructors. Targeted areas included increasing the scope of this program and testing its flexibility and adaptability to different research environments. To probe these aspects of the program, our research group has continued to host a GURP program over the past three years. During this time, seven additional courses were taught by several different instructors, bringing the total number of students who have participated in our program from 20 to 162. Students utilized three substantially different data sets, and multiple programs were held partially or fully online during the 2020 and 2021 semesters. Graduate students teamed up with undergraduate alumni of the GURP program to instruct the course, and student-designed experiments were implemented in several course iterations.

From our analysis of these program adjustments, we have found that this research model is effective at developing research skills for undergraduates through a variety of implementations. The majority of student learning outcomes appear to be positive and relatively independent of the course content and instructors. Follow-up studies with program alumni demonstrated that this program is also effective in helping students find and continue to engage with campus research. The program was readily adapted to an online format with minimal complications for the 2020 and 2021 semesters. This type of program may find significant success in remote learning, in cases where undergraduate research is limited (such as by the SARS-CoV-2 pandemic), or for research groups designing a cross-institutional research experience. Given the adaptability and resilience of this program, we have begun maintaining public data sets and lesson plans (generated by our research group) for those hoping to start similar implementations of this research model.

## ■ PROGRAM INNOVATIONS

After the success of our pilot 2018 research program, we decided to expand the scope and scale of the program to impact a larger number of students. We evaluated the following questions to assess the program:

(1) Is the program successful with a greater diversity of research areas and data sets?
(2) Are instructor assessment and student self-assessment of learning gains of scientific content and process similar through multiple sections with varied instructors and a larger number of students?
(3) Does this program act as a springboard for student engagement in research?

One of the outstanding questions after the first iteration of the program was whether the GURP model would be adaptable to other research groups seeking to start their own undergraduate research programs. The 2018 research program consisted of undergraduate students studying transmission electron microscopy videos of metal nanoparticles. The visual nature of the data used in the first iteration of the program may have been more approachable to freshman students and thus played an important role in the program’s success. With this in mind, we also created an additional GURP course based on absorbance and emission spectra of perovskite nanocrystals that was less visual in nature. We were also concerned that the size of this data set could present challenges for research groups that may not have the time or resources to collect large amounts of data. Even for research groups that do have access to large data sets, the analysis needed to obtain meaningful results could be too complex to teach first-year undergraduates in one semester. To investigate these concerns, we created a GURP course based on an external data set, the Materials Project Database, that was related to our research groups’ domain knowledge of materials chemistry. Through analyzing GURP programs based on different data sets, we planned to obtain a better understanding of whether this model could be adapted to other research groups with different research focuses or data sets.

While the results from the first GURP were promising, we determined that more student data was needed to fully assess whether this model could consistently produce positive learning outcomes. Many of the students in the program’s first cohort showed significant growth as undergraduate researchers; however, this may have been a result of highly motivated undergraduates (looking for research positions) applying for the course. Additionally, the improvement in student research skills may have been tied to the instructors who taught the first iteration of the program. To investigate this, we increased cohort sizes of the 2020 and 2021 iterations of the GURP program to three 20 student sections. By tripling the number of students in the program, we reduced program selectivity and encouraged a greater proportion of the freshman chemistry population to enter this program. These additional sections also required more instructors. To provide institutional knowledge of the program, at least one instructor who had previously taught the course served as a lead instructor for each of the three sections. New graduate students interested in the program served as coinstructors, and each section also included an undergraduate instructor, who was either very familiar with the section's data set or was a GURP alumnus. This mentorship model for instructors provided the background and training to run the course.

Lastly, we investigated the ways in which the GURP model could be improved to better prepare students for laboratory positions. The 2018 iteration of the program provided students with one data set for the entire semester; however, this is contrary to most research settings in which initial data prompts a hypothesis which is tested through follow-up experiments. To create a more representative research experience, the robotic instrumentation used to collect the perovskite data set used in 2019 allowed students to propose new experiments for the graduate student instructors to carry out. Each group designed a set of experiments to generate new data similar to the original data set with some new potential variables. The experiments were conducted and returned to the class in an aggregate data set that students could analyze to test their hypothesis. Unfortunately, due to the SARS-CoV-2 pandemic, this revision was not possible during the 2020 semester but would have been implemented under normal circumstances. However, students were still asked to create and evaluate a hypothesis about a new data set supplied by the instructors. Two iterations of experiment proposal and data acquisition were carried out in the perovskite section during the 2021 semester. While introducing experiments allowed us to teach students how to test a hypothesis through experiments, we did not observe any significant differences in surveys between GURP versions that did and did not implement experiments.

