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Translatable Research Group-Based Undergraduate Research Program for Lower Division Students

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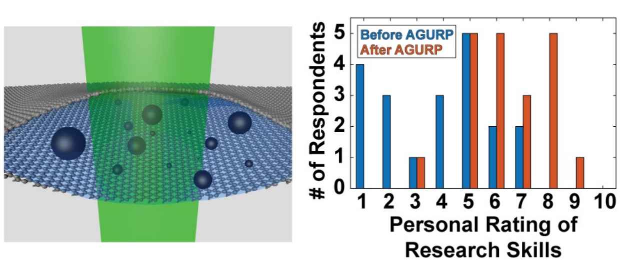
ABSTRACT

Participating in undergraduate research yields positive outcomes for undergraduate students, and universities are seeking ways to engage more students in undergraduate research earlier in their academic careers. Typically, undergraduate students perform research either as part of an apprenticeship where a student receives individual mentorship in a research lab setting from an experienced researcher in the field of interest or in a course-based undergraduate research experiences where students work in a classroom or teaching laboratory to investigate open-ended research questions. In this work, we implement a model of undergraduate research that combines aspects of those two methods to provide benefits to undergraduate students and research groups. A cohort of twenty first-year undergraduate students at the University of California-Berkeley were recruited to work on a project investigating data previously collected by the Alivisatos research group. Over a semester, these students learned about nanomaterials and the research process, pursued curiosity-driven research in teams, and presented their results at a formal poster session. Students from this program showed quantifiable gains in their self-identification as researchers and scientists. This program was developed to be a model for other research groups, departments, and universities to combine the benefits of traditional apprenticeship research and course-based undergraduate research to provide a research experience for large numbers of undergraduate students early in their college education.

GRAPHICAL ABSTRACT



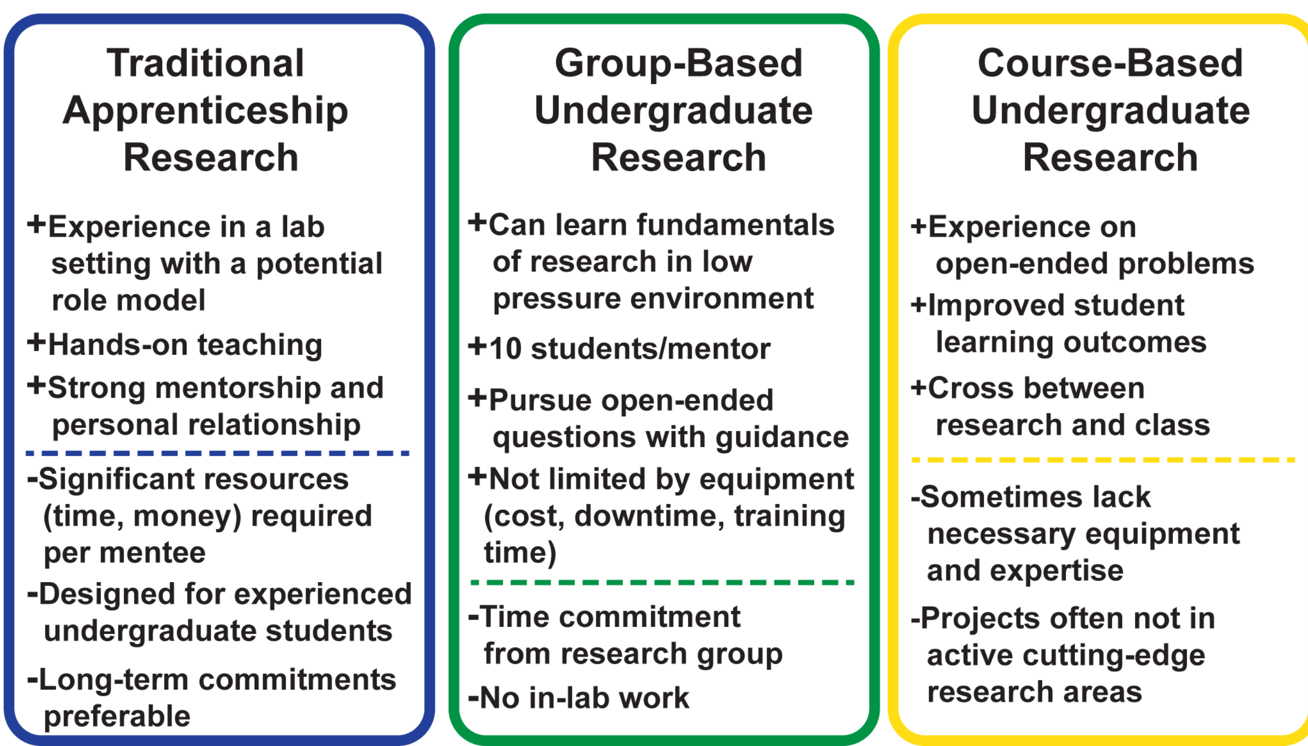
KEYWORDS
Materials Science, Nanotechnology, Collaborative Learning, First-Year Undergraduate, Hands-On Learning

INTRODUCTION

Undergraduate research has numerous positive outcomes for the participating students ranging from improved performance in classes, higher self-identification as scientists, better graduation rates, and better retention of students from underrepresented demographics.[1–7] Exposing undergraduate students to the world of scientific research in addition to their foundational classes can help ignite scientific passion and can inform their career trajectories. Schools and scientific support agencies and foundations have realized the importance of undergraduate research and have made it a priority for their organizations.[8] As a result, significant effort has been put into defining what the goals should be for a research experience and how undergraduate research can be structured to achieve those goals.[9,10] By developing, implementing, and evaluating different undergraduate research models, universities are working to provide high quality research opportunities that improve the education experience for every STEM student.

