ACS NANOSCIENCE Au
AN OPEN ACCESS JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

pubs.acs.org/nanoau

Perspective

The Primarily Undergraduate Nanomaterials Cooperative: A New Model for Supporting Collaborative Research at Small Institutions on a National Scale

Steven M. Hughes,* Mark P. Hendricks, Katherine M. Mullaugh, Mary E. Anderson, Anne K. Bentley, Justin G. Clar, Clyde A. Daly, Jr., Mark D. Ellison, Z. Vivian Feng, Natalia I. Gonzalez-Pech, Leslie S. Hamachi, Christine L. Heinecke, Joseph D. Keene, Adam M. Maley, Andrea M. Munro, Peter N. Njoki, Jacob H. Olshansky, Katherine E. Plass, Kathryn R. Riley, Matthew D. Sonntag, Sarah K. St. Angelo, Lucas B. Thompson, Emily J. Tollefson, Lauren E. Toote, and Korin E. Wheeler

Cite This: *ACS Nanosci. Au* 2021, 1, 6−14

Read Online

ACCESS | Metrics & More | Article Recommendations

ABSTRACT: The Primarily Undergraduate Nanomaterials Cooperative (PUNC) is an organization for research-active faculty studying nanomaterials at Primarily Undergraduate Institutions (PUIs), where undergraduate teaching and research go hand-in-hand. In this perspective, we outline the differences in maintaining an active research group at a PUI compared to an R1 institution. We also discuss the work of PUNC, which focuses on community building, instrument sharing, and facilitating new collaborations. Currently consisting of 37 members from across the United States, PUNC has created an online community consisting of its Web site (nanocooperative.org), a weekly online summer group meeting program for faculty and students, and a Discord server for informal conversations. Additionally, in-person symposia at ACS conferences and PUNC-specific conferences are planned for the future. It is our hope that in the years to come PUNC will be seen as a model organization for community building and research support at primarily undergraduate institutions.

KEYWORDS: *PUI, PUNC, Nanomaterials, collaboration, undergraduate, research, cooperative, nanoscience*

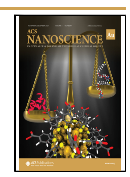
■ INTRODUCTION

Nanomaterials research has become a particularly interdisciplinary science, with the most impactful work often involving multiple research areas ranging from synthesis to analytical characterization, computational modeling, and demonstration of applications. This is increasingly challenging for faculty at primarily undergraduate institutions (PUIs), where time, facilities, and personnel constraints usually result in publishing at a slower pace. This leads to a continuation of the belief that cutting-edge research cannot be done at PUIs. The Primarily Undergraduate Nanomaterials Cooperative (PUNC, pronounced "punk") was founded to rewrite this narrative. PUNC works to support, highlight, and advance the impressive nanomaterials research at PUIs by establishing a national network of collaborative faculty and leveraging our collective voice and research efforts. In doing so, we also hope to promote PUNC as a model organization for researchers at PUIs in other scientific disciplines. We strongly believe that building a connected national community of researchers within a small scientific subfield can enhance the research power of all of its members.

Cooperatives are built on the idea of sharing, and ours is no different. While any one member of PUNC may have a limited toolset and focused expertise, all of our members together have the resources to tackle any scientific problem with a depth comparable to that of our colleagues at major research institutions. If the historic past year and a half has taught us anything, we have learned that there are many ways of collaborating, communicating, and sharing our research even while spread out across the country. Remote meetings, speaker invitations, online conferences, virtual poster sessions, and chat tools have been normalized. We plan to use these resources and our experiences from the past year to manage a nationally delocalized research cooperative.

Most importantly, PUNC is striving to create a community. While PUIs tend to have strong communities built around teaching, the absence of researchers in related fields on one's home campus can leave faculty feeling isolated in terms of their

Received: August 26, 2021
Revised: October 5, 2021
Accepted: October 11, 2021
Published: November 1, 2021



