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Integration of Authentic STEM Practices in Real-World Education and Research Environments: Lessons from the PDP

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Abstract

A significant focus of the ISEE Professional Development Program (PDP) is identifying authentic STEM practices, so that educators and scientists can develop and assess these practices as intentionally as they would scientific content knowledge. In addition to the classic inquiry-based learning activities, PDP alumni also find themselves using and teaching these STEM practices in other contexts. Many PDP participants have benefited from recognizing "STEM practices" as its own category of specific skills and knowledge, allowing them to build these practices into their work intentionally, rather than simply expecting these skills to develop naturally as a by-product of learning STEM content. We present four instances where PDP lessons have been put to work by alumni of the program in this manner, either in teaching and mentoring students, performing real-world scientific research, or both. First, we consider two instances of alumni using their PDP training to inform the way they build authentic STEM practices into college classrooms and college mentorship, at the College of St. Scholastica and at UC Santa Cruz. Next, we describe a course-based undergraduate research experience (CURE) in which students learn and employ authentic STEM research practices at the University of Colorado at Boulder. Finally, we present an example of an alumna who has used her identification of widely-applicable STEM practices to broaden her own research horizons at Lawrence Berkeley National Laboratory.

Keywords: CURE, equity & inclusion, inquiry, research, STEM identity, STEM practices

1. Introduction

For many years, discourse around education in science, technology, engineering, and mathematics (STEM) almost invariably focused on how to teach STEM *content* (*e.g.*, the laws of physics, the principles of chemistry). Much less attention was placed on the teaching of STEM *practices*, a category which encompasses both specific laboratory methods (pipetting, titration, *etc.*) and broad aspects of the scientific process (such as iteration, collaboration, and peer review). The understanding seems to have been that students would either pick up these principles informally during the course of their study, or else would be formally trained in them as-needed when they left the education system for employment.

However, in the last twenty years, an emerging body of scholarship has argued that the two aspects of STEM education should be taught in an integrated and comprehensive manner (Bryan et al., 2015). One organization consistently pushing the importance of this integrated perspective has been the Institute for Science and Engineering Education (ISEE) through its Professional Development Program (PDP), which since its inception has argued for teaching and learning STEM in a way that mirror authentic STEM practice (Metevier et al.*,* 2022).

The four authors of this paper have all participated in the PDP to various degrees and at various stages of their professional careers as scientists and educators. Among the wide array of valuable lessons we gained from our experiences, we share a belief that intentional, authentic instruction in STEM practices can have transformative effects for young scientists, both inside and outside the classroom. In particular, our experiences showcase the value of incorporating explicit instruction in STEM practices within higher education, both in courses that otherwise focus on STEM content as well as in the curriculum more broadly. We also argue that ongoing consideration of the nature of STEM practices is invaluable for researchers in the field, and indeed that under the right conditions, undergraduate students can become field researchers in their own right while still learning STEM practices in the classroom context.

This paper is organized as follows: In section 2, Lynne Raschke describes her use of inquiry-based educational principles in her classroom at the College of St. Scholastica. In section 3, Susanna Honig presents her experiences incorporating STEM practices into the mentorship training curriculum at the University of California, Santa Cruz. In section 4, Colin West describes an ongoing experiment in teaching authentic research in the classroom by engaging students in a publishable research project at the University of Colorado, Boulder, and in section 5, Lauren Lui describes the ways in which PDP perspectives on learning and pedagogy have influenced her own approach to a research career.

2. Inquiry-based learning and STEM practices in the college classroom

—Lynne Raschke

Considerable emphasis in the current K–16 education system is placed on “hands-on” science activities in classrooms and labs. However, while many of these activities are fun and interesting, in many cases the main “skill” conveyed to the learner is how to read and follow directions carefully so they will get the “right answer” and a good grade (Wilcox and Lewandowski, 2018). In college, these activities also included learning error analysis techniques, which without proper presentation teaches students only to show that they really did get the “right answer” within the uncertainty of the measurements made (Pollard et al., 2020).

For me, the connection between most of the hands-on science activities I engaged in as a student and the actual practice of doing science was never clear — especially as I began engaging in research projects in college and early graduate school.

2.1 Lynne’s experiences in the PDP

In my third year of grad school, I attended the first ever PDP in April 2001. One of the first activities we did was “Three Kinds of Hands-on Science” with foam (Figure 1). This activity and the subsequent discussion immediately made a huge impact on my thinking about how I taught and how I wanted to approach teaching science in the future. The two fundamental ideas I took away were: (1) not all hands-on science activities serve the same

Figure 1: Lynne Raschke at the first PDP in 2001, participating in the "Three Kinds of Hands-on Science" activity.

purpose, and (2) educators should make deliberate choices when designing activities to achieve the learning outcomes they have for their students–including what scientific practices they actually intend for their students to learn. My subsequent years of participation in the PDP both as a returning participant and as a staff member further developed my thinking about scientific practices and how to explicitly teach them in my courses.

2.2 The college classroom context

Currently, I teach at the College of St. Scholastica in Duluth, MN. St. Scholastica has approximately 1500 traditional undergraduates with a focus on serving first-generation students from rural communities in northern Minnesota and Wisconsin. Two of the courses I teach are primarily for elementary education majors — many of whom have fears about taking science courses and/or have the misconception that learning science means primarily memorizing facts and equations. One course — Concepts in Physics — is a conceptual introduction to physics and the other course — Cosmic Systems — covers topics in earth science and astronomy. These two courses are two of the three science courses that education majors must take. (The third course covers life science.) These courses are not intended to be science pedagogy or methods courses — but rather are intended to cover the scientific knowledge that pre-service teachers need. As a result, they must meet state-mandated scientific content standards for teachers.