Apprenticeship in a research laboratory is the most common model associated with undergraduate research, and while it is an important part of undergraduate education, it is challenging to scale to accommodate every undergraduate student.[11] One-on-one mentorship from a graduate student, post-doctoral researcher, or professor in an active research setting can be an immersive and engaging experience for an undergraduate student. The hands-on teaching of scientific techniques from a mentor allows the undergraduate student to develop their scientific skills while the mentor relationship provides valuable guidance as the undergraduate student develops their career goals. However, to provide this experience, a significant amount of time and money are needed for every undergraduate researcher. These positions are usually designed for experienced undergraduate students who are willing to make long-term commitments. Additionally, the projects are often formulated by the mentor or primary investigator to advance their research and not necessarily with the undergraduate student's development as a starting point. Although traditional apprenticeship positions are suitable for advanced undergraduate students who plan to go into academic research, apprenticeship models exclude large numbers of early stage students who simply want to explore curiosity-driven research.[12]

As a result of the limitations of the apprenticeship model, course-based undergraduate research experiences (CUREs) have been developed to allow all lower division students the opportunity to explore scientific research.[13] Students



enroll in a laboratory course where they are able to pursue open-ended scientific questions. Unlike “cookbook”-style experiments commonly performed in lower division laboratory classes, undergraduate students can work through the scientific method and experience a more realistic scenario of experiments without a known answer. CUREs have been shown to increase positive student learning outcomes and have been implemented in many schools including the chemistry curriculum at the University of California-Berkeley.[7,14,15] While CUREs are capable of engaging large numbers of undergraduate students, we believe the research projects’ scope can be limited due to difficult access to specialized equipment and expertise needed to pursue cutting-edge research topics typically found in apprenticeship models. An integrated approach where undergraduate students have an early exposure to research groups may provide a more realistic experience, one which the undergraduates themselves may perceive as more authentic.

Figure 1. Comparison of the advantages and disadvantages of common undergraduate research models from our experiences. The group-based undergraduate research model attempts to combine the advantages of the traditional apprenticeship research with Course-Based Undergraduate Research Experiences.

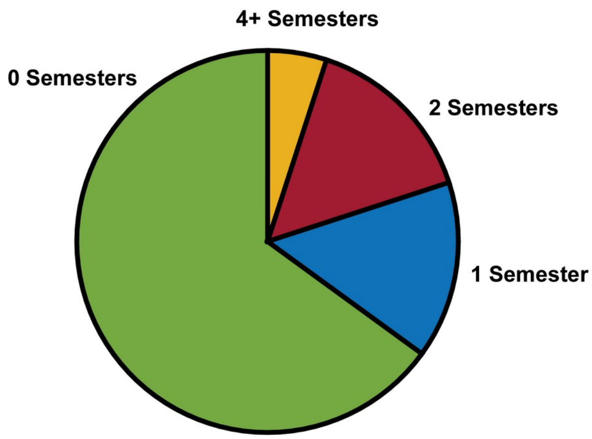
A Hybrid Approach to Undergraduate Research

We attempt to combine the advantages of apprenticeship-style research and CUREs by proposing the research group-based undergraduate research program (GURP). (Figure 1) Our implementation of this model has graduate student or post-doctoral mentors lead groups of lower division undergraduate students on a curiosity-driven research project over a semester using pre-collected data from the research group. Undergraduate students learn the fundamentals of research in a supportive environment under the guidance of an experienced researcher in the field and gain confidence by tackling a tractable problem in an authentic research context without having to worry about mistakes leading to a poor grade. The undergraduate students are able choose their own projects, within the scope of the research data provided by the group, which encourages them to be creative while also thinking critically about the subject matter. First-year students can identify as part of a research group and feel a sense of being part of the scientific community. This model has a CURE-like multiplicity factor of tens of undergraduate students per mentor that could make it advantageous for a large department to implement if they wanted to engage all first-year students in a first research experience. For this model to be successful, research groups need to think carefully about how the undergraduate student work will add to their research. To achieve this, we focused on research projects with large amounts of pre-collected data whose analysis is not easily automated and open-ended enough to allow for multiple hypotheses to be explored and tested. Later, we will discuss in greater detail the type of projects that work best for this type of program, but ideally, they should be data sets that are time intensive but not overly complicated to analyze. Observational data sets such as microscopy, imaging, or combinatorial chemistry studies are often rich enough to support many hypotheses and iterations. By having the undergraduate students perform data analysis without lab work, time and resources are also saved by the research group. Additionally, by not being locked into the course-system, research groups can run the program whenever they have suitable data. Although this model removes the in-lab experience for the undergraduate students, they still engage in data analysis, arguably one of most important aspects of research, and as no specific scientific instruments are required for the undergraduate students to use, it is relatively easy to scale the program to fit student interest. Undergraduate students are also able to get through an entire cycle of scientific analysis in a single semester without spending excessive time learning instrumentation or struggling with experiments that often require significant troubleshooting to get functioning. We believe that focusing on question development, data analysis, synthesis of results, and next steps with cutting-edge data in a supportive environment will allow larger numbers of lower division undergraduate students to be engaged in the research process.