## ■ METHODS

### Recruitment

Given that the GURP program is neither a traditional course offered by the university nor a college requirement for students, program recruitment was necessary to generate student interest. Instructors performed program outreach by posting informational fliers in the chemistry buildings on campus as well as made announcements and directly handed out fliers in first-year chemistry courses. Visiting the lab sections of the students proved most effective. We also sent information to mailing lists for new transfer students. Informational sessions were offered to introduce course projects and answer prospective students' questions. All forms of recruitment emphasized that no prior research experience or knowledge was necessary for participation in the program. One innovation to the program that we tried to implement was a section specifically for transfer students, but the program did not garner much interest among transfer students; only a couple of students applied and were placed in a section alongside freshman students. We further found that the junior-level transfer students felt out-of-place in the mixed freshman/transfer sections. Students applied for the program by answering two short essay questions which required student applicants to demonstrate a threshold level of motivation and interest (see Supporting Information for a copy of the flyer). From the students who submitted applications, a cohort was formed via random application selection with the purpose of ensuring that the selected program members formed an unbiased, accurate representation of the initial applicant pool. In the third and fourth program iterations, three course sections were offered each semester allowing nearly all students who applied to the course to participate.

### Program Structure

The program was held during the spring semesters, and courses consisted of roughly 20 students and several instructors who met for one hour twice a week. This program was designed to be taught during the spring semester to ensure that students had a background of at least one semester of university-level physical science classes. Starting in the spring semester also allowed the freshmen participants the entire fall semester to acclimate to the university and their major course loads. The team messaging and project software program Slack was used to assist students with collaboration in their research groups and rapidly communicate with instructors outside of class. Assignments, general announcements, and relevant course files were also posted on Slack.

During the first three to four weeks of the course, the instructors gave lectures on required background information. These lectures included topics related to the course data set, how to read scientific literature, and guidance and suggestions on potential projects within the data set that students could investigate. Students were also introduced to a programing language or data analysis software they would need to analyze the data set (e.g., MATLAB, Python, or ImageJ) and were discouraged from using spreadsheet programs such as Microsoft Excel. During this first portion of the course, instructors also led a tour of the research lab where much of the data had been collected. This laboratory tour provided students an opportunity to see an active academic research laboratory and gain a better understanding of the instruments involved in the data acquisition process. Additionally, during the 2021 sections, we attempted to organize a "career panel" with early career academic and industry chemists, but unfortunately interest and attendance were low for this event.

For the remainder of the course, students developed and collaborated on research projects in small teams. Student teams typically consisted of three to four students and were chosen by students based on common research interests. Team Slack channels were used for project specific communication, which helped instructors stay informed about the progress and setbacks of each team. Students were expected to work approximately six hours a week outside of class either individually or with their group members. Work outside of class was supported by instructors through office hours or via Slack messaging. In-class time was spent discussing updates with the instructors and getting feedback on the work that had been performed. Throughout the semester, students gave in-class presentations on scientific literature relevant to their project, along with short presentations summarizing their research goals and progress in the style of a "group meeting". This allowed instructors and students to ask questions and make suggestions about projects, and even facilitated several collaborations between groups. At the end of the course, students were expected to produce a scientific research paper based on their work along with a poster to present to classmates and faculty at a poster session. For further details on the course structure and implementation, we direct the reader to our previous work.[25]

### Online Course Iterations

Due to the SARS-CoV-2 pandemic, the second half of the 2020 iteration of the program and the entire 2021 iteration were taught remotely. For the online iterations of the GURP