In addition to addressing the state-mandated content standards, I have my own goals for the students that are primarily attitudinal: 1) I want to get them excited about learning science so they will be excited to teach science, 2) I want to influence their perception of what science is; that it's not just a body of knowledge to be memorized but instead a way of learning and discovering about the universe, and 3) I want to provide them with a sense of agency and ownership with respect to science — that it's something they can engage in and be successful at.

2.3 Inquiry-based activities and STEM practices

In each of the two courses, students engage in approximately 10 activities designed to teach both scientific content and one or more scientific practices. For example, in Concepts in Physics, students start the semester by designing and conducting experiments to measure average speed, velocity, and acceleration in different situations. Later in the semester, students are asked to design DC circuits that meet specific requirements for the number of light bulbs and the relative brightness of the various bulbs. In Cosmic Systems, students conduct experiments on the physical properties of a variety of unknown minerals and then use the results of those investigations to explain and justify their identifications of the minerals. In an activity on moon phases, students use both a physical model of the Earth–Moon system and a table of moon data to make predictions about moonrise and moonset over the course of a month. Finally, students in Cosmic Systems conduct an inquiry investigation on streams and erosion where they develop investigable questions and design experiments with a focus on controlling variables and making appropriate measurements that are relevant to their investigation question. At the end of this activity, students also must explain their investigation and their results using evidence to support their claims.

At the end of each activity, students are asked to reflect in writing on what they learned — both the scientific content and the scientific practices they engaged in. I also ask students to think about how they might approach teaching similar content and practices in their future teaching.

2.4 Discussion and future directions

My hope is that these activities will make the scientific content more memorable for my students. But more importantly, I hope that by explicitly centering the activities around authentic STEM practices and then discussing them to highlight how the students have used them to engage in science and to learn scientific content, my students will gain the agency and ownership discussed above.

As with any curricular element, I also recognize where these activities could benefit from further development. In some activities, I am struggling to balance the content standards I need to cover with the scientific practices I want to develop. As a result, some activities are more prescriptive and leave less room for developing scientific practices — but I think there are revisions that could be made that could allow for a better balance between the two.

I also am still working on better assessment of scientific practices — both formative and summative assessment. For example, I use a rubric for assessing a student's overall stream and erosion inquiry investigation, but I haven't used more tailored rubrics for specific scientific practices in that activity or other activities. One outgrowth from reconnecting with ISEE and the PDP over the past 1.5 years has been learning about the rubrics for assessing scientific practices that were developed since I last participated in the PDP in 2009. I'm currently adapting some of these rubrics for my own use in these two classes.

Overall, I think that by designing these activities to explicitly teach scientific practices in addition to scientific content, my students' attitudes and ideas about science have been positively impacted. I also think that my students are better equipped to teach science in their own classrooms because they have a better understanding of what it really means to "do science" and develop scientific understanding.

3. Redesigning mentorship training curriculum to include STEM practices at the UC Santa Cruz Academic Excellence Program

—Susanna E. Honig

I have always been fascinated by the hidden processes and skills that underpin mastery in any discipline. During the years of my graduate studies in ecology and evolutionary biology, I learned that there were a myriad of practices that I needed to operationalize in order to succeed in acquiring funding for and performing scientific research. These skills were "forged in the fire" for my peers and I as we navigated applying for grants, designing field studies, and writing up our theses for publication. After graduate school, I decided to specialize in science education, and it became apparent to me that science faculty whose courses I was supporting were eager to explicitly prepare their students to perform the same STEM practices I had implicitly "picked up" along the way. Together, we began to observe the many ways in which incorporating STEM practices into our teaching benefited our students by providing them with deeper understanding of course materials and also creating opportunities for students to gain confidence in their scientific journeys and identities. Since then, teaching and assessing STEM practices has become a foundational component of my research and teaching interests.

While there are clear advantages to incorporating STEM practices directly into the STEM classroom, integrating STEM practices into supplemental instruction programs presents a unique opportunity to reinforce the importance of these practices while also providing a near-peer mechanism for recognition of STEM practice performances. In this section, I describe one such effort to bring instruction in authentic STEM practice into a mentor training course for an academic support program at my university. This effort has naturally drawn extensively on my background with the PDP.

3.1 Susanna's experiences in the PDP

I attended the PDP during the first and second years of my teaching postdoc position in Molecular, Cell & Developmental Biology at UC Santa Cruz (2016 and 2017), and I gained valuable experiences while attending as a participant and a design team leader. Throughout the PDP, I was struck by the elegance in which all three focus areas (equity and inclusion, inquiry, and assessment) were intertwined with one another, and the way in which we engaged in these themes as participants allowed me to gain practice designing my own active learning curriculum with multiple focus areas in mind. For example, I learned in the PDP that inquiry exercises like Light and Shadow (Hunter and Metevier, 2010) could provide students with an authentic entry point into the practices of science and engineering (STEM practices) and could therefore offer students from diverse backgrounds an opportunity to develop a sense of belonging, feel recognized for their engagement, and gain a sense of science identity. In effect, well-designed inquiry always includes formative and summative assessments, and these assessments can in and of themselves lead to targeted feedback and recognition of students, leading to equitable outcomes. This synergy mindset has fundamentally contributed to my own teaching philosophy and has found its way into every piece of curriculum I now design as Director of the Academic Excellence Program.