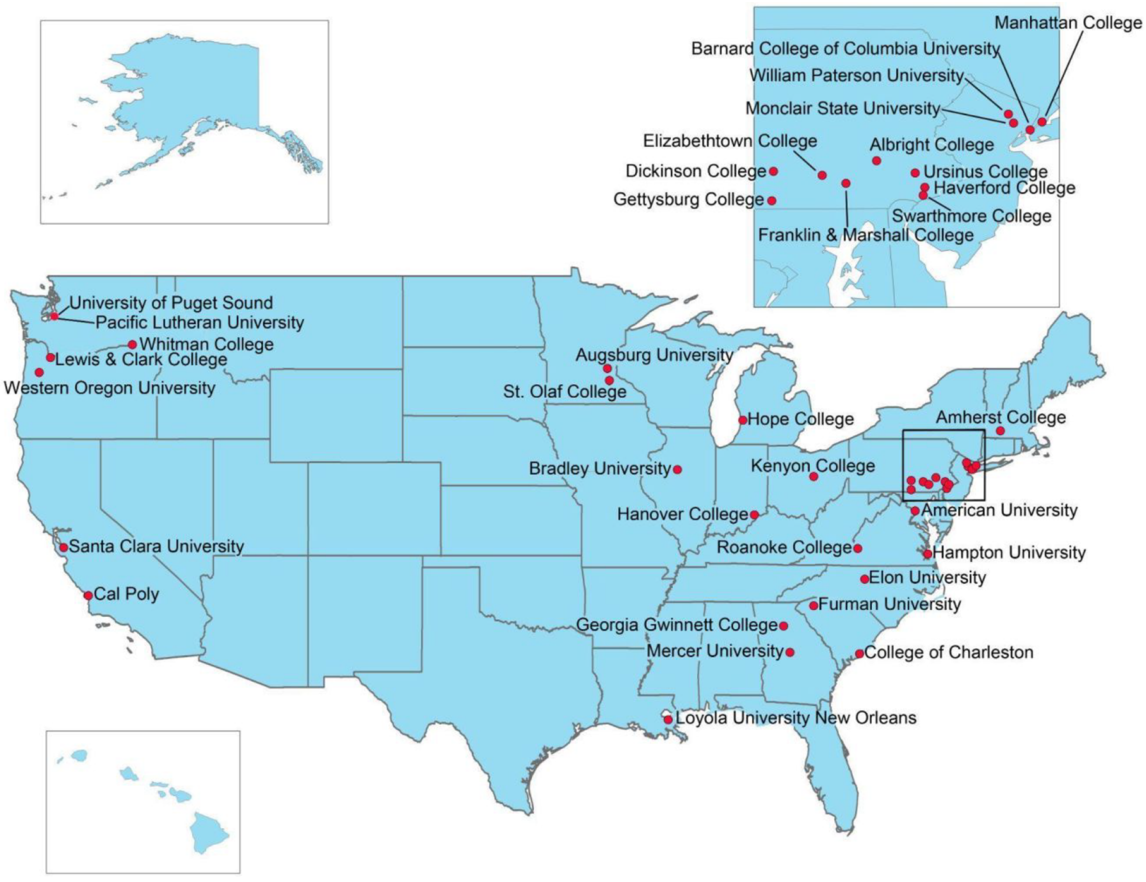


Figure 1. Map showing the locations of current PUNC members' home institutions.

science. The ability to have regular open dialogue with one's peers is essential for both developing sound and innovative research as well as maintaining momentum in the lab. Without this, ideas can become stale, and obstacles to progress can sometimes seem daunting. This scientific community is more accessible at large universities and national laboratories, and PUNC aims to provide comparable opportunities for brainstorming, sharing ideas, and seeking help for PUI faculty.

Of course, PUNC is not the first group to develop a community to support faculty, and we have borrowed ideas from a variety of successful organizations. For instance, the Interactive Online Network of Inorganic Chemists (IONiC) and the associated Virtual Inorganic Pedagogical Electronic Resource (VIPEr)[1] represent an amazing group of inorganic faculty who have built a thriving online community.[2,3] This group, as their name suggests, is focused on supporting faculty engaged in developing new pedagogical materials in inorganic chemistry. From their Web site and forums to the VIPErPit, their Discord server, this group has shown how to use modern technology to maintain a community. Similarly, the Genomics Education Partnership (GEP) is a nationwide collaboration of over 100 institutions focused on developing new Course-based Undergraduate Research Experiences (CUREs) to support education in bioinformatics and genomics.[4,5] While these groups are focused more on pedagogy than lab-based research, they have demonstrated the power of bringing together a large group of faculty whose goals are aligned to support each other in their academic ventures.

Meanwhile, the Molecular Education and Research Consortium in Undergraduate computational chemistRY (MERCURY) has demonstrated the power of shared resources to enhance undergraduate research.[6] Currently representing 38 faculty from 32 institutions, MERCURY members are computational chemists who share time on an NSF-funded computational cluster. Due to the nature of the shared time on the cluster, membership in MERCURY is more tightly managed, and growth of the group is typically tied to grants for additional resources. One of the highlights of the MERCURY consortium is their annual user meeting, where both faculty and students have the opportunity to present their research in the form of student-presented posters, hear from a diverse group of invited speakers, and build their research network. While MERCURY's membership model is very different from the open design of PUNC, they have clearly shown the power of bringing together research active faculty at PUIs, and through their user meetings have demonstrated the value of conferences dedicated to showcasing the research of its members.

PUNC is currently composed of 37 faculty members from 18 states across the United States pursuing nanomaterials research at PUIs, which can range from private liberal arts colleges to medium-sized regional public universities (Figure 1). PUNC has an open membership model, where joining only requires submitting an application at nanocooperative.org, with applicants self-identifying their institution as a PUI and that their research relates to nanomaterials. Thanks to these policies, PUNC has rapidly grown since its inception in summer of 2020. The research interests of the members are diverse and include synthesis, environmental chemistry, surface chemistry, sensors, biomedical applications, catalysis, charac-

https://doi.org/10.1021/acsnanoscienceau.1c00020
ACS Nanosci. Au 2021, 1, 6−14

terization of optical properties, energy applications, and computational studies (Figure 2). Over the last 5 years, current PUNC members have raised over $7.5 million USD in external funding as PIs or co-PIs and published nearly 100 peer-reviewed journal articles.

Figure 2. Many areas of scientific exploration represented by members of PUNC.

In the sections below, we highlight three areas that often distinguish nanomaterials research efforts at PUIs from those at R1 institutions. These differences include (I) the smaller size of our departments and institutions, (II) facilities that are teaching-focused, and (III) the lack of Ph.D. graduate students involved in most of our research programs. Importantly, PUIs exist on a spectrum with a broad range of sizes, balance of teaching and research, and student bodies, so how these differences are manifested at each institution varies. We describe the challenges associated with each of these differences, as well as the advantages and adaptations that allow us to thrive in these environments. We also highlight our vision for the role of PUNC in each of these areas.

DIFFERENCE I: SMALL SIZE OF DEPARTMENTS AND INSTITUTIONS

Challenges:

PUIs are often small institutions relative to the average R1 institution in the United States, which results in correspondingly smaller departments. This means we often find ourselves as the sole nanomaterials expert at the institution or perhaps one of a handful of peers in related fields. This lack of a field-specific intellectual community creates a range of challenges; we rarely have colleagues with similar expertise with whom we can share interesting papers, brainstorm about experiments, and troubleshoot obstacles. Our student researchers are prone to feeling a similar sense of scientific isolation and struggle to see how their research fits into the traditional disciplinary silos, e.g. "organic", "inorganic", or "physical", or into the broader nanomaterial research community. The smaller size of our departments also means our teaching loads are often focused on the core undergraduate courses with few opportunities to bring our research expertise into the classroom or is limited to optional electives that cannot be offered regularly.

Advantages and Adaptations:

Our primary response to the small or nonexistent nanoscience community at our home institutions is to collaborate, both with colleagues outside our field at our own institutions and with peers in our field at other institutions. Collaboration is an essential component of the scientific endeavor and even more critical for those of us at PUIs. Meaningful research happens when we work together, sharing our expertise, ideas, and resources.