In this paper, we will share the implementation of our research group-based undergraduate research program (GURP) for first-year undergraduate students in the College of Chemistry at the University of California-Berkeley. The research area will be explained with insights into the types of projects that we found worked well for this model. Finally, we will discuss the outcomes of this program and our plans for continuing this program in the future. Our goal is that other research groups, departments, and universities will be inspired to implement their own group-based undergraduate research programs, increasing the number of lower division students who can be exposed to the positive effects of undergraduate research.

RECRUITING GURP STUDENTS

Our recruitment goal was to appeal to all lower division students pursuing a degree in chemistry, chemical engineering, or materials science and engineering. We made an announcement in the Chem 4A class, a required introductory chemistry course in the Fall semester of the first year for Chemistry and Chemical Engineering majors at the University of California-Berkeley, and also posted flyers around the chemistry department. (Figure S1, with S denoting Supporting Information) It was especially important to us that we did not simply attract the highest-achieving undergraduate students to participate in this program. One concern with the positive learning outcomes associated with undergraduate



research is the possibility that the highest-achieving undergraduate students are self-selecting into research, and thus the undergraduate researchers are not representative of their entire class.[16] Our recruitment stressed that this research program required no previous knowledge and was actually designed for lower division students with no previous research experience. We highlighted the skills we would hope to teach the undergraduate students and included the dates of our two informational meetings where we would share in greater detail the program structure. Finally, our recruitment flyer included application requirements consisting of only two 400-word essay questions where prospective students could share their interest and curiosity. We did not ask for transcripts, resumes, or letters of recommendation because we wanted a realistic cross-section of the first-year class to better understand if group-based undergraduate research programs could benefit students from all backgrounds. As long as the undergraduate students were motivated, we believed we could provide them the fundamentals and guidance to perform the research.

Figure 2. Prior research experience for students admitted into the GURP. The majority had never previously been involved in research.

Our recruitment yielded 60 applications for the 20 slots in our program. The first selection criteria was whether the applicant had attended an informational session or contacted us directly about the program. Since this program would require a time commitment from the undergraduate students, we were concerned that applicants who applied without attending the information sessions might be unaware of the expectations. From the remaining 40 undergraduate students, the 20 participants and 10 wait-listed students were selected by a random number generator to provide a random cross-section of the applicants. We read the essays of the admitted students to ensure genuine interest in the program, but no undergraduate students were removed due to inadequate essays. The majority of the admitted students had no prior research experience, and this aligned with the goals of the program. (Figure 2) Although the admitted students were not truly a random cross-section of the first-year class as some students may have felt too unqualified to apply, we attempted to ensure that any motivated undergraduate student regardless of skill level would have an equal opportunity to participate in our program. We note that, if such programs were implemented at scale at a single school or in a single department with many research groups in the same semester, no selection would be required, and such an experience could be offered to every undergraduate student.

PROGRAM STRUCTURE

Devising a single semester research program for first-year students was ambitious; however, by strategically dividing the semester into subsections of fundamentals, open-ended research, and dissemination of results, undergraduate students were able to pursue open-ended research while also increasing their knowledge of the research area and the scientific process. We chose to run this program during the Spring semester to ensure that all of the undergraduate students had already taken one semester of college-level introductory chemistry, providing a baseline level of knowledge that we could build from in the GURP. It was assumed that the undergraduate students had minimal to no prior knowledge in our research area of nanomaterials, and thus, we included lectures on the relevant fundamentals. The undergraduate students were also taught how to use scientific literature to learn about the most recent advances and discoveries. Connections between research lessons and topics from the undergraduate students' introductory chemistry classes were emphasized, and we were careful to focus on only the necessary content. We understood that most of the undergraduate students likely would not pursue a career in nanomaterials, so the research lessons were designed to be applicable to a variety of fields. Ultimately, we wanted this program to be a curiosity-driven research environment, so lectures were kept to a minimum, and all activities were designed around student-driven ideation and problem solving.

Introduction to Research and Nanomaterials

The structure of the program was divided into Introduction to Research and Nanomaterials (4 weeks), Open-Ended Research Time (7 weeks), and Presenting

Research Results (4 weeks). (Figure 3) Each week involved 2 one-hour meetings with roughly 6 hours of unsupervised work expected for the rest of the week, and participating students received two course credits for independent research. This was not a departmental course because we wanted to easily adjust to the needs of the undergraduate students in the same way as apprenticeship research positions. In essence, two graduate students were taking on 20 undergraduate students to work on a research project. The introduction period focused on providing the undergraduate students the knowledge needed to complete the project. This in... on cr... s well as... nes, ho... sc... hared what information different types of publications contained (articles, communications, reviews, and perspectives), which journals have strong nanomaterials research, how to find the articles, how to pick out the important information in a paper, and how to determine if an article is of high quality. Then, students were assigned to find an article related to this program's research, and share a 2-minute oral summary with the class. This literature activity served the dual purpose of exploring scientific literature as well as engaging the undergraduate students in peer learning about nanomaterials.