3.2 The Academic Excellence Program

At the University of California, Santa Cruz (referred to hereafter as UC Santa Cruz), the Academic Excellence (ACE) Program works to increase the diversity of students earning their bachelor's degrees in Science, Technology, Engineering, and Mathematics (STEM). Founded in 1986 and based on Uri Treisman's collaborative learning model (Treisman, 1992), the ACE Program supplements gateway STEM courses with active learning problem-solving sessions, peer mentorship, and community building opportunities for undergraduate students. ACE is open to all UC Santa Cruz STEM students, but when waitlists occur, students who belong to the Educational Opportunities Program (EOP) are prioritized for admission. EOP student status indicates that students are either the first in their family to attend college (first generation college students) and/or they come from low-income or educationally disadvantaged backgrounds. By prioritizing EOP students for participation in ACE, students who have been minoritized in higher education are given access to inclusive, evidence-based pedagogical support and mentorship. ACE has a proven track record for improving student outcomes; year after year, ACE students outperform their demographically matched non-ACE peers in STEM coursework, and recent regression analyses indicate that ACE students graduate at significantly higher rates than their demographically matched non-ACE peers within the STEM field at UC Santa Cruz.

Students who participate in the ACE Program commit to attending two collaborative problem-solving sessions per week for 1.5 hours each (3 hours total) in addition to a 1-hour weekly peer mentoring session, amounting to 4 hours of mandatory programming for the entire ten-week quarter. Problem-solving sessions range in size from 10–40 students, and they are led by professional Learning Skills Advisers (LSAs) and co-facilitated by ACE student employees.

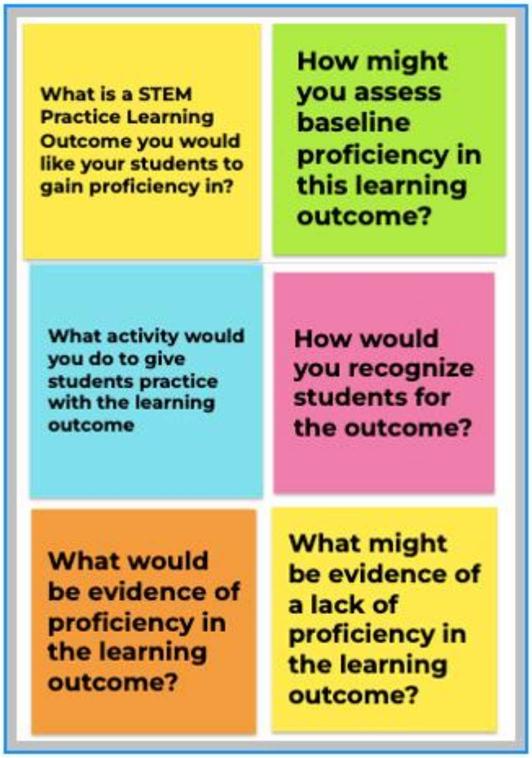
In addition to co-leading problem-solving sessions, these ACE student employees (referred to hereafter as "peer mentors") are responsible for designing and facilitating weekly peer mentoring sessions for small groups of 3–5 ACE students. Peer mentors are required to have participated in at least one ACE session as a student prior to applying for the position, and during their first quarter working as a peer mentor they enroll in PBS 182, the ACE Service Learning Course. This course is taught by the ACE Program Director and is meant to engage peer mentors in the theory and practice of active learning pedagogy and give them professional development in mentorship.

3.3 Incorporating STEM practices into mentorship training

As emphasized in the PDP, studies show that engaging students in STEM practices and recognizing them for performing these practices can increase student motivation, science identity, and intention to pursue future STEM careers (Starr et al., 2020). STEM practices may provide students with the perspective of authentically "doing science" rather than learning about others who do science, and being recognized by meaningful others (Carlone & Johnson, 2007) for this engagement can be disproportionately beneficial for minoritized groups (Starr et al., 2020). In order to utilize these equity benefits, ACE redesigned the Spring 2021 PBS 182 curriculum (a virtual course) to incorporate explicit mentorship training that emphasized STEM practices.

In order to familiarize peer mentors with the concept of STEM Practices, mentors read Starr et al., 2020 and received an active learning style lecture on the topic. Next, they engaged in several collaborative activities aimed at helping them explore their own experience with STEM practices. First, mentors participated in a "brainstorm chat" in Zoom by sharing STEM practices they had learned and utilized during their college career. The instructor synthesized the brainstorm activity by highlighting practices that had been brought up multiple times and asking follow up questions about where and how mentors had learned each practice (*i.e.*, in class vs. in a laboratory or while doing homework). Then, using a backward design framework (Wiggins and McTighe, 1998), the instructor asked students to pick a relevant STEM practice learning outcome for their mentoring sessions and design a mentoring activity that would engage students in this learning outcome (Figure 2). Mentors included their plans for assessing proficiency in the practice, opportunities to intentionally recognize students for performance of each practice, and development of evidence that might be useful in a future rubric for the course activity they designed.