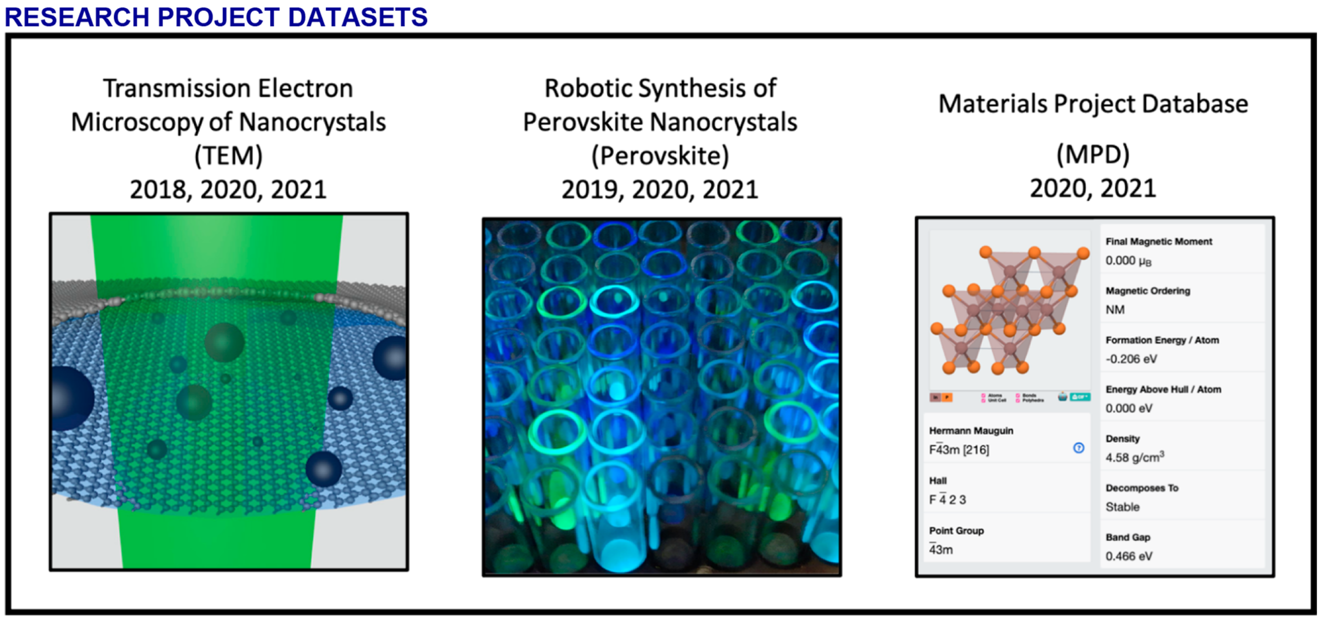


**Figure 1.** Overview of the different types of data sets that students used to construct research projects. From left to right: schematic of a liquid graphene cell used to image nanocrystals for TEM data sets (used for courses in 2018, 2020, and 2021); arrayed reaction vials containing perovskite nanocrystals during automated data collection (used for courses in 2019, 2020, and 2021); representative sample of material properties available from an open-source database (used for courses in 2020 and 2021). Copyright 2019 American Chemical Society, 2021 Materials Project.

program, the use of Slack was continued for course communication, and all scheduled classes and meetings were held through video conference sessions on Zoom. End of the year poster sessions were also held during online semesters through several simultaneous Zoom meetings each hosting a different student groups' work. Links to join these video conferences were organized in an abstract book that was distributed to all attendees.

Across the online courses, instructors adopted two different instructional forms for the research component of the course. For the 2020 iteration of the transmission electron microscopy (TEM) based course, each student project group would video conference directly with an instructor for 30 min twice a week during the regular class time. During these meetings, an instructor would address student questions, talk about the project's progress, and set goals for the next week. However, iterations of the 2020 and 2021 perovskite courses, the 2020 and 2021 Materials Project based courses, and the 2021 TEM course iteration used a different approach, employing a more direct translation of the traditional classroom environment to online instruction. At the beginning of each session, the entire class would join one video conference to discuss general announcements before dividing students into breakout rooms based on their teams. The instructors would then move between the breakout rooms of student teams based on requests in the chat or on Slack to discuss student projects. For groups that did not have questions during in-class time, an instructor would check-in briefly with the group to discuss research progress.

## Instructor Assessment of Learning

Students were expected to participate in the course by completing assignments, presentations, and final projects. These assessments provided tangible goals for the students, particularly toward building their semester long project, and provided the instructors opportunities to gauge student learning. Many of the assignments such as scientific literature presentations and their final reports were not focused on getting a right or wrong answer, but rather on integrating the scientific content and producing results that indicated that the students understood the material they were presenting, referred to as integrated learning. To help students accomplish this task and understand the metrics, rubrics for the assignments were provided that assisted students in achieving these objectives (see DOI 10.6078/D1HD9G for examples). Some integrated learning objectives that student work was based on were the following:

(1) Developing appropriate data analysis techniques for the given data set
(2) Drawing logical conclusions from the analyses of data sets
(3) Understanding implications and broader impacts of data conclusions
(4) Develop ability to work in teams toward a common goal
(5) Develop oral and written scientific communication skills

To aid with grading of student work as objectively as possible, grading rubrics were designed that allowed instructors to determine if certain learning objectives had been achieved, such as thorough exploration of past literature and whether the student's conclusions were logical. Students typically exceeded expectations and developed quality work that impressed us as instructors.

Beyond the graded work that students turned in, we were able to assess student learning through the many personal interactions that we had with the students. During class time, we would meet with the individual student groups and ask about the progress that had been made on the project and if there were concerns that they had. On the basis of the work performed and the questions asked, we could evaluate the effort that students had put in and what they were learning, and as with other aspects of the course, students appeared highly engaged and the questions that they asked demonstrated the work that they had put into the course.


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### Surveys

To determine student self-assessment of learning quantitatively, we surveyed students before and after the course. Students self-evaluated their skills in research, scientific communication, scientific literature, nanomaterials knowledge, and their desire to attend graduate school in chemistry, chemical engineering, or materials science on a scale from 1 to 10. Study protocols were approved by the Institutional Review Board (IRB reference no. 2018-04-10956) of the University of California, Berkeley. At the beginning and the end of the course, we asked students to assess their growth as researchers, and whether they had tried to join a research group. Students in the 2018 and 2019 iteration of the program were asked to complete additional surveys a year and two years after completing the program to determine whether they had successfully joined a research group. We did not collect student demographic information due to the small class sizes, but we believe that investigating how a GURP program influences self-perception of ability in STEM fields by members of underrepresented groups would be a promising future area of study. The survey questions as well as enrollment numbers and response rates for the surveys are included in the Supporting Information.