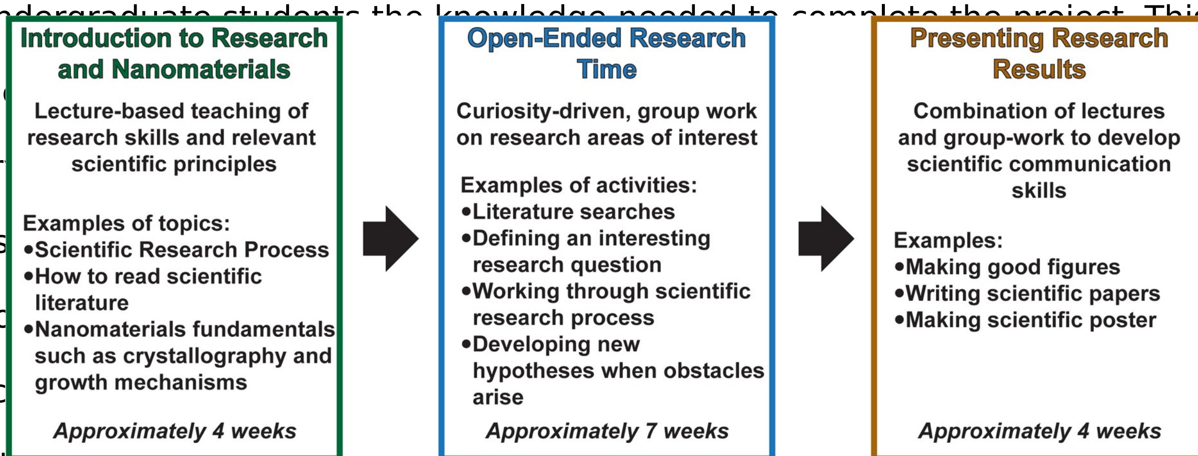


Figure 3. Structure of our GURP. After building a foundation of relevant nanomaterials and research knowledge, undergraduate students were able to pursue open-ended research before wrapping up with presentations on their results.

Open-Ended Research Time

Once the undergraduate students had a suitable foundation, we asked them to determine a question they would like to investigate about the data, and then grouped the students into teams according to their interests. The first week of the course, we asked the students to look at the data and find a feature in the data set that intrigued them. Although the student researchers did not yet have all the tools to fully dissect the data, exposing them early to the data kept it in the back of their minds while learning fundamentals. After learning more about materials chemistry and the scientific method, the participants were asked again to make a hypothesis about the data. The variety of ideas did not all appear to have equal merit, but a strong benefit of our program was that undergraduate students had the opportunity to test out their own ideas and learn how to pivot from a failed idea to a more promising direction without fear of negative consequences. Each group of students provided a short presentation on their work every week with the associated successes and failures, similar to a group meeting in a traditional research group. Ideas were shared across groups, and undergraduate students were able to engage in peer learning. The graduate student mentors were available to answer questions, but undergraduate students were encouraged to think through problems in their teams. As the undergraduate students were frequently told during the program, research does not *a priori* lead to meaningful answers, so often the best way to figure out a research problem is to design experiments to test hypotheses.

Presenting Research Results

The final part of the program was designed to help the students understand the different ways scientists can share their results with the scientific community and the public. An underappreciated aspect of being a scientist is the ability to coherently and understandably communicate research to a broader audience. In addition, assembling a presentation of data can help young researchers better understand the flow of their project and changes their mindset from simply doing a task to thinking about how that task fits into a larger body of scientific work. After students were given lessons on making figures and writing scientific papers, each group of students was required to submit a formal paper in an ACS journal format and prepare a scientific poster. The semester culminated in an open poster session where the undergraduate students shared their research with friends and classmates. The undergraduate students were able to take ownership of their work and experience a cycle of scientific research from start to finish. The skills learned and developed throughout this program should be applicable to their course-work in addition to their future research endeavors.

RESEARCH PROJECTS

The appropriate data and area of research are crucial for engaging the undergraduate students as they work through various hypotheses during the semester. As mentioned previously, this program ideally is mutually beneficial to the undergraduate students and the research group, and thus, the data should require time intensive, but relatively straightforward, data analysis. The data analysis could be repetitive or one that could benefit from analysis in multiple different ways. The project should be interesting yet manageable for groups of first-year students to complete over a semester. The undergraduate students in our program commented that it was motivating to work with data that was cutting edge and relevant to active research because unlike many of the contrived experiments in their coursework, the results of this work could actually matter to other scientists in the field.