To ensure that mentors used the module on STEM practices in their subsequent mentoring sessions, the instructor created a course assignment requiring mentors to submit a lesson plan that would highlight a STEM practice learning outcome (Figure 3).



What is a STEM Practice Learning Outcome you would like your students to gain proficiency in?

How might you assess baseline proficiency in this learning outcome?

What activity would you do to give students practice with the learning outcome

How would you recognize students for the outcome?

What would be evidence of proficiency in the learning outcome?

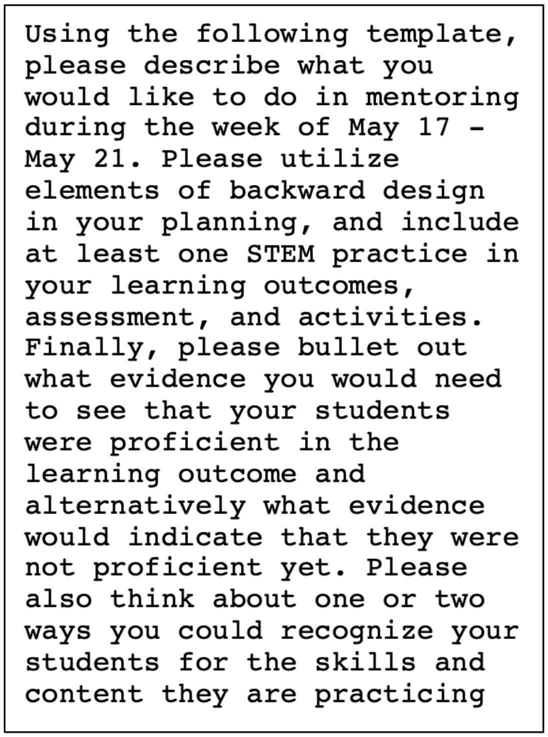
What might be evidence of a lack of proficiency in the learning outcome?

Figure 2: Example slide from a PBS 182 mentorship training curriculum. Google Jamboard was used to discuss with students how to design a mentoring activity that would engage students in their chosen learning outcome.

3.4 Lessons learned and future directions

By incorporating STEM Practices curriculum directly into the Mentorship training course at ACE, mentors gained familiarity with the concept and were incentivized to develop lesson plans for ACE students that involved these practices, thereby leveraging the number of students who could benefit from authentically engaging in STEM Practices and being recognized for this engagement. While mentors absorbed the content quickly, they found the rubric development and assessment piece particularly abstract. In the future, we aim to build out more structured activities on the assessment of STEM practices that separate student proficiency in content versus practice.

We also hope to assess our curriculum redesign efforts by conducting observations of a subset of mentoring sessions to gauge how recognition of STEM practices is being implemented in an authentic context. We believe that ACE peer mentors are a crucial source of recognition for minoritized STEM students at UC Santa Cruz, and we hope to advance educational equity by utilizing STEM practices to bolster STEM identity and sense of belonging.