The saying "necessity is the mother of invention" applies to many of us: when we are the only nanoscientist at our institution, we find common ground with other researchers at our institutions and invent new collaborations with them. At a recent PUNC meeting, it was common for faculty to introduce themselves by describing their own research and then their "side projects" that represented an array of applications of nanomaterials across broader disciplines. An internal collaboration between Kate Plass and Jennifer Morford at Franklin & Marshall College, for example, joins nanomaterials and oceanography, applying the skills of a solid-state nanomaterials chemist to understanding the accumulation of trace metals in ocean sediments. At Roanoke College, Steve Hughes is working with Chris Lassiter in the biology department to study the effects of semiconductor nanoparticle accumulation in zebrafish embryos. At Ursinus College, Mark Ellison is working with Tony Lobo in biology to develop carbon nanomaterials to deliver antibiotics to antibiotic-resistant bacteria. These types of collaborations are often not planned but provide an appreciated partnership to tackle these interesting scientific questions.

Beyond our home institutions, many of us turn to collaboration with others at PUIs or colleagues at R1s, government laboratories, or industry. For example, a variety of collaborations among PUI faculty (and now PUNC members) emerged at the 2017 Environmental Nanotechnology Gordon Research Conference. In a collaboration between Kathryn Riley and Korin Wheeler, their research teams were able to troubleshoot their way through a finicky fluorescence titration, sharing data and tips from across the country to find the best approach for the experiment, while expanding students' communication, scientific literacy, and technical skills. These skills are further improved when students must explain their work to collaborative teams. In a collaboration between Korin Wheeler and Clyde Daly, the research teams utilize their respective wet lab and computational techniques to further their mutual scientific goals. Students (and PIs) gain a deeper understanding of the research through sharing results with their counterparts and from exposure to the different approaches of the other team. These collaborations can occur between faculty at similar stages in their career or between senior and junior faculty. As an example of the latter, Vivian Feng, a senior investigator in the National Science Foundation (NSF)-funded Center for Sustainable Nanotechnology, invited Kathryn Riley to present a seminar to the center, which led to a collaboration between their groups to study the dissolution kinetics of $LiCoO_2$ nanoparticles. As described in subsequent sections, many of us also collaborate with R1 institutions, which similarly provide opportunities to

https://doi.org/10.1021/acsnanoscienceau.1c00020
ACS Nanosci. Au 2021, 1, 6−14

engage with peers in our field, including both our faculty collaborators as well as the postdocs and graduate students in their research groups.

In addition to collaboration and our own research groups, many of us attempt to incorporate our nanoscience expertise into our foundational courses since we often teach our field-specific courses less frequently, thereby providing another opportunity to intellectually engage with others related to our field. The recent addition of nano- and mesoscale materials into the ACS Committee on Professional Training (CPT) Guidelines has encouraged us to highlight our work in nanomaterials within the courses we teach.[7] Furthermore, many of us have developed course-based undergraduate research experiences (CUREs) that allow us to leverage our time teaching undergraduate laboratories to pursue research questions with our students, often providing research opportunities to a much larger student population than is possible within our research groups. For example, Korin Wheeler developed a CURE based on nanoparticle synthesis, characterization, and ecological impacts, and Mary Elizabeth Anderson worked with lab students to compile data for a publication on a modified polyol synthesis of thermoelectric nanomaterials.[8,9] However, many of us have also found that while CUREs are highly beneficial as a student experience, it is not always feasible to obtain useful or publishable data in a teaching lab setting.

Role of PUNC:

One of the unique aspects of PUNC is our focus on doing science in community as a cooperative. For faculty, this means broadening and strengthening our networks and our base of support. Collaborations among PUNC members are encouraged by providing introductions between faculty with mutual research interests, through either our Web site, virtual events, or future in-person conference sessions. PUNC also serves as a community itself, thereby alleviating some of the isolation experienced by many PUI nano researchers, including both faculty and students. PUNC provides opportunities for us to model the collaborative spirit that is essential to a successful career in research for our students, who may not be exposed to such interactions on a regular basis. The undergraduate students in PUNC also have the opportunity to develop relationships with their peers and with faculty at other institutions. This both broadens the types of research they are exposed to and provides them with a sense of belonging in the scientific community.[10−12]

As an example of this community in action, the inaugural PUNC summer group meeting series has been an exceptional opportunity for building community between faculty and students at different institutions. Our cooperative is taking advantage of our new familiarity with Zoom to hold weekly student seminars throughout the summer research season. At these group meetings, 2−5 students from different institutions give short presentations on their research. It has been great to see student attendees regularly asking questions and starting discussions with their peer presenters. Many students will "zoom" in from a classroom or lab full of student researchers, thus providing "windows" through which to see nanoscience research in action across the country. This has helped to remove some of the scientific isolation felt by students and faculty alike. In the past, the cost and time for travel has created barriers for PUI faculty to give talks at multiple institutions and has also limited our ability to invite speakers to our campuses. At this moment, we have the opportunity to broaden the pool of scientists we can "bring" to talk to our students.

The PUNC Discord channel meets additional community needs. Discord is a free chat app that allows members to post questions and share other content about their research. If one of us is struggling with a new technique, we can put a question on Discord and our peers who have worked with a similar instrument or who have relevant experience can provide us with ideas for troubleshooting, which is especially valuable as many of us do not have dedicated instrument technicians. While the experimental channel is used by both students and faculty, with responses coming from both, other aspects of the Discord channel are faculty-focused. For example, the faculty Discord channel serves as a safe place to ask for administrative and teaching advice since we all juggle a similar set of responsibilities and face similar challenges in these realms.