Data Set Considerations

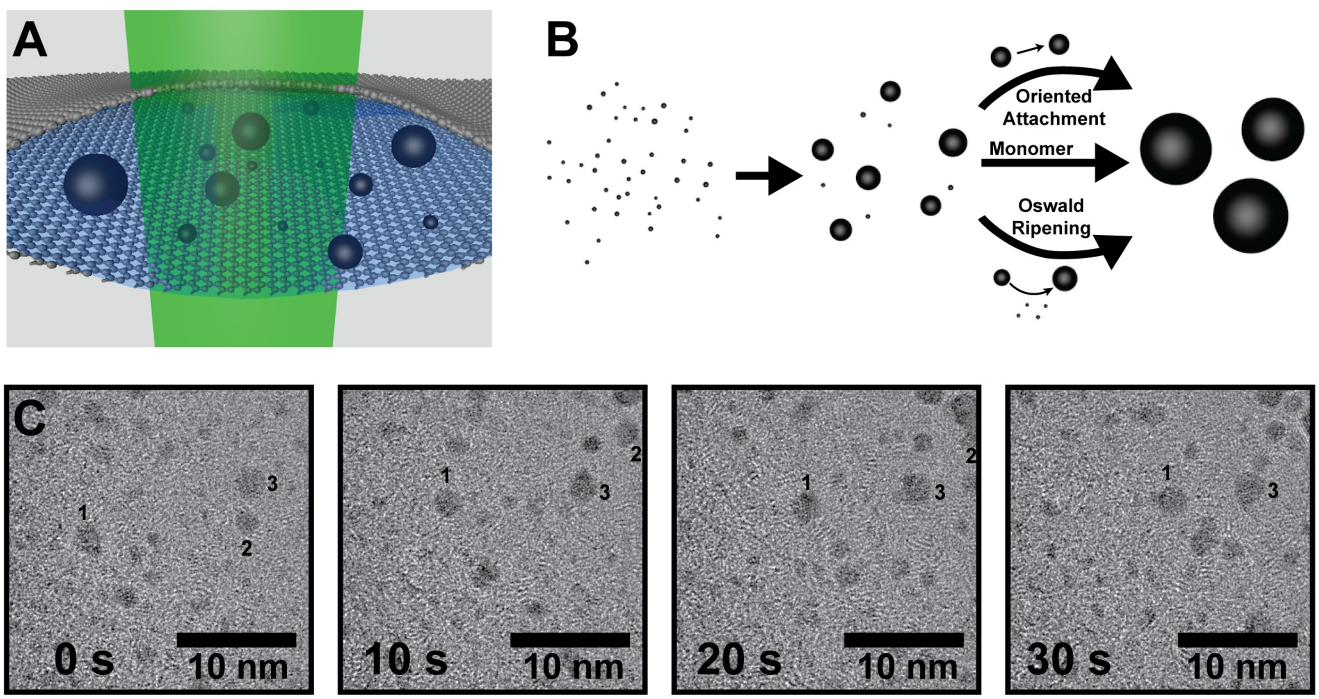
The type of data set is critical for the success of a GURP, and suitable data is actually more prevalent than it may appear. Many research endeavors seek to collect large data sets and then cycle through hypotheses and analysis on those data sets. (Figure S2) As the scale of instrumentation advances, examples of this structure of research are growing across many scientific disciplines from high energy physics and astronomy consortia to satellite earth observations and large-scale recordings of neural networks, all of which have examples of open-ended discovery through examination of publicly available data sets. The same can be said within chemistry, with observational chemists such as atmospheric chemists, crystallographers, and spectroscopists at instruments such as synchrotrons, as well as microscopists and combinatorial chemists using big data to develop new syntheses. In this model of research, significant time is spent analyzing and processing large scale data sets that were complex and intensive to acquire. These data sets need to be rich enough that they can be looked at in various ways to find new patterns or phenomena. Based on this criteria, future GURPs could be developed for almost any field. With many research groups already choosing to make their data open access after publication,[17,18] and with the trend of funding agencies requiring this is as a condition of public support, this type of research opportunity can be expected to grow.[19] Even colleges without cutting edge equipment could design new GURPs that take advantage of local expertise and instrumentation. In our specific instance, we tried to find a project with visual data where undergraduate students could actually see the dynamics of the nanomaterials; however, we believe this type of program should also work for other non-visual datasets.

Since the dataset is such a critical aspect for the success of a GURP, the next two paragraphs will provide some background on the nanomaterials area investigated in our program and how the students' work fit into the broader research area. Colloidal nanocrystals are small metals or semiconductors suspended in solution, usually between 1 and 100 nm in size, and these nanocrystals have been an intense focus of research due to their size dependent properties which can be harnessed for a variety of optical, energetic, biological, and other applications.[20–22] Watching the dynamics of these nanocrystals in solution is valuable for understanding how they grow and interact with each other, but the nanometer length scales of the nanocrystals makes *in situ* visualization challenging. Electron microscopy has the spatial resolution to image nanocrystals, frequently at atomic resolution. By encapsulating the solution with the nanocrystals between thin membranes such as graphene, videos of nanocrystal dynamics can be collected with the necessary spatial and temporal resolution.[23–25] (Figure 4A) Liquid cell electron microscopy has been able to provide novel information about nanoscale processes such as nanocrystal growth,[26–29] etching,[30–33] attachment,[24,34,35] and assembly.[36–39] In liquid cell electron microscopy, scientists often collect large amounts of data but only have the capacity to analyze a small fraction of it. Graphene liquid cell videos of nanocrystal dynamics provide good datasets for teams of undergraduate students to spend a significant amount of time understanding and analyzing to provide useful statistics on the nanoscale processes.