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Using the following template,
please describe what you
would like to do in mentoring
during the week of May 17 -
May 21. Please utilize
elements of backward design
in your planning, and include
at least one STEM practice in
your learning outcomes,
assessment, and activities.
Finally, please bullet out
what evidence you would need
to see that your students
were proficient in the
learning outcome and
alternatively what evidence
would indicate that they were
not proficient yet. Please
also think about one or two
ways you could recognize your
students for the skills and
content they are practicing
```

Figure 3: Assignment prompt for peer mentors incorporating STEM Practices curriculum.

4. Authentic research in the classroom
—Colin West

Another approach to bringing authentic practices into STEM education is to make the STEM classroom itself a site for genuine scientific research. In this section, I describe an ongoing project at the University of Colorado at Boulder to provide students with an opportunity to learn STEM practices while engaging in authentic research in their freshman physics lab. While the notion of authentic research in the classroom has certainly existed apart from the PDP, it was my own participation in the ISEE PDP that first put the concept on my radar. In general, there is less literature and institutional knowledge on which to draw when teaching STEM practices in the classroom compared to STEM content, and I drew heavily on the principles of inquiry-based activities which I learned there during the development and deployment of this course.

4.1 Colin's experiences in the PDP

I was only fortunate enough to take part in the PDP during the second year of my postdoctoral appointment at UC Santa Cruz. However, the experience was an eye-opening one for me. At the time, I considered myself well-versed in pedagogical theory from the world of physics education research, but nevertheless, I found myself thinking about teaching in a variety of new and different ways during the course of the program.

Among the many lessons I took away from the PDP was the idea of teaching STEM practices intentionally, as an explicit goal of a course, rather than expecting students to simply absorb them osmotically during the course of their education in STEM content or in their first forays into research. As others have remarked above, this differed (quite positively) from my own experiences as a student and left me keenly aware of how valuable it would be for a student to be able to study the *way* we do science–especially if this could be done *while doing actual science*.

4.2 Course-based undergraduate research

A course-based undergraduate research experience ("CURE") is a formal class in which students use authentic STEM practices to address a question of genuine interest to the scientific community. In other words, it engages students in real research practices to perform "real research"– where "real" here means crucially that the answer to the research question is as unknown to the instructors and to the broader scientific community as it is to the students themselves.

In the past decade, CUREs have become increasingly popular at the college level because they offer students the widely-documented benefits of an undergraduate research experience (Auchincloss et al., 2014), but with fewer barriers to entry. After all, a CURE is simply one of many courses in a college catalog, and open to all who choose to enroll.

I first became aware of CURE programs through biologists I met at the PDP. Indeed, the majority of CURE programs described in the literature are centered in bioscience or to a slightly lesser extent in chemistry (Dolan, 2016). Biology educators in particular have excelled at creating CUREs on a large scale (hundreds of students or more per term) and at the introductory level (Hanauer et al., 2017; Brownell et al., 2017). There have also been instances of programs called "CUREs" (or related names) in my field of physics, but prior published instances have either been much smaller (see for example Walcott et al., 2018), reaching perhaps a few dozen physics students per year, or else have featured student inquiries into interesting and unique topics but not necessarily ones which engage students in research that would be of value to the broader scientific community (see for example Chippendale, 2016).

4.3 PDP principles in a CURE

For many years after my time in the PDP I found myself daydreaming about the prospects of a large-scale physics CURE that would engage students in authentic research. In many ways a CURE represents one of the purest forms of the PDP's values. Ideally executed, it would allow students to engage in inquiry at the highest level, and would create a space for them to learn authentic STEM practices through both traditional instruction and by putting them to work in a research context (Auchincloss et al., 2014). Like a more traditional undergraduate research experience, it would promote agency and sense of STEM identity by letting students see how their own thoughts and decisions are directly incorporated into publishable research (Hunter, Laursen, and Seymore, 2007). And it would promote equity and inclusivity in undergraduate research experiences by creating a space for research with low barriers to entry and which does not favor students with connections and/or disposable income (Bangera and Brownell, 2014). With these goals in mind, a smaller, more selective CURE (which would not achieve the broad-reaching equity benefits) or a "CURE" whose central project lacked real scientific novelty (which would not offer the full array of benefits for STEM identity) felt woefully insufficient.

Unfortunately, my enthusiasm for the concept of a large-scale CURE featuring authentic research seemed perpetually to collide with two impassable obstacles. First, instituting a CURE on a large-scale would require completely replacing a traditional course taken by hundreds of students with something wholly experimental. And secondly, it would require finding a project that (with sufficient scaffolding) would be comprehensible to a freshman student, and yet interesting enough to produce a publishable result. As an added challenge, I hoped to find a research question which could be worked on by hundreds of students, but without leaving students the impression that their work was largely redundant, or that it could have been replicated more efficiently by an automated algorithm.

Sadly, I cannot claim credit for having overcome either of these two obstacles through my own cleverness. The resolution to both arrived via external factors, beginning with the onset of the COVID-19 pandemic in the spring semester of 2020. This event necessitated a complete redesign of the freshman lab course at CU Boulder into something that could be completed entirely online. I struggled at first to think how a "lab," with its quintessential focus on hands-on learning, could be completed remotely. Eventually, many instructors found clever ways to make this happen (for example, see Hoehn et al., 2021), but in my case, my PDP-training lead me in a different direction: much of the value of "hands-on" lab work is that it offers students a chance to engage in authentic STEM practices, like operating an oscilloscope or keeping a proper lab notebook. Knowing these authentic STEM practices were valuable learning goals in their own right, I reasoned that some form of CURE research project could be suffused with authentic experimental research skills like collaboration, literature review, uncertainty analysis, and peer review–skills that are unquestionably from the practical "lab" domain, but can be taught without any physical equipment. We felt that a very valuable "lab" experience for the students could be designed around three broad learning objectives: that students would learn authentic STEM research skills, that students would have positive teamwork experiences (since collaboration is also an authentic STEM practice) and that they would have a positive experience with experimental science (since affective course impacts are important to considerations of equity and STEM identity).