Through both the Discord channel and weekly virtual "coffee" chats, the PUNC community is strengthened, thereby helping us improve as researchers, teachers, and mentors. To list a few examples, we provide each other with advice and mentorship about teaching courses, running a research group at a PUI, tips for purchasing equipment and supplies, and how to develop research projects that can work with the fragmented time available to undergraduates during the academic year. It has also allowed us to compare notes on how our individual institutions are navigating the challenges of the ongoing COVID-19 pandemic.

Although the PUNC virtual community has proven valuable to both students and faculty, we hope to complement this with in-person community-building events in the future. With volunteer leadership from among our membership, we intend to host symposia, student poster sessions, and receptions at upcoming ACS national meetings. As PUNC grows, we envision the potential for a biennial national conference.

■ DIFFERENCE II: TEACHING-FOCUSED FACILITIES

Challenges:

PUIs are traditionally focused on teaching and, therefore, often have fewer structural and instrumentation resources dedicated to research. Laboratory space and instruments may be prioritized for courses. The small size of our departments and institutions also plays a role in this, as our departments often house fewer specialized or major instruments due to the smaller number of research groups. Even when instrumentation is available at a PUI, upkeep often falls to faculty, which can include routine maintenance, troubleshooting software, replacing parts, and dealing with service calls.

The limited scope of instrumentation is particularly challenging for nanomaterials researchers, as our field exists at the nexus of chemistry, physics, materials science, and biology and often requires advanced tools and characterization techniques from a number of these fields in order to complete a research project. For example, transmission electron microscopes (TEMs) often play a critical role in the basic characterization of many nanomaterials but are uncommon at small institutions like PUIs due to the cost, technical maintenance, and historical absence from the standard curricula in chemistry or physics. We hope and expect this will change, however, as TEMs become more affordable, user-friendly, and commonplace in chemistry research. Much like nuclear magnetic resonance, TEM is becoming a standard tool

https://doi.org/10.1021/acsnanoscienceau.1c00020
ACS Nanosci. Au 2021, 1, 6−14

in subfields of chemistry, physics, and biology, and undergraduate students who have experience operating a TEM will be advantaged postgraduation.

Advantages and Adaptations:

One approach to dealing with the challenges associated with a limited scope of instrumentation is to make do with what we have access to onsite, particularly for routine experiments. This often takes the form of choosing experiments and material targets strategically, such that the instruments accessible meet the needs of the research. This can sometimes result in understanding our samples at a more fundamental level. By undertaking chemical analysis such as NMR or other spectroscopies as a primary analysis rather than imaging, we are forced to approach the samples at a chemical level instead of trying to interpret a micrograph. However, this sometimes results in prioritizing indirect characterization that can be done with accessible instruments—like relying more heavily on UV−vis spectroscopy to estimate nanoparticle size, shape, and composition—when more conclusive techniques are not as accessible.

The often-limited support staff at our institutions for maintaining instruments can impede the pace of our work, but it also ensures the faculty are engaged with the research and instruments and provides our students with first-hand experience in maintaining and troubleshooting instrumentation, critical skills for success as a scientist. As our students gain experience, they are able to take a more active role in maintaining and troubleshooting instrumentation themselves, further deepening their preparation for a career in research.

When critical instrumentation is not available onsite, we must seek out the instrumentation needed for our scholarship from external sources. This can be achieved in a variety of ways including taking advantage of national or regional consortia of user facilities. For example, the NSF-funded National Nanotechnology Coordinated Infrastructure (NNCI) includes 16 user facility sites and their affiliated partners across the United States, as well as a coordinating office. Multiple PUNC members have taken advantage of NNCI sites, including the National Center for Earth and Environmental Nanotechnology Infrastructure (NanoEarth) at Virginia Tech and the Southeastern Nanotechnology Infrastructure Corridor (SENIC) at the Georgia Institute of Technology, which provide access to university user facilities with leading-edge fabrication and characterization tools, instrumentation, and expertise within all disciplines of nanoscale science, engineering, and technology. PUI faculty can often be trained as a user on the tools and instrumentation or can send samples for analysis by trained technicians at the site. An additional model is represented by the Pennsylvania State University's Materials Characterization Laboratory, part of the NSF funded Materials Research Science and Engineering Centers (MRSEC), that grants instrumentation time for PUI faculty through their Materials Research Faculty Network (MRFN) and has been piloting remote instrument use aimed at making facilities more accessible to PUIs.

Unfortunately, these methods of outsourcing our instrumentation needs often have significant costs in both money and time. While grants to cover monetary costs at these national centers sometimes exist, frequently they do not, and many faculty at PUIs simply do not have the financial resources to cover regular costs, particularly if they are being charged at external rates. For many though, the larger hurdle comes in the form of time. During the academic year faculty at PUIs have significant teaching loads and finding the time to take an afternoon off to drive to a user facility and run a handful of samples is extremely challenging. Sending samples for technicians to analyze is an option but is more expensive and limits the first-hand experience we strive to provide to our students.

Many PUI faculty find it more useful to leverage networking and collaborations for access to specialized instrumentation. At the local level, some PUNC faculty have utilized shared-instrumentation agreements with industrial partners to access specialized instrumentation, while others have forged opportunities through collaboration and networking with faculty at nearby institutions, both large R1s and small peer PUIs, for access to their facilities. For instance, Peter Njoki at Hampton University, a Historically Black College and University (HBCU), and Charles Machan at the University of Virginia collaborate, providing the Njoki lab access to the state-of-the-art materials characterization available at the UVA Nanoscale Materials Characterization Facility. The Machan lab also helped analyze copper-based nanoparticles via scanning transmission electron microscopy and electrochemical techniques. Collaborations such as this come with fewer barriers to accessing needed instrumentation and include the benefits of a scientific collaboration but can be challenging for faculty to initially identify and develop. Building partnerships outside of academia, Korin Wheeler at Santa Clara University previously worked with the startup BioSpyder Technologies, while Justin Clar at Elon University actively collaborates with local startup BNNano. These partnerships can provide new research challenges, as well as access to materials and instrumentation their home institutions do not have. Additionally, the undergraduate students benefit from networking opportunities with industry professionals who can help them envision a variety of career paths to which they may not have been previously exposed.