Figure 4. Using graphene liquid cell electron microscopy to observe platinum nanocrystal growth. (A) Schematic of nanocrystals (black) encapsulated in solution between two graphene sheets while imaging with the electron beam (green beam). (B) Schematic showing examples of the pathways of growth for nanocrystals from a solution of monomer platinum atoms. The examples shown are attachment, monomer addition, and Ostwald ripening. (C) Example images from the electron microscopy video of platinum nanocrystal growth. Nanocrystals can be seen moving and growing in size. Three example nanoparticles are labelled.

Example: Fitting GURP Students' Work into Broader Research Aims

A recent paper in Science by the Alivisatos group witnessed the growth mechanisms of platinum nanocrystals for the first time with atomic resolution,[24]



but only a few of the collected videos could be fully analyzed by the small team of researchers working on the project. Students in our GURP were able to analyze the other high-quality videos, collected using a state-of-the-art transmission electron microscope,[40,41] investigating cutting-edge topics that are typically too expensive or experimentally complex for undergraduate students to research. A variety of mechanisms of nanocrystal growth have been proposed and studied including monomer attachment where single atoms add to the growing nanocrystal, oriented attachment where two nanocrystals attach on the same crystallographic facet, and Ostwald ripening where atoms are removed from smaller nanocrystals and added to larger nanocrystals.[42] (Figure 4B) By watching and tracking a large number of single nanocrystal growth trajectories, information could be gathered on the relative amounts of each pathway and the interplay between the various mechanisms. Each video contained many trackable nanocrystals (Figure 4C), and some videos even had atomic resolution. The research projects that the undergraduate students chose were curiosity-driven, so a wide variety of ideas were investigated. Example titles from their papers include *Exploring Orientation Patterns of Platinum Nanoparticles During Coalescence* and *The Dynamic Nature of the Aggregative Growth Rate Constant in Platinum Nanocrystals*. One of the most important aspects of the GURP was that undergraduate students understood that their work was directly related to a recent publication and could potentially be a future scientific publication. The undergraduate students took a significant amount of pride in knowing they were contributing to work that could potentially be appreciated by other scientists.

Much like any research endeavor, the development of the undergraduate students' questions and research area followed a unique path for each nanomaterials project; however, the general progression of the projects should apply to any implantation of a GURP, regardless of research topic. After being given the TEM videos, students found different phenomena in the data that interested them, with most falling under the categories of movement, growth, and attachment of nanocrystals. Since the TEM videos are open-ended and do not have an obvious single direction of research, students were able to be creative in their ideas about the data set. The students were then asked to search out what the scientific literature said about that topic and determine some outstanding questions that still remained in the field. From this information, the students were tasked with formulating a question about their topic of interest that could potentially be answered by careful analysis of the data set. Although the mentors tried not to directly tell the students to pursue or not pursue a question, probing questions were used by the mentors to help the students understand what could be a more promising or feasible direction. The next step for the students was to determine a measurable that could be tracked to test their hypothesis or answer some outstanding question in the literature. Then, the students had to develop a plan for how they would actually extract that information from the data set.

As we discussed with the students in the introduction of the program, research is not a linear process, so encountering roadblocks and iterating are necessary parts of the research process. Each group had different points in the project where they needed to rethink their plan and develop a new strategy. Some groups found making the measurement challenging, and progressed from manually measuring particles to automated image analysis using ImageJ and MATLAB. Exchange of information between groups and peer learning was extremely powerful in dealing with these issues as the students had varying expertise and could collaborate to solve problems that were affecting multiple groups. For example, one student with a passion for coding wrote a MATLAB script to track nanoparticles, and this script was shared with other groups who were working on completely different questions. Other groups struggled with understanding the meaning of their data and were encouraged to go back to the literature to think more deeply about what behavior would be expected and whether their data supported or refuted that model. For example, students looking at movement of nanocrystals found they could use mean squared displacement to learn about the diffusive motion of the nanocrystals and then ask new questions about how the movement of nanocrystals in the graphene liquid cell related to bulk diffusion. One group studying attachment found an interesting pattern they were not expecting concerning the size of the nanocrystals and the likelihood of attachment. The students changed their question and found scientific models in the literature to understand the mechanisms behind their observation. Based on their literature search, no one had previously been able to test this attachment model on observable nanocrystal attachments, so the students' work using this cutting-edge TEM data had the potential to actually be useful to other scientists in the field. These are just a few examples of how students proposed ideas, encountered obstacles, and reformulated new plans on their research projects.

MEASURING GURP STUDENTS' PERCEPTIONS AND OUTCOMES

To assist in meeting the needs of our students as well as provide quantitative metrics of success for this new program, undergraduate students in our program took pre- and post-program surveys to measure how the undergraduate students perceived themselves and their skills. Questions were written to help the mentors gauge the research background and interest of the undergraduate students (such as asking about how many semesters of research the students had previously had and why they wanted to enroll in the program) as well as provide the students an opportunity to evaluate themselves on where they were in development of their scientific skills. Questions were purposefully designed to be neutral towards the students, and the results were anonymized so students would feel free to write honest responses.