## ■ RESEARCH PROJECT DATA SETS

### Transmission Electron Microscopy

During the first iteration of the program in 2018, students were tasked with analyzing TEM videos of platinum nanocrystal growth (denoted as TEM '18).[25] Platinum nanocrystals were grown in a solution encapsulated between graphene layers, known as a graphene liquid cell. TEM videos were recorded that observed the nanocrystals at atomic resolution, allowing for the analysis of nanocrystal movement, growth, and coalescence.[26,27] After learning about the basics of transmission electron microscopy and nanocrystal chemistry, students performed image analysis of the data set using ImageJ image processing software. Some students were also introduced to MATLAB during their research projects to help organize, analyze, and visualize the data set. Students hypothesized and investigated the mechanisms of nanocrystal growth, movement, and interaction using the videos collected.

During the spring semesters of 2020 and 2021, students conducted research on TEM data sets of cadmium selenide/cadmium sulfide core−shell nanocrystal samples (denoted as TEM '20 and TEM '21, respectively). In TEM '20, the data set (Figure 1) focused on highly ordered nanocrystal assemblies, referred to as superlattices, of cadmium selenide/cadmium sulfide core−shell nanocrystals.[28] For the first 3−5 weeks of the semester, students learned about concepts relating to nanocrystal synthesis and assembly as well as image analysis techniques. Students then analyzed the data set to identify imperfections in the TEM images of ordered nanocrystal superlattices. This data set encouraged students to think about how materials pack together, what types of defects can exist in crystal lattices, and how these superlattices might be optimized.

Beyond ordering in superlattices, these core−shell nanocrystals are highly luminescent. The ratio of photons emitted to photons absorbed is referred to as quantum yield. In TEM '21, TEM images of two cadmium selenide/cadmium sulfide core−shell nanocrystal samples were investigated: one with near-unity photoluminescence quantum yield[29] and the other with approximately 90% photoluminescence quantum yield. The first 3−5 weeks were devoted to lectures on nanocrystal synthesis, quantum yield, and crystalline defects such as stacking faults. Students employed ImageJ and MATLAB to investigate the structural character of the nanocrystals: size, shape, and defect concentration. In both TEM '20 and '21, students utilized and modified instructor-provided custom MATLAB scripts to identify the size distributions of nanocrystals and locate defects. The introduction of previously developed software allowed students to customize and use complex code, whose entire ground-up development would have been outside the scope of the course. These data set comparisons allowed students to hypothesize structure−property relationships in nanocrystals and develop ideas about how defects affect materials.

### Perovskite Nanocrystal Synthesis and Transformation

During the spring semesters of 2019, 2020, and 2021, students analyzed the absorbance and emission spectra of lead halide perovskite nanocrystals. Perovskite nanocrystals are easy to synthesize and have interesting optoelectronic properties; however, they remain sensitive to degradation, and significant work has been conducted to understand their stability.[30,31] These semiconducting nanocrystals absorb and re-emit light, and the efficiency at which they do that is attributed to defects on their surfaces which can be induced by different chemicals. The 2019 iteration of the course utilized a data set of roughly 1000 absorption and photoluminescence spectra of $CsPbBr_3$ perovskite nanocrystals after being exposed to different amounts of degrading additives (denoted as Perovskite '19).[32] The 2020 iteration of the course utilized a similar data set that consisted of the absorption and luminescence spectra of different cesium lead bromide nanomaterials synthesized with different concentrations and ratios of precursors (denoted as Perovskite '20). The 2021 iteration of the course expanded this data set[33] and provided relative species fractions that had been extracted in the associated research paper (denoted as Perovskite '21).[34]

In these iterations of the course, students were introduced to the field of lead halide nanocrystals, including the basics of absorption and emission spectra and fundamentals of nanocrystal synthesis. Students were simultaneously given instruction on data modeling, visualization, and analysis with Python using a series of hands-on instructor-led coding tutorials. Student groups then selected a feature of the data set to focus their projects on and utilized the data modeling techniques taught in the beginning of the course to generate predictions for reaction conditions to produce their desired result. From these wide sets of data, students were able to hypothesize about nanocrystal reaction kinetics, how and why the nanocrystals degrade, and what precursors and conditions influence what types of nanocrystals are grown.

Student groups generated their analyses in Python using Jupyter Notebooks (a Python environment). Using their hypotheses, about halfway through the semester of 2019 students proposed follow-up experiments performed by instructors to validate or disprove their findings. This was not possible in 2020 due to research limitations related to the SARS-CoV-2 pandemic; instead, students were given experimental inputs for a new data set and asked to predict their chosen feature for a subsection of their choosing, and then provided with the experimental results. During the 2021 semester, we performed two rounds of follow-up experiments,