The idea would have died on the vine without a proper research question to build a CURE around. This problem, fortunately, was solved by fortuitous networking. I began thinking about the prospect of designing a large-scale physics CURE alongside my colleagues Heather Lewandowski and Alexandra Werth, both experts in physics lab design. Through their connections to the Laboratory for Atmospheric and Space Physics (LASP), we eventually found a scientist there, James P Mason, whose own projects involving solar physics research fit the requirements to a T.

4.4 The C-PhLARE Project

Dr. Mason was interested in studying the infamous "coronal heating problem," which, broadly stated, asks why the sun's corona is millions of kelvin hotter than its photosphere, despite being much further from the center of the sun itself (Klimchuk, 2006). There are generally two primary mechanisms which could generate large transfers of energy from the bulk of the sun to its corona, which would in turn explain the anomalous heating. Very small solar flares called "nanoflares" could transfer sufficient energy if they occur frequently enough to make up for their individual low energies; alternatively, large, discrete transfers of energy through magnetohydrodynamic waves could fit the bill (Klimchuk, 2006). It is generally believed that both mechanisms contribute to some degree, but it is an open question which mechanism is dominant. However, it has been shown (Hudson, 1991; Veronig et al., 2002) that a careful study of the frequency of nanoflares compared to larger flares could resolve the question. In particular, one can measure a parameter α which characterizes the frequency distribution of flares as a function of their total energy; if the magnitude of α is less than two, then nanoflares do not occur frequently enough to be the dominant mechanism (Hudson, 1991).

This problem turned out to be perfect for the CURE context for three reasons. First, the data analysis involved (integrating a light curve to find total flare energy, and plotting a histogram to observe the frequency distribution of energies) is tractable at the freshman level. Second, it authentically requires many groups to participate; a solid analysis should involve hundreds of flares, so small teams of students can each analyze a distinct flare without redundancy. Finally, it is authentically easier for hundreds of individual humans to do this work than to attempt to do so algorithmically. The noisy nature of solar flare data can require careful human analysis to parse, and prior attempts to automate the process have shown unacceptably high event rejection rates (Mason et al., 2019).

We formed the Colorado Physics Laboratory Academic Research Effort (C-PhLARE) to study this problem over three semesters in the context of our introductory physics lab. This course enrolls approximately 400 to 800 students per semester; working in teams of three or four, students analyzed individual flares while also practicing (and being explicitly taught) about principles of scientific research, experimental design, and data analysis (Werth, West, and Lewandowski, 2022). To our knowledge this project represents the first instance of a large-scale CURE in introductory physics, and also an unprecedented attempt to address the nanoflare question: while previous works have studied the same flare frequency distributions (see Schimizu, 1995; Aschwanden and Freeland, 2012; Shibayama et al., 2013), the sheer manpower of our collaboration allowed us to analyze many more flares and sample across a wider window of time (encompassing an entire solar cycle) than previous efforts.

4.5 Results and future directions

While final data analysis for the project is ongoing, the C-PhLARE collaboration has a paper in preparation for *The Astrophysical Journal* which we believe makes a significant contribution to the literature on the solar heating problem, and which features over 1200 students who completed the course as co-authors. We also analyzed the course outcomes from multiple perspectives to assess whether we achieved our various learning goals, and our preliminary findings suggest considerable success on all three fronts (Werth, West, and Lewandowski, 2022). For example, students reported substantial gains in confidence in areas like coding and data analysis, which were consistent with our observations from formative and summative assessments. Similarly, they overwhelmingly reported satisfying teamwork experiences, which we are currently studying in greater detail using an assessment tool called the “Adaptive Instrument for Regulation of Emotions,” (Järvenoja, Volet, and Järvelä, 2013) which surveys the ways students used both individual and shared strategies to deal with challenges that arise in collaborative learning environments. Finally, we found that students described the experience extremely positively and reported significant gains in categories like “confidence in my ability to contribute to science,” and “confidence in my ability to do well in future science courses” (Werth, West, and Lewandowski, 2022).

Given the apparent success of this project, I was extremely grateful for my PDP training, without which I would never have thought of “teaching authentic STEM practices” as a viable objective around which to build a remote lab course. Core PDP principles like authentic inquiry, student agency, diversity and equity considerations, and use of both formative and summative assessment to measure our learning outcomes also drove much of our design process for the course. In fact, in my assessment, a true CURE cannot exist without incorporating these principles into its structure.

Despite the promising results, the future of projects like this at CU Boulder is uncertain. After all, we have returned to in-person instruction in a more traditional freshman lab, and even if we had not, we have exhausted the necessary data analysis for the coronal heating research question. The latter fact is perhaps the most problematic; the true power of a CURE appears to come from blending an authentic research experience with a classroom structure, but research questions that fit the requirements remain difficult to identify in physics and come with a finite lifespan. It is challenging to envision a sustainable physics CURE because the effort involved in constantly finding new research questions and redesigning the materials appropriately seems prohibitive. However, I remain hopeful that, as appropriate research problems present themselves, we may be able to deploy CUREs sporadically going forward. Alternatively, we may be able to find "near-CURES" that achieve most but not all of the essential elements of a CURE, while still accruing substantial benefits for students. After all, the inquiry-based activities taught at the PDP do not generally involve novel research questions, and are still quite powerful for students. Future projects and further research may find ways to strike a happy and practical medium in this respect.

5. PDP principles in scientific and engineering research —Lauren Lui