Role of PUNC:

Cooperatives are built on the idea of sharing, and in PUNC, we each agree to share our time and instrumentation. Any single given institution has a limited set of instruments, which is largely built around a standard core set of tools (NMR, UV−vis, AA, etc.) and more niche equipment (high-speed laser techniques, Raman, ICP-MS, electron microscopes, etc.) based on the research of the faculty at a particular institution. However, when you bring faculty and these tool sets together, you create a very robust set of instrumentation. Additionally, using this cooperative model where instrumentation is shared and faculty volunteer to run samples for one another, knowledge and expertise are being shared, as well. This is not something that can simply be purchased with a new instrument but must be acquired from years of experience. In this model, when samples are run and results are disseminated, researchers have the opportunity to share and discuss their interpretation of the results. In this way, PUNC's cooperative not only helps faculty access more specialized tools and instrumentation for studying nanomaterials but also facilitates important dialogues in understanding the meaning and interpretation of the results.

In a recent online group meeting, a student was asked about the size dispersion of their nanocrystals, and they responded that they did not know due to lack of access to a TEM but were hoping sometime in the future to get access to the

https://doi.org/10.1021/acsnanoscienceau.1c00020
ACS Nanosci. Au 2021, 1, 6−14

instrumentation at a nearby national lab. Another member quickly stepped in and offered to run the student's samples; just drop them in the mail. The natural ease and convenience of the entire interaction encapsulated what PUNC is striving for: a community working together to support each other. In addition to alleviating monetary costs, the collective burden on faculty time is lowered since the PUNC member running the samples is working on their own instrumentation and, in many cases, may have their undergraduate researchers performing the analyses.

Our emphasis on cooperative instrument use can also be leveraged to submit competitive federal grants to acquire new state of the art instruments.[13] Recently, a grant was awarded to bring a TEM to the South Puget Sound region of Washington State. The proposal was written in collaboration with faculty from three PUIs located within 20 min of each other, including PUNC members Emily Tollefson and Andrea Munro: the University of Puget Sound, the University of Washington-Tacoma, and Pacific Lutheran University. The TEM will be housed at the University of Puget Sound, and participating faculty from the three PUIs will share duties in training and maintaining the instrument. In total, six major users submitted projects for the proposal, ranging from investigating neural synapses to synthesizing and characterizing novel zinc chalcogenide nanocrystals, with a further 13 faculty who identified projects that will all benefit from an accessible TEM.

■ DIFFERENCE III: NO PH.D. STUDENTS

Challenges:

Whereas faculty at R1 institutions split their time between teaching undergraduates and supporting their graduate students, faculty at PUIs do not have Ph.D. students to advise. This usually means faculty at PUIs have heavier teaching loads without full-time student researchers to drive research forward. The lack of Ph.D. students and more intense teaching schedules results in myriad challenges, but time constraints and student turnover are among the two most noteworthy.

Teaching schedules vary across PUIs but are generally heavier than at research institutions. Multiple courses per semester at various instructional levels are common. Depending on the individual situations, faculty support for preparation and development of laboratory courses can range from minimal to excellent. For some faculty, the preparation and development of laboratory courses is a significant aspect of teaching that can be very time-consuming. Additionally, PUIs have strong expectations for faculty availability for office hours and communication with students. While teaching assistants may be employed by departments, they are often undergraduates, as well, and they do not run course or lab meetings and have minimal (if any) responsibilities for grading. The time and effort required for teaching at PUIs leave less time for scholarly activities. Another impact of the time constraints of PUI faculty is that we have fewer opportunities to travel to conferences, thereby limiting our connections with the field and our ability to speak about our work.

Working with undergraduate students on research projects is one of the most rewarding aspects of working at a PUI; however, the challenges of training undergraduate students to complete publication-worthy research can be daunting. In contrast to students who perform research in the traditional chemical subdisciplines, nanomaterials research students are rarely taught the fundamentals of nanomaterials in their regular coursework. Students do not usually perform research for the entire 4 years of their undergraduate education—often they begin research their sophomore or junior year, conducting research for credit during the academic year and, when funds are available, for a stipend during the summer. Because of their other courses, undergraduate time is fragmented during the academic year and they may only be able to carve out a few hours of research time a week. Summers are often the most active and productive times in a PUI research lab when we work with our students full time, typically for 8 or 10 weeks. This stop-and-go nature of research at a PUI can make it hard to maintain a steady research momentum.

Furthermore, the time and attention required to train undergraduates must be repeated as students cycle out of the lab and graduate. For those of us able to sustain larger research groups, the possibility for peer-to-peer learning is greater and alleviates some pressure from us to provide training directly, but smaller groups of only a few students require close and continuous faculty oversight. Although this mentoring experience is rewarding and valuable for faculty and students alike, it does limit the rate at which projects can be disseminated in the literature. When a project is ready for publication, the data analysis and writing generally fall to us rather than graduate students or postdoctoral scholars. Our undergraduate students may contribute to this phase of the project, as well, but are generally graduated and unavailable to assist. If undergraduates are available to assist, there is further mentoring required to help them gain the perspective, analysis skills, and written expression appropriate for a publication. Again, PUIs are institutions where students gain skills through experience and mentorship, but including undergraduates is a labor-intensive pursuit different from working with graduate students and seasoned postdoctoral scholars.

Advantages and Adaptations:

One approach many of us take to help alleviate the burden of training new students is to support peer-mentoring structures in which more experienced undergraduate researchers are responsible for training new students. This peer-mentoring provides continuity and high-impact experiences. Students who are being mentored receive a welcome introduction to the potentially intimidating research environment; peer-mentees report a lower bar for asking questions of their peer-mentor and comfort in hearing about their mentors' past successes and failures. Peer-mentors have to articulate their understanding of all aspects of their projects at a new level of detail to their mentees. This provides important opportunities for deep reflection on their own learning and experiences, professional development, and practical training.