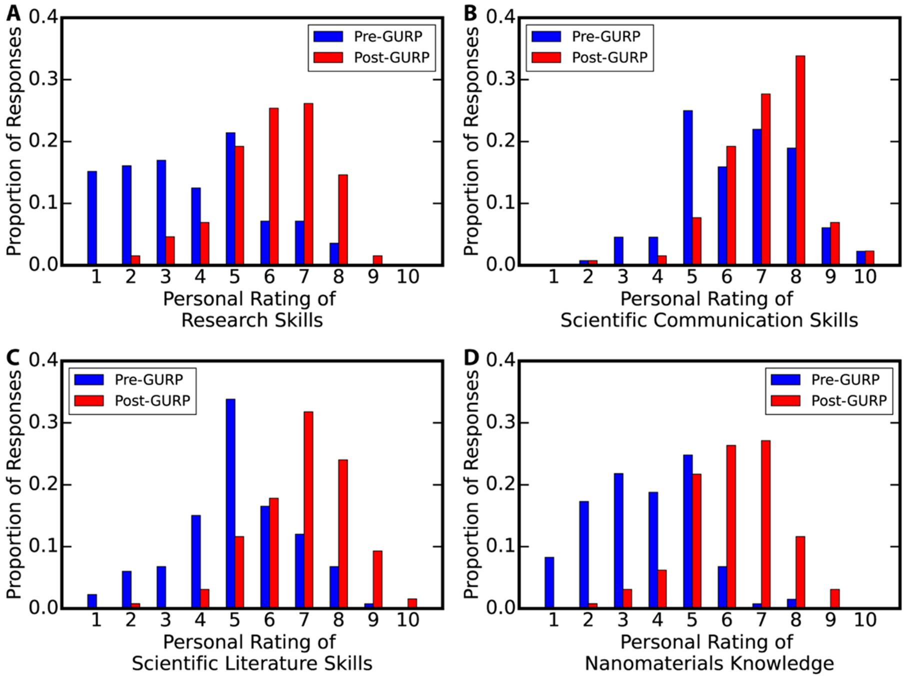


**Figure 2.** Aggregate data of students' responses to the survey questions before and after the GURP program. (A) Students' personal rating of their research skills. (B) Students' personal rating of their scientific communication skills. (C) Students' personal rating of their scientific literature skills. (D) Students' personal rating of their nanomaterials knowledge.

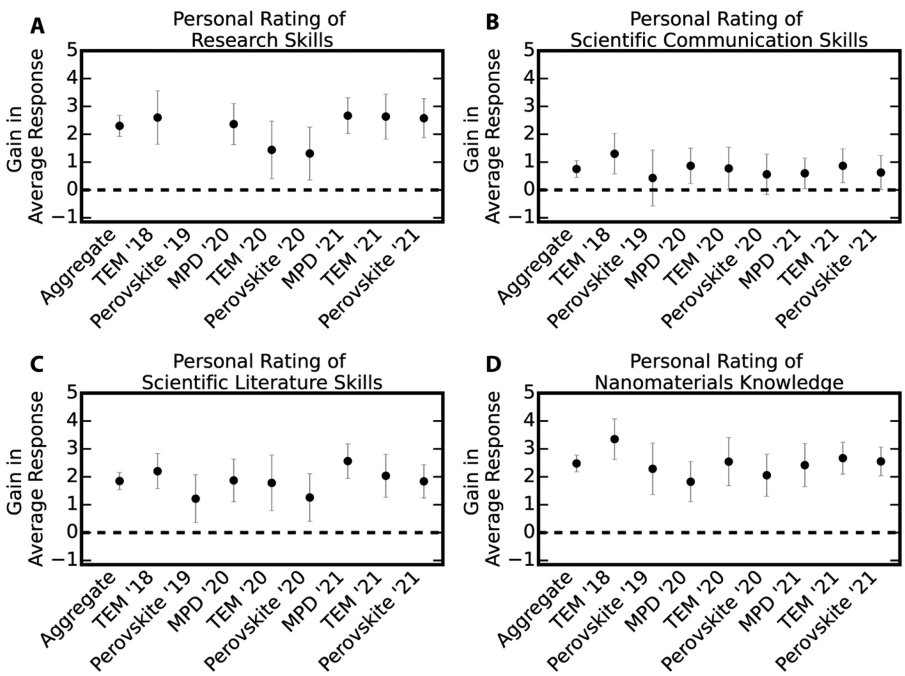


**Figure 3.** Average gains in student responses for each course iteration (course data set type followed by iteration number) and the aggregate of all courses taught, with error bars representing 95% confidence intervals. (A) Average gain in personal rating of student research skills. The precourse survey for Perovskite '19 was missing the personal rating of research skills question; thus, the gain in average response could not be determined. (B) Average gain in personal rating of student scientific communication skills. (C) Average gain in personal rating of student scientific literature skills. (D) Average gain in personal rating of student nanomaterials knowledge.

allowing students to reformulate their hypothesis after the first set of experimental data.