Although the core of the PDP is to train scientist- and engineer-educators in practices and principles that help them become better mentors and teachers, I found that my experiences in the PDP also made me a much better researcher. As a program whose methods are meant to embody authentic STEM practices, this seems obvious in retrospect but it was not obvious to me while in PDP training. The PDP themes of Inquiry, Diversity and Equity, and Assessment have permeated and influenced how I conduct scientific and engineering research from the time I participated in the PDP as a graduate student at UC Santa Cruz until now as a Project Scientist at Lawrence Berkeley National Laboratory (LBNL). I have used PDP principles in teaching opportunities beyond those in the PDP, but, to expand the discussion beyond the classroom examples presented above, I will focus on how the PDP affected my work as a professional researcher. My PDP experience made me realize that the practice of STEM research is more than just the technical details of the work itself; it's also about the unique experiences and perspectives that people bring to their work and research.

5.1 Lauren's experiences in the PDP

I participated in the PDP in 2011 as a trainee, in 2012 as a Design Team Lead, and in 2013 briefly to help with a Special Projects Group to develop a guide for people interested in adapting PDP principles and activities for other contexts ("Discussion Guide Development Group"). During each of these experiences I was a doctoral student in the Biomolecular Engineering and Bioinformatics program at UC Santa Cruz. After I graduated, I did my postdoctoral work at LBNL and have continued there as a project scientist.

At first, learning science and engineering appears to be mostly about using facts and applying them to evaluate hypotheses, but rarely are students explicitly taught what skills are used in research. Even if skills such as generating research questions (science process skill) or identifying constraints (engineering process skill) are stated, understanding how and when these skills are used is not fully realized until participating in an inquiry activity. Even though the main purpose of participating in the PDP was to be trained in teaching these skills, my PDP experience also had the side effect of solidifying my research skills. An excerpt from the 10 Year PDP Alumni Conference volume notes this experience as well (emphasis added):

> "In graduate school, scientists and engineers are in a prime position to learn about and reflect on *how research skills are acquired* and *how they might be taught* and to consider *how laboratory units and courses can be tapped to provide students with experiences that impart relevant content knowledge and reasoning skills*. They are in a position to teach research skills explicitly and intentionally, so that their students can develop research abilities through coursework rather than just by good luck. In that position, they can use these developing research skills to strengthen students' scientific/engineering reasoning skills and teach content knowledge with understanding. As they carefully consider research

> skills, reasoning skills and content understanding, graduate students become better teachers and develop as future mentors. This reflective practice also enhances their own learning, making them better researchers." (Hunter et al, 2010)

From this perspective, I will discuss revelations from my PDP experience in relation to being a researcher, loosely around the three PDP themes. These revelations are (1) how research changes how one approaches the structure of knowledge (Inquiry theme), (2) failure is part of the research process (Diversity and Equity theme), and (3) understanding how one judges others research and how others judge mine (Assessment theme). Each of these revelations has shaped how I intentionally use PDP principles and STEM practices in conducting research, how I mentor, and how I give feedback to my peers and mentees.

5.2 PDP Principles in research

5.2.1 Structure of knowledge

During my first year in the PDP, I did not have any expectations going into the training, but participating in the Light and Shadow Inquiry Activity (Hunter et al., 2010) was so different from what I had experienced as a graduate student that I began to rethink the research process. I was struck by how experiencing the inquiry process taught you that research was not a linear process that is typically taught in grade school. I distinctly remember in middle school learning the "observation, hypothesis, design experiment, analysis, and conclusions" description of the scientific method. As I went through the PDP training, it gave me time to reflect on the true nature of the research process in terms of discovery, pursuing scientific questions, generating knowledge of the natural world, and how it isn't necessarily a linear process.

During my second year in the PDP, I was able to lead a group in designing a computational biology lab. I was deeply interested in building a computational biology inquiry-based experience since this was my field. I also wanted to figure out how to do inquiry in a computer-based setting, as compared to manipulating physical objects the way we had learned during the PDP training. As we were designing the lab (using Backward Design, of course) my group felt overwhelmed by what background information to give to the students and what prompts we could provide. I remember when my facilitator Anne Metevier asked, "what is the core concept you are trying to teach? The enduring understanding concept?" I realized that the concept that I was trying to teach was homology, that DNA sequence similarity indicates a common ancestor or common function. This concept underlies much of computational biology, from classifying organisms based on their genome, or assigning function to genes based on DNA sequence. Realizing that this was the concept that we wanted to teach, we were able to more easily design the rest of the workshop content. This realization also made me reflect on what I was doing in my own research, and how much of it was based on this single concept and what assumptions it makes of the data. This has made me a better researcher in that I examine my underlying assumptions about phenomena more closely and I typically build testing theoretical models into my research goals. I also tend to lead with concepts in presentations so that the audience understands my overall goals and doesn't get lost in the details of my work.

The idea of generating deep, enduring understanding in research continued to solidify when I took a brief teaching course from the Science Education Partnership and Assessment Laboratory (SEPAL) Center at San Francisco State University. During the workshop we participated in a card sorting exercise of superheroes. We learned that novices often sort on surface features, such as if the heroes had capes or could fly, but experts sorted on deeper, unseen concepts such as whether the heroes were from DC or Marvel comics. This same idea applies to science and engineering students. SEPAL researchers provided a similar exercise to biology undergraduates, graduate students, and faculty, except the cards were biology experiments (Bissonnette *et al*., 2017). Novices sorted on what they could see because that's all the knowledge they had to work with; they typically sorted based on the organisms under study. Graduate students and professors sorted on concepts and the theory being studied in the experiment, or "deep features". As researchers, this is the leap we attempt to make with inquiry-based learning and our research. How do we go from novices working from only what we can see to experts studying underlying phenomena that we can't see?