As described above for dealing with the other differences, collaborations between PUIs and R1 institutions can also help us maintain steady research momentum and provide students from PUIs with opportunities to learn about graduate school. For example, collaboration with the Schaak laboratory at Pennsylvania State University has both accelerated the pace of research in the Plass laboratory at Franklin & Marshall College (F&M) and provided development opportunities for undergraduates and graduate students. Interactions have varied from quick email consultations about a procedure, to virtual 1 h group meetings, to all-day end-of-summer research meetings at Penn State or F&M, to focused student visits to Penn State to learn a particular skill. They have involved other nanomaterials faculty from the southeastern PA region as well, including

https://doi.org/10.1021/acsnanoscienceau.1c00020
ACS Nanosci. Au 2021, 1, 6−14

Sarah St. Angelo from Dickinson College, Lucas Thompson from Gettysburg College, and Matthew Sonntag from Albright College. Undergraduate student researchers get help and learn to carry out detailed scientific discussions within a rigorous, yet supportive, culture. They also gain a perspective on the value of their own research work.

Our undergraduate students often express surprise at learning that graduate students are doing similar work as they are; they make an assumption that because they are at a small school, they are doing small science. This experience of "holding their own" with graduate students and R1 faculty is invaluable in building confidence and self-identification as a "real" scientist. Exposure to near-peers in graduate school helps undergraduates see themselves following the same path and starts to establish their professional networks. Such interactions expose the undergraduate students to the everyday experience of being a graduate student, and when given this opportunity, undergraduate students can re-evaluate their career plans and give serious consideration to pursuing a graduate degree. This is particularly important for under-represented minorities, including but not limited to African-Americans, Latinx, LGBTIQ+, and first-generation college students, who might not have been aware that such an option was open to them.[14,15] With the skills and confidence gained at the PUI combined with experience working in a lab at an R1, undergraduate students can realize that a career in research is a good fit for their talents and interests.

Graduate students at R1s also benefit from collaborations between R1s and PUIs. Through these collaborations, graduate students who did not attend a PUI are often introduced to the PUI experience. For some, such as Leslie Hamachi, now a professor at Cal Poly, this can be a career-inspiring interaction. She was first introduced to research at PUIs during a collaboration between her graduate school lab and Andrew Crowther's lab at Barnard College (a PUI). Further interactions with faculty and students in the Barnard College chemistry department highlighted the high level of research possible with undergraduates and the exceptional training these students obtained from their close interactions with faculty, which led her to pursue her own career, leading a nanomaterials research group at a PUI.

It is generally accepted that due to the more demanding teaching schedule and lack of full-time Ph.D. students that we publish at a lower rate than R1 institutions, which requires us to select research projects strategically that can be impactful even if they take longer to reach fruition. An advantage of this pace, however, is that results are often reproduced by multiple generations of students over multiple years, thereby ensuring that the data are robust and reproducible. This is in contrast to projects led by graduate students, where it is normal for a single graduate student to be the primary author of a paper and do the bulk of the experiments themselves without the need for others to reproduce the majority of the work.

While we may be slowed down by running our research laboratories primarily with undergraduate students, it also means that we are able to provide the authentic experience of exploration and discovery at the cutting-edge of chemistry for a substantial number of undergraduate students. Research at PUIs requires a greater level of ownership and engagement on the part of undergraduate student researchers than in R1 laboratories, where full-time graduate students can take responsibility for continuity and success of a project. We pride ourselves on the training and mentorship we provide our students and believe they are exceptionally prepared for graduate school or other scientific endeavors. Engagement with research of this quality and rigor not only results in excellent technical training, but also empowers students to identify as scientists themselves.[10]

Role of PUNC:

Every year, members of PUNC are publishing quality research in highly respected journals such as *Chemistry of Materials*, the *Journal of Physical Chemistry C*, *ACS Applied Nano Materials*, and *Nature Communications*. While the productivity of our undergraduates may be slower, the quality of the work produced in our research laboratories is excellent. Part of this comes from the PUI faculty being more hands-on in our laboratories and maintaining high standards for our students. The R1 faculty that collaborate with us recognize this, and it is one of the many reasons that these collaborations endure.[16] One of the goals of PUNC is to help our members highlight this research and increase awareness of the work being done at our institutions. This is among the primary reasons that PUNC is organizing symposia at ACS conferences and future PUNC-specific conferences. We want to actively promote this research and put both our member faculty and their undergraduate researchers front and center for the broader nanomaterials community.

In a recent survey of PUNC members, we found that on average our faculty mentored 4−5 undergraduate research students annually. Even in this last year of unforeseen pandemic-related disruptions, PUNC members managed to cumulatively mentor 131 undergraduate students in nanomaterials research. Furthermore, over 75% of these students belong to the NSF's under-represented groups in STEM fields (women, persons with disabilities, Blacks or African Americans, Native Americans, and Hispanic Americans) or self-identified as LGBTIQ+. This compares to the overall undergraduate population who studies chemistry which is 49% women and 18% Blacks or African Americans, Native Americans, and Hispanic Americans according to the 2014−16 NSF statistics. The close mentoring of undergraduate students is important in the retention of students in STEM fields, particularly those from groups that have been historically excluded.[11,14,17−21] In fact, over 60% of the students who have participated in research at the undergraduate level with a PUNC member have pursued postgraduate degrees that include PhD, Masters, and professional postbaccalaureate degrees such as MD or PharmD.

Because of our collective record in high-quality mentorship of undergraduate research students, PUNC can also be a source of mentorship for junior faculty members. Having colleagues that understand both the specifics of our research as well as the nature of research at a PUI can provide junior faculty members with valuable sounding boards for how to best setup and run their laboratories. Although we all must recognize the range of institutional cultures that exist across the spectrum of PUIs, PUNC provides informal opportunities for faculty-to-faculty mentorship. Finally, the networking opportunities PUNC provides can also allow junior faculty to identify potential external reviewers of their research in tenure and promotion cases.