## Materials Project Database

For the spring semester of 2020 and 2021, the Materials Project Database (MPD) was introduced as an additional data set.[35−39] The Materials Project Database is a free, publicly available, online resource containing material properties (computed by advanced density functional theory calculations) for hundreds of thousands of materials. These properties included energy of formation, band structures, magnetic moments, relative stability between polymorphs, and diffraction patterns, to name a few. During the first month of this


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iteration of the course, students were taught basics of materials science and Python. Students were then instructed to investigate inorganic material trends in MPD using their new knowledge of the domain and principles taught in their general chemistry courses, such as periodic trends, atomic size, electronegativity, and crystal structure. Students used Jupyter Notebooks and pymatgen (a Python library created in association with MPD) to access and analyze material properties from MPD. Students were provided with some simple starter-code to query the database and were encouraged to also use the Materials Project website in their research efforts.

Student inquiry using this data set was markedly different from the other iterations of the GURP program, as unlike the other programs which focused on one material class and property, a wide variety of materials and properties were at the disposal of the students. Projects included students investigating correlations between material properties and crystal structures, elemental composition and properties, or thermodynamic stability. Students also compared the computed properties with reported values in literature and were able to use the database to predict what materials might have useful applications or what experimental properties might be that had not been reported in the literature.

## ■ RESULTS AND DISCUSSION

### Student Self-Perception of Learning Gains Is Consistent across Multiple Sections with Varied Instructors and Data Sets

Collectively, students' personal evaluation of their research skills and knowledge increased in all categories (Figure 2). These observations are supported by Welch's *t* tests, which indicate that the differences in responses before and after taking the course were all statistically significant (Table S2). All iterations of the research program showed aggregate gains in learning outcomes, with minimal differences between the course data set, instructors, and number of iterations held (Figure 3). A Kruskal−Wallis analysis of variance found that the only statistically significant difference in the precourse surveys between cohorts was that the 2021 cohort had a greater desire to attend graduate school. A similar Kruskal−Wallis analysis of postcourse surveys found that the only statistically significant difference between sections was for the personal rating of scientific communication skills. These findings were supported by a Games−Howell posthoc *t* test. The 2021 cohort was found to be statistically significantly different from the 2019 and 2020 cohort in terms of desire to attend graduate school before the course, and TEM '18 was statistically significantly different than MPD '20 and Perovskite '20 in terms of scientific communication after the course (Tables S3−S5).

### GURP Can Be Adapted to a Virtual Format

The third and fourth iterations of this course, the spring semesters of 2020 and 2021, were held through a partially or fully online format. Compared to most laboratory or research courses, we quickly observed that our course's structure was easily adapted to virtual instruction. The use of video conferencing did present restrictions for instructors, as it was difficult to judge student engagement and respond to questions when they arose. However, student conversations were more intimate as the whole class was no longer constrained to a single physical room. Virtual poster sessions also stimulated meaningful discussions about student research, and instructors found them at least as effective as an in-person poster session for providing an opportunity to share work and feel a sense of accomplishment. The online poster sessions also had the financial benefit of forgoing the printing of student posters. Additionally, the two approaches used to teach the research portion of the course online yielded similar student outcomes.

Prior to the 2021 iteration of the program, it remained unclear how much the previous year's in-person component influenced student learning outcomes. During the 2020 semester, students had the opportunity to meet their instructors and peers and form research teams in-person before switching to online learning. The 2021 iteration did not include any of these activities in-person and instead attempted to replicate them in an entirely online setting. Running the entire program online did not significantly change student growth from our perspectives as instructors or from the feedback and data in the postcourse surveys. While there are likely a variety of factors that contributed to the success of a full remote program, we speculate that the program's emphasis on active student participation and community building may be particularly beneficial in an online setting.[40,41] The success of this program in a variety of learning environments is compelling evidence for its strength in providing research experiences for undergraduates.

### Instructor Assessments of Student Learning Support Student Self-Assessment

Observations from working with students also appear to support this quantitative finding and suggest that many of the program's key learning outcomes were achieved. Emerging from this program, students were expected to confidently locate, read, and communicate scientific literature. Students were also expected to have developed their scientific communication skills through both formal and informal discussions with their peers and instructors. Greater competency in creating effective scientific figures, writing a formal report, and using a programing language, were several other important skills that students were expected to have developed through this program. In discussions and postcourse surveys, many students cited the benefits of becoming familiar with a programing language, becoming exposed to scientific literature, and solving open-ended problems as some of the most positive aspects of the course. Student work reflected gains in these areas as well. Student papers utilized in-depth code-assisted data analyses and references to numerous publications, while remaining clear and concise. Past students have expressed how the scientific research and communication skills they developed in GURP have helped them succeed in more traditional research environments. One student commented that "learning how to look for relevant scientific literature and break it down into understandable sections" has been a crucial skill that helped them succeed in "internships and undergraduate research across different areas of chemistry and physics." and that "tackling a research project as part of a group was hugely beneficial and taught me early-on important communication skills that I continue to use today." From these comments, it can be inferred that the GURP can be an effective step in the scaffolded learning in undergraduate degrees to prepare students for independent scientific research.[42]

While we observed that students needed additional instruction and effort to engage with the more abstract spectroscopy and computational chemistry data sets, the


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majority of student projects met or exceeded instructors' expectations. We also felt that the disparate data sets used did not affect the overall student experience, which was supported by the survey results of student self-assessment (Figure 3), and we believe that many other data sets could be used in a similar program. While most students eventually excelled in the course, with some of the more coding heavy data sets (such as the Perovskite and MPD sections) some students who had no experience with coding expressed some frustrations. A potential improvement to the course would be more in-depth coding tutorials that would be optional for students to complete.