Survey Methodology and Analysis

During the first week of the course, surveys were administered online, and all twenty students enrolled in the course completed the survey. After final presentations were given by the students, a second survey was given to the students, and all twenty students completed this survey as well. The anonymized data was collected for studying the effects of group-based undergraduate research programs on undergraduate student self-identification and career goals. Study protocols were approved by the Institutional Review Board (IRB reference no. 2018-04-10956) of the University of California-Berkeley. While some questions differed between the two surveys (for example, the first survey included a question about what the students wanted to gain from the course, while the last survey inquired about what the students learned from the course), five of the questions were identical for quantitative analysis. For these questions, students were asked to rate their research skills, nanomaterials knowledge, scientific literature skills, scientific communication skills, and their likelihood of pursuing graduate education in chemistry, chemical engineering, or materials science on a scale from 1 to 10.

The impact of the course was quantitatively measured through a one-sided Welch’s unequal variance t-test of the survey results. The Welch’s unequal variance t-test was used to account for the unequal variance in the responses. While a paired t-test may have been more appropriate, the data were anonymized to help protect the students, so we were unable to match students’ pre- and post-program scores. The mean, standard deviation, difference, and calculated p-values for each of the survey questions are included in Table 1. Based on the calculated p-values, differences from the pre-course and post-course surveys are statistically significant for all quantitative questions except for their likelihood to pursue graduate education in chemistry, chemical engineering, or materials science.

Table 1. Results of Program Surveys

Question	Pre-Course Mean[a] ± SD	Post-Course Mean[a] ± SD	Difference	p-Value
How would you describe your research skills?	3.8 ± 2.0	6.4 ± 1.5	2.6	$p < 0.001$
How would you describe your nanomaterials knowledge?	3.6 ± 1.7	7.0 ± 0.9	3.4	$p < 0.001$
How would you describe your scientific literature searching skills?	5.2 ± 1.5	7.4 ± 0.8	2.2	$p < 0.001$
How would you describe your scientific communication skills (oral, written, PowerPoint)?	6.8 ± 1.5	8.1 ± 1.2	1.3	$p < 0.001$
How likely are you to pursue a graduate degree in Chemistry/Chemical Engineering/ Material Science?	7.9 ± 2.5	7.8 ± 2.5	-0.1	0.55

Table 1 shows the quantitative results from the pre- and post-program surveys. There were 20 participants, and students could give scores from 1 to 10. The difference is calculated by subtracting the pre-program mean from the post-program mean.

[a]The scale has a range of 1-10, with higher numbers indicating a greater positivity; N = 20.

GURP PROGRAM RESULTS

The immediate results from running the GURP are promising from both informal verbal feedback from the participants and the quantitative data from their pre- and post-program surveys. Our two main goals for undergraduate students in the program were to expose them to research and build a sense of self-identification as scientists. Identifying as a scientist is a significant predictor of success in STEM, and developing a student's identity as a scientist can be especially helpful in retaining and graduating underrepresented students in STEM.[1,43] For our program, self-identification as scientists and researchers was quantified beyond the qualitative observations that the participants took ownership of their status as researchers and nanomaterials experts in our conversations. Pre- and post-program surveys were collected, asking the undergraduate students to rate their abilities in areas such as research skills, nanomaterials knowledge, scientific literature, and scientific communication on a scale from 1 to 10. (Figure 5) Entering the program, the participants rated their skills as low in all areas except scientific communication; however, after participating in the GURP, the undergraduate students rated their skills as above average in each of the categories. Although the undergraduate student alumni of this program undoubtably still had much to learn about nanoscience, the fact that the undergraduate students felt pride in their recognition as potential experts is significant. This feeling of accomplishment that arose from understanding concepts as complex as nanocrystal growth, proposing a research question, and beginning to answer that question will serve the undergraduate students well whenever they encounter self-doubts along their STEM undergraduate journey.