■ CONCLUSIONS

Maintaining a thriving research program at a PUI is different than at an R1. It is true that we are more scientifically isolated

https://doi.org/10.1021/acsnanoscienceau.1c00020
ACS Nanosci. Au 2021, 1, 6−14

on our smaller campuses, our facilities are more limited, and we do not have Ph.D. graduate students. However, this can drive us to find new communities, build more collaborations, think creatively about project design, and mentor many amazing undergraduates who go on to thrive in graduate school and other scientific endeavors. Yet each of these can be a challenge in its own right, and different challenges call for different needs. PUNC's goal is to create a welcoming community that can answer these needs in a way that works for our members. Working as a community and building collaborations has always made science stronger, and that is clearly the case here, as well. By tearing down roadblocks such as limited access to instrumentation and creating space for regular scientific conversations, PUNC is helping nanomaterials research flourish at our member institutions. While PUNC has been developed for the nanomaterials community, this model can be applied to other scientific fields, as well. The unique aspects of managing research at a PUI are faced by many disciplines, and we believe that the best way to thrive under these conditions is within a community built to support one another.

AUTHOR INFORMATION

Corresponding Author

Steven M. Hughes – *Department of Chemistry, Roanoke College, Salem, Virginia 24153, United States;* orcid.org/0000-0002-1704-2739; Email: shughes@roanoke.edu

Authors

Mark P. Hendricks – *Department of Chemistry, Whitman College, Walla Walla, Washington 99362, United States;* orcid.org/0000-0003-1295-9879

Katherine M. Mullaugh – *Department of Chemistry and Biochemistry, College of Charleston, Charleston, South Carolina 29424, United States*

Mary E. Anderson – *Department of Chemistry, Furman University, Greenville, South Carolina 29613, United States;* orcid.org/0000-0001-8369-2177

Anne K. Bentley – *Department of Chemistry, Lewis & Clark College, Portland, Oregon 97219, United States;* orcid.org/0000-0003-1353-6042

Justin G. Clar – *Department of Chemistry, Elon University, Elon, North Carolina 27244, United States*

Clyde A. Daly, Jr. – *Department of Chemistry, Haverford College, Haverford, Pennsylvania 19041, United States*

Mark D. Ellison – *Department of Chemistry, Ursinus College, Collegeville, Pennsylvania 19426, United States;* orcid.org/0000-0003-3201-8478

Z. Vivian Feng – *Department of Chemistry, Augsburg University, Minneapolis, Minnesota 55454, United States;* orcid.org/0000-0002-3329-3781

Natalia I. Gonzalez-Pech – *Department of Chemistry, Hope College, Holland, Michigan 49423, United States*

Leslie S. Hamachi – *Department of Chemistry & Biochemistry, California Polytechnic State University, San Luis Obispo, California 93401, United States;* orcid.org/0000-0001-6299-8695

Christine L. Heinecke – *Department of Chemistry & Biochemistry, Loyola University New Orleans, New Orleans, Louisiana 70118, United States*

Joseph D. Keene – *Department of Chemistry, Mercer University, Macon, Georgia 31207, United States;* orcid.org/0000-0003-0874-9019

Adam M. Maley – *Mund-Lagowski Department of Chemistry and Biochemistry, Bradley University, Peoria, Illinois 61625, United States;* orcid.org/0000-0003-1851-984X

Andrea M. Munro – *Department of Chemistry, Pacific Lutheran University, Tacoma, Washington 98447, United States;* orcid.org/0000-0001-7669-350X

Peter N. Njoki – *Department of Chemistry & Biochemistry, Hampton University, Hampton, Virginia 23668, United States;* orcid.org/0000-0001-5085-1178

Jacob H. Olshansky – *Department of Chemistry, Amherst College, Amherst, Massachusetts 01002, United States;* orcid.org/0000-0003-3658-1487

Katherine E. Plass – *Department of Chemistry, Franklin & Marshall College, Lancaster, Pennsylvania 17601, United States;* orcid.org/0000-0002-4544-5471

Kathryn R. Riley – *Department of Chemistry & Biochemistry, Swarthmore College, Swarthmore, Pennsylvania 19081, United States;* orcid.org/0000-0003-4883-4197

Matthew D. Sonntag – *Department of Chemistry & Biochemistry, Albright College, Reading, Pennsylvania 19612, United States;* orcid.org/0000-0002-8883-1030

Sarah K. St. Angelo – *Department of Chemistry, Dickinson College, Carlisle, Pennsylvania 17013, United States;* orcid.org/0000-0003-3294-7963

Lucas B. Thompson – *Department of Chemistry, Gettysburg College, Gettysburg, Pennsylvania 17325, United States;* orcid.org/0000-0003-3805-2431

Emily J. Tollefson – *Department of Chemistry, University of Puget Sound, Tacoma, Washington 98416, United States*

Lauren E. Toote – *Department of Chemistry & Biochemistry, Elizabethtown College, Elizabethtown, Pennsylvania 17022, United States*

Korin E. Wheeler – *Department of Chemistry & Biochemistry, Santa Clara University, Santa Clara, California 95053, United States*

Complete contact information is available at: https://pubs.acs.org/10.1021/acsnanoscienceau.1c00020

Notes

The authors declare no competing financial interest.

REFERENCES

(1) Virtual Inorganic Pedagogical Electronic Resource | VIPEr; https://www.ionicviper.org/ (accessed 2021-08-16).

(2) Jamieson, E. R.; Eppley, H. J.; Geselbracht, M. J.; Johnson, A. R.; Reisner, B. A.; Smith, S. R.; Stewart, J. L.; Watson, L. A.; Williams, B. S. Inorganic Chemistry and IONiC: An Online Community Bringing Cutting-Edge Research into the Classroom. *Inorg. Chem.* **2011**, *50* (13), 5849–5854.

(3) Raker, J. R.; Pratt, J. M.; Watson, L. A. Building Community: A Reflection on the Interactive Online Network of Inorganic Chemists. *Advances in Teaching Inorganic Chemistry Vol. 1: Classroom Innovations and Faculty Development*; ACS Symposium Series; American Chemical Society, 2020; Vol. *1370*, pp 131–139.