Smaller student assignments were evaluated on the basis of completion and returned with feedback highlighting successes as well as possible areas of improvement. For larger assignments, content and formatting guidelines were provided during tutorials on scientific figure creation, poster design, and report writing (see examples of assignment guidelines at 10.6078/D1HD9G). Students were evaluated on the basis of their adherence to these guidelines and responsiveness to instructor comments during the revision process. Students often went above and beyond in their completion of these assignments, visiting instructors in office hours to obtain more in-depth feedback and collaborating outside of class to prepare and practice their presentations. Over all program iterations, all but one of the students achieved or surpassed the expected competency in literature review, informal and formal scientific communication, poster design, and report writing and were awarded grades of A−B. In general, the students were highly motivated and put significant personal effort into developing their projects.

### GURP Serves as a Springboard for Further Research Positions

As mentioned previously, one of the main goals of this course is to act as a springboard for students seeking UREs in chemistry. At the time of the postcourse survey, the majority of students had not tried to get a research position or had been rejected; however, numerous students expressed interest in continuing on-campus research or similar research experiences. The participation in research rates before and immediately after the course (37% and 34%, respectively) were similar to rates of freshman students in the University of California, Berkeley College of Chemistry, indicating that the students in the course may be representative of the population of students as a whole (40%). One year after the research course, 82% of students from the 2019 cohort had found a research opportunity that they had been engaged with, and after two years 86% of students in the 2018 cohort had engaged in research (Figure 4). The participation in research of undergraduate students at the time of graduation between 2013 and 2019 in chemistry, chemical engineering, and chemical biology majors ranged from 30% to 90%, and for a given major and year the median response for participation was 75%, indicating that this course may increase participation in research compared to students who have not taken this course, but this is inconclusive. Unfortunately, we are not including research participation data from students in the 2020 cohort due to limitations of research opportunities due to the extenuating circumstances of the SARS-CoV-2 pandemic, as this is likely not a fair comparison. One interesting aspect of the survey data was that the course did not increase students' desire to attend graduate school (Figures S1 and S2). While

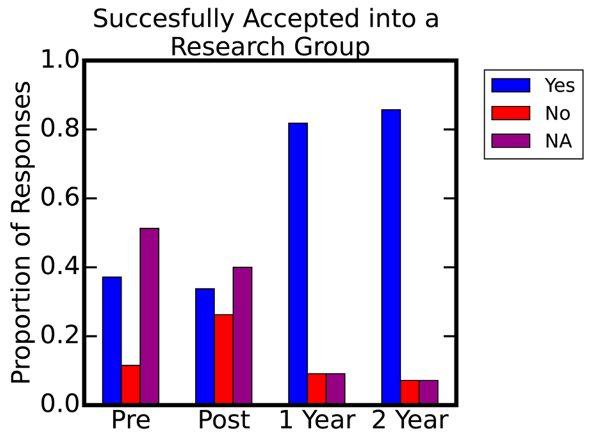


**Figure 4.** Follow-up survey results of the student participation in a research group from Perovskite '19 and TEM '18 performed one and two years after the course. Follow-up surveys were not performed in 2021 due to complications of the SARS-CoV-2 pandemic with undergraduate research.

there is currently insufficient data to determine why there is not greater desire to attend graduate school, this may be related to the fact that a large portion of prospective chemistry majors change majors.[43] Additionally, this question asked only about pursuing a degree in chemistry, chemical engineering, or materials science and did not account for students who plan to pursue graduate degrees in a related physical science. In discussing future career plans with students, it was evident that many students were still considering a variety of careers and only beginning to plan for life after university. However, we find it compelling that most of our students tried and were successful in receiving research positions. Part of this success could be attributed to instructors meeting individually with students to discuss their research goals and advising those interested in research on how to find other positions at the university. The program also allowed students to refer to the graduate student instructors for letters of recommendation and provided students with valuable resume skills such as programing literacy and prior research experience. Instructor knowledge of students is particularly valuable at a large university, where professor and teaching assistant knowledge of individual students can be limited due to large class sizes.