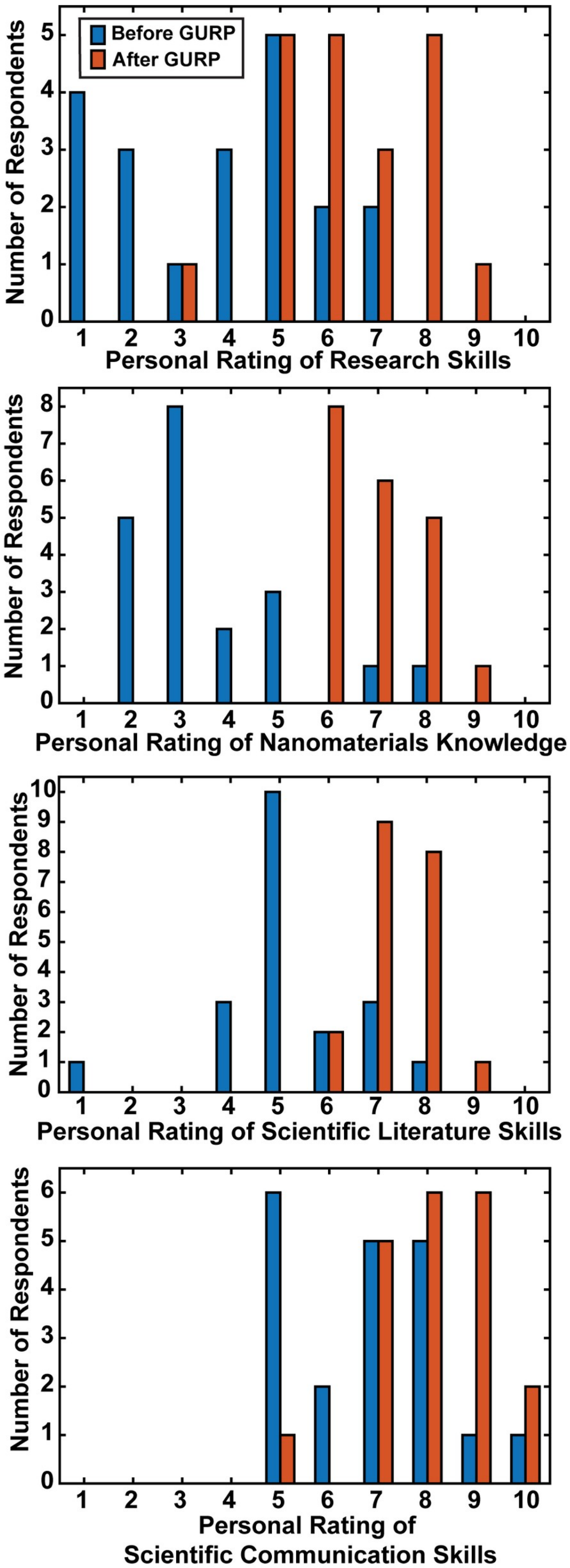


Figure 5. Student personal ratings on pre- and post-program surveys for research, nanomaterials, scientific literature, and scientific communication skills.

Other outcomes from the GURP showed that the program had a positive impact on the undergraduate students and potentially positive impacts for the research group. Through the surveys and personal conversations, the undergraduate students reported a high likelihood of recommending the program to future students. (Figure S3) The students' survey responses did not indicate a significant change in how likely they were to pursue a graduate degree in a chemistry field (Figure S4), but convincing participants to pursue a graduate degree was not a goal of the program. Rather, in addition to helping students identify as scientists, we wanted to expose undergraduate students to research early in their academic career, so they could better plan their STEM future. In conversations with participants, this program was helpful in determining their interest in research, and students were able to apply for internships or research positions accordingly. We were not able to quantify how many participants received research or internship positions for the summer after the program, but multiple undergraduate students said that this program helped them earn a research position for the summer. This program was also designed in the hope that it would be mutually beneficial to the sponsoring research group, and some of the participants' projects showed promise. Potentially, a system where one semester's work was used as the starting point for the next semester's undergraduate students would allow the undergraduate students' work to eventually build to a publishable result. Although the 20 first-year students in our program are a small sample size and no long-term studies on the effects of the program are available at this time, the early gains in self-identification as researchers and the positive feedback from participants suggest group-based undergraduate research programs could have a valuable place in the undergraduate curriculum.

FUTURE DIRECTIONS

Based on the initial success of the first iteration of the GURP, the Alivisatos research group plans to continue running the program each spring while learning how to improve the program and be a better model for other research groups. While we think the visual nature of the electron microscopy videos analyzed in this iteration of the GURP may have helped engage the undergraduate students in the subject matter, we would like to use different types of data in future iterations of this program to test how the undergraduate students respond to non-visual data, such as measured performance of materials over a variety of synthetic conditions. Additionally, future iterations will be run with different graduate student mentors to investigate whether the model is reproducible and transferable. We will also incorporate feedback from the previous participants in our program by including more lab tours to help them better understand how the data was collected. Peer student-leaders from past GURP iterations may also be implemented to increase student learning[44] and decrease mentor time commitment. Running the program required about 10-15 hours per week for the graduate student mentors during the semester and about 80-100 hours designing and organizing the program. Future iterations should require less start-up time with a pre-developed program structure and a better understanding of logistics such as course enrollment and classroom scheduling. In developing this program, we hoped to create a hybrid apprenticeship/CURE-like model which aimed to capture the advantages of both systems. In particular, we were able to engage large numbers of first-year undergraduate students in a cutting-edge research topic. With further study, it may be possible for multiple research groups from a department to run group-based undergraduate research programs allowing every first-year student the opportunity to do research in their area of interest. With roughly 20 undergraduate students for two mentors, the GURP allows more undergraduate students to engage in research than traditional apprenticeship models. Additionally, this program can be more agile than a departmental course because there are no structure requirements, and these programs can be offered by different research groups whenever their research provides suitable data. Unlike a course run by a professor with teaching assistants, GURPs can be organized and run by graduate students, post-doctoral scholars, and even advanced undergraduate students.

Research group-based undergraduate research programs have the ability to provide first-year students an exposure to cutting edge research and this research model may provide an additional tool in the arsenal to engage undergraduates in research.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available on the ACS Publications website at DOI: 10.1021/acs.jchemed.XXXXXXX.

Recruitment flyer; schematic of research cycles, figure showing student responses to questions on post-program likelihood of recommending program and pre- and post-program interest in graduate school (PDF)

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