(4) Genomics Education Partnership; https://thegep.org/ (accessed 2021-08-16).

(5) Shaffer, C. D.; Alvarez, C.; Bailey, C.; Barnard, D.; Bhalla, S.; Chandrasekaran, C.; Chandrasekaran, V.; Chung, H.-M.; Dorer, D. R.; Du, C.; Eckdahl, T. T.; Poet, J. L.; Frohlich, D.; Goodman, A. L.; Gosser, Y.; Hauser, C.; Hoopes, L. L. M.; Johnson, D.; Jones, C. J.; Kaehler, M.; Kokan, N.; Kopp, O. R.; Kuleck, G. A.; McNeil, G.; Moss, R.; Myka, J. L.; Nagengast, A.; Morris, R.; Overvoorde, P. J.; Shoop, E.; Parrish, S.; Reed, K.; Regisford, E. G.; Revie, D.; Rosenwald, A. G.; Saville, K.; Schroeder, S.; Shaw, M.; Skuse, G.;

Smith, C.; Smith, M.; Spana, E. P.; Spratt, M.; Stamm, J.; Thompson, J. S.; Wawersik, M.; Wilson, B. A.; Youngblom, J.; Leung, W.; Buhler, J.; Mardis, E. R.; Lopatto, D.; Elgin, S. C. R. The Genomics Education Partnership: Successful Integration of Research into Laboratory Classes at a Diverse Group of Undergraduate Institutions. *CBE Life Sci. Educ.* **2010**, *9* (1), 55−69.

(6) Shields, G. C. Twenty Years of Exceptional Success: The Molecular Education and Research Consortium in Undergraduate Computational Chemistry (MERCURY). *Int. J. Quantum Chem.* **2020**, *120* (20), No. e26274.

(7) American Chemical Society. *ACS Guidelines and Evaluation Procedures for Bachelor's Degree Programs*; https://www.acs.org/content/acs/en/education/policies/acs-approval-program/guidelines-supplements.html (accessed 2021-10-22).

(8) Amaris, Z. N.; Freitas, D. N.; Mac, K.; Gerner, K. T.; Nameth, C.; Wheeler, K. E. Nanoparticle Synthesis, Characterization, and Ecotoxicity: A Research-Based Set of Laboratory Experiments for a General Chemistry Course. *J. Chem. Educ.* **2017**, *94* (12), 1939−1945.

(9) Holder, C. F.; Rugen, E. E.; Anderson, M. E. Comparative Growth Mechanism Study for Two Thermoelectric Compounds. *Nanomater. Energy* **2014**, *3* (6), 206−214.

(10) Lopatto, D. Undergraduate Research as a High-Impact Student Experience. *Peer Rev.* **2010**, *12* (2), 27−31.

(11) Nagda, B. A.; Gregerman, S. R.; Jonides, J.; von Hippel, W.; Lerner, J. S. Undergraduate Student-Faculty Research Partnerships Affect Student Retention. *Rev. High. Educ.* **1998**, *22* (1), 55−72.

(12) Lopatto, D. Undergraduate Research Experiences Support Science Career Decisions and Active Learning. *LSE* **2007**, *6* (4), 297−306.

(13) Shields, G. C. The Benefits of Forming a Consortium for an NSF-MRI Proposal. *Council on Undergraduate Research Quarterly* **2002**, 80−81.

(14) Graham, M. J.; Frederick, J.; Byars-Winston, A.; Hunter, A.-B.; Handelsman, J. Increasing Persistence of College Students in STEM. *Science* **2013**, *341* (6153), 1455−1456.

(15) Estrada, M.; Burnett, M.; Campbell, A. G.; Campbell, P. B.; Denetclaw, W. F.; Gutiérrez, C. G.; Hurtado, S.; John, G. H.; Matsui, J.; McGee, R.; Okpodu, C. M.; Robinson, T. J.; Summers, M. F.; Werner-Washburne, M.; Zavala, M. Improving Underrepresented Minority Student Persistence in STEM. *LSE* **2016**, *15* (3), No. es5.

(16) Rovnyak, D.; Shields, G. C. A Roadmap to Successful Collaborations between Primarily Undergraduate Institutions and Research Institutions. *Credit Where Credit Is Due: Respecting Authorship and Intellectual Property*; ACS Symposium Series; American Chemical Society, 2018; Vol. *1291*, pp 105−127.

(17) Aikens, M. L.; Robertson, M. M.; Sadselia, S.; Watkins, K.; Evans, M.; Runyon, C. R.; Eby, L. T.; Dolan, E. L. Race and Gender Differences in Undergraduate Research Mentoring Structures and Research Outcomes. *LSE* **2017**, *16* (2), No. ar34.

(18) Russell, S. H.; Hancock, M. P.; McCullough, J. Benefits of Undergraduate Research Experiences. *Science* **2007**, *316* (5824), 548−549.

(19) Rodríguez Amaya, L.; Betancourt, T.; Collins, K. H.; Hinojosa, O.; Corona, C. Undergraduate Research Experiences: Mentoring, Awareness, and Perceptions—a Case Study at a Hispanic-Serving Institution. *Int. J. STEM Educ.* **2018**, *5* (1), 9.

(20) Jin, L.; Doser, D.; Lougheed, V.; Walsh, E. J.; Hamdan, L.; Zarei, M.; Corral, G. Experiential Learning and Close Mentoring Improve Recruitment and Retention in the Undergraduate Environmental Science Program at an Hispanic-Serving Institution. *J. Geosci. Educ.* **2019**, *67* (4), 384−399.

(21) Barlow, A. E. L.; Villarejo, M. Making a Difference for Minorities: Evaluation of an Educational Enrichment Program. *J. Res. Sci. Teach.* **2004**, *41* (9), 861−881.

https://doi.org/10.1021/acsnanoscienceau.1c00020
ACS Nanosci. Au 2021, 1, 6−14