## ■ CONCLUSIONS AND IMPLICATIONS

Due to the consistent student growth across different data sets and instructional forms, we believe this type of group-led research experience model could easily be extended to many other fields and institutions as outlined in Figure 5. In a comparison with our pilot program, we found that the results in student self-assessment learning outcomes were fairly uniform across different data sets and the online experiences, and while implementing an iteration on data sets generated by student hypotheses appears to be a valuable addition to the original program, no significant changes in student outcomes was observed. Research groups specializing in chemistry or other experimental sciences such as astronomy or biology could implement similar programs through use of our data sets or publicly available data sets as outlined in SI Table 1. Additionally, research groups with a background in data science would be well-suited to host similar programs because of their domain knowledge and access to large data sets. To help research groups looking to start GURPs, we have


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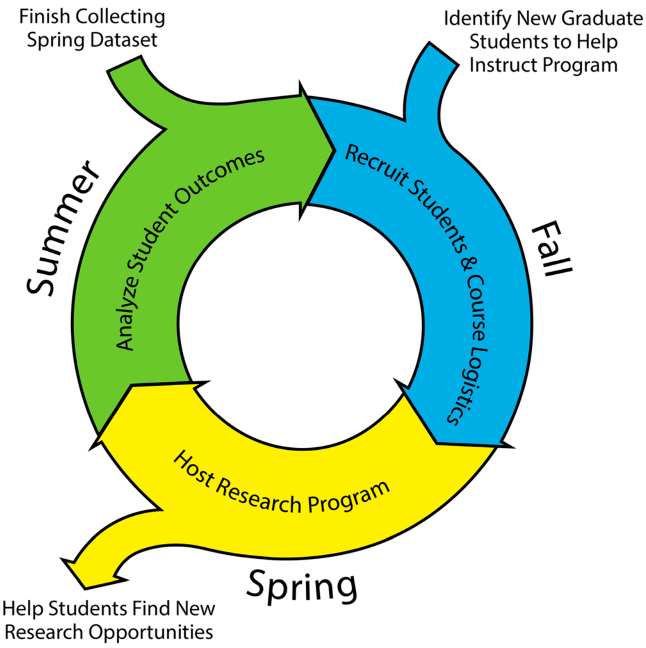


**Figure 5.** Schematic depicting key steps in the long term process of maintaining an effective GURP. Depending on the program adaptation, each cycle step could be adjusted to occur one term earlier or later than depicted. A greater discussion on implementing and maintaining similar research models can be found in the Supporting Information.

provided multiple experimental data sets collected by our group as well as lesson plans on Dryad (DOI 10.6078/D1HD9G). We believe that this model could also be adapted into a fall or summer section devoted to transfer students, with the goal of helping these students develop a sense of community and engage in campus research more rapidly.

The model of a group-led undergraduate research program has proven successful at our university. This course introduces undergraduates to research without a large upfront investment by the students or the mentors, both financially and logistically. Students demonstrated positive quantified learning outcomes independent of course focus and instructors. After completing the course, most students showed an increased self-perception of competence as researchers and have continued to engage in campus research. Additionally, this course transitions well to the online format and shows promise as a model for online research courses in cases where in-person research experiences are not possible.

## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.1c01065.

Additional guidance for program implementation, survey questions, further survey results as well as the statistical analysis of survey information, and an example recruitment flyer (PDF, DOCX)

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### Notes

The authors declare no competing financial interest.
Data sets regarding TEM videos and images, perovskite nanocrystal absorption and emission spectra, and course plans for GURPs are provided free of charge at DOI 10.6078/D1HD9G.

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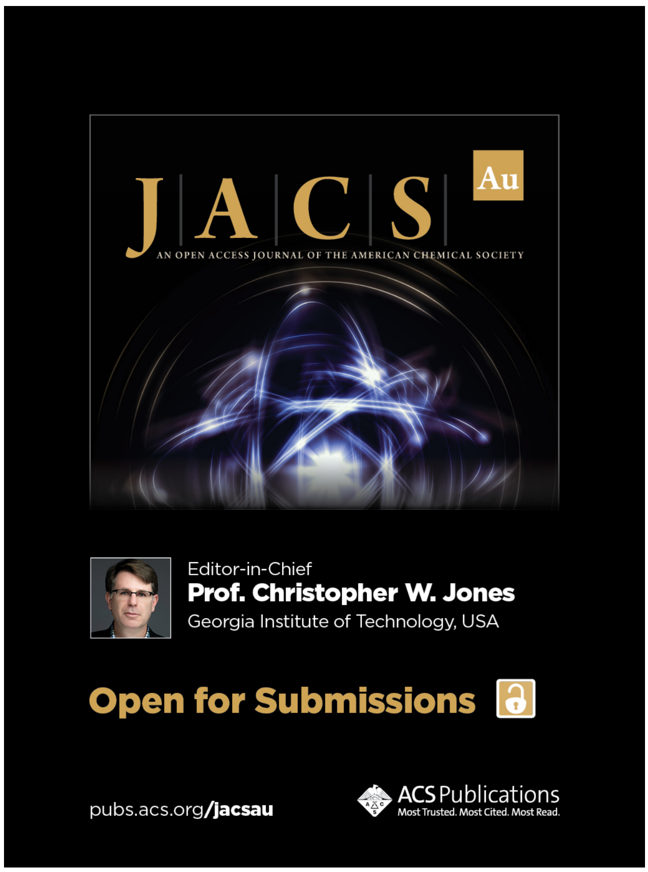



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