As students, we can begin to reach the "enduring understanding" with the help of our teachers providing theoretical concepts and frameworks on which to hang facts (National Research Council, 1999; Bissonnette *et al*., 2017), but what happens when we are doing research and these concepts don't exist or haven't been proven? Suddenly the simple act of defining a research question becomes difficult and one has to examine their assumptions. Through testing and research, making hypotheses and experimentation, and some guidance from our mentors, we can build novel structures of knowledge of our world. Science is more than just learning and discovering new facts; it is the process of discovering the theoretical principles that govern how the world works.

5.2.2 The role of failure in research

A critical piece of the research process that isn't always discussed is the *confidence* to do the research in the first place. Even when it is acknowledged, people may not understand how it relates to diversity and equity in research. The PDP provided a safe place for me to learn about inquiry. There was no penalty for being unable to figure out the question I had picked for the Light and Shadow activity, and in fact my facilitators never appeared frustrated with my partner's and my progress during the activity. The feeling of safety and encouragement made me feel like I could figure everything out. And indeed, in time we were able to figure out the problem we had picked. How we are treated during our research endeavors has a big impact on how we perform and is tied in with the Diversity and Equity PDP theme.

Gaining the confidence that I could *figure out how to do something* and I didn't have to succeed the first time was critical to my success in graduate school. In a male-dominated field, I didn't necessarily realize that I was experiencing stereotype threat on top of general gender bias. I was afraid to fail with any experiment. Starting any experiment was terrifying because failure would prove that I didn't belong in graduate school or my field of study. My experience in the PDP taught me that failure wasn't a reflection of my abilities because it is an integral part of the research process. During the Light and Shadow Activity we tried many hypotheses before we got to the right one. It wasn't all trial and error; each failure taught us something new that helped us reach an explanation for the phenomena we were studying. Although fear of failure was never explicitly discussed in my PDP training, after I had experienced a supportive environment, I realized how much I expected myself to come up with a correct hypothesis every time in my own work.

Related to failure in the research process is the concept of fixed vs. growth mindset. The idea that I could "grow" into being a researcher meant that if I tried, I could learn how to do research. Failure didn't mean that I couldn't eventually become a great researcher. As I continued through graduate school, I realized that my confidence in my studies didn't just come from being an expert in my field and knowing all of the material, it also came from the confidence that I could attempt something that had never been done before by anyone. This feeling of empowerment has persisted through my research career, that I have the confidence to pursue new questions that I am interested in even though I did not receive formal training in a particular area. I have the confidence that I can do the research process and apply it to new situations.

5.2.3 The nature of evaluation

Knowing that fear of failure is what can hold some scientists back, I have learned to carefully examine how I give feedback and how I receive feedback. Evaluation of methods and results is a critical part of STEM research. Unfortunately, this can often come as telling a researcher or student what is wrong with their work and not necessarily how it can be improved. Criticism and comparison can also often come without rubrics, so sometimes feedback can feel unhelpful and applying for grants can feel like roulette. When I am giving feedback, I am careful to give someone suggestions on what they can do to improve their research because I know that vague feedback can be discouraging.

When I mentor, I try to create a psychologically safe environment for my mentees to ask questions, and I tell them what research skills I am teaching them. I ask them to explain how they might approach the research, so I can assess their understanding and if I need to provide more background knowledge. In relation to creating a safe environment, I also encourage my students to pursue research questions that they come up with during their work. I ask them questions to help refine their hypotheses instead of indicating whether it is a good hypothesis or not. I hope that in this type of environment they feel ownership of their learning and feel empowered to be in research.

Scientists and engineers may not realize that they are biased in their approach to assessment. Often, they have not defined what they are assessing. During a grant review process, I began to realize the difference between how science and engineering is evaluated. As an engineer by training, I often focus on optimizing methods. My proposal focused on optimizing a method to improve data quality, which in turn would enable the ability to ask more detailed genomics questions. After an initial evaluation, nearly all of the reviewers wanted me to focus on the science questions, even though the heart of the proposal was developing the method. After talking with my mentor, I realized that since I was presenting to a group of nearly all biologists, they did not think in terms of engineering principles and I was able to rewrite the proposal and it was funded. Even though we are doing research, we may have unconscious ways that we're evaluating other people's work. If I had not explicitly learned differences between engineering and science approaches in the PDP, I may not have figured out what was happening in the evaluation.

Evaluation and assessment are intertwined with diversity and equity, not just appraisal of student understanding of material. Not setting clear criteria for assessment, such as creating a rubric, can reduce the quality of feedback and lead to unconscious bias of underrepresented groups (Uhlmann and Cohen, 2005). Although I understand my responsibility to present my work clearly in presentations, papers, and grants so that it is easier to evaluate, I also understand my responsibility as an evaluator to use different assessment methods to help provide the best feedback that I can.

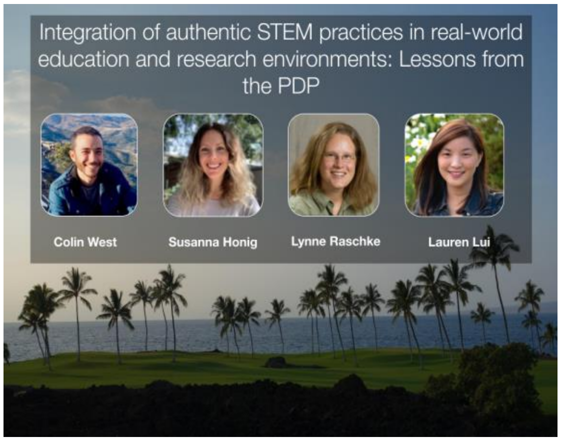
5.3 Conclusions

The fact that the PDP names STEM practices and experiences makes the research process less mysterious. Putting names to experiences helps us realize that others are experiencing the same thing. The PDP has made me a better researcher in terms of how I do my research, but also in how I act to increase diversity and equity in science and engineering. Much of the practice of science and engineering is working with immutable, incontrovertible facts, but much of it is also about the diverse perspectives and experiences of the people doing the research. Intentionally incorporating STEM practices into training students acknowledges the human side of science and engineering and improves their confidence, quality of research, and mentorship of others.

6. Summary and Conclusions

Looking at the projects described above, it is clear that, although the authors work in a variety of contexts, there are many commonalities in the way we approach our roles in STEM. All four authors engaged specifically with work to analyze and/or teach authentic STEM practices within the scope of their professional work, covering a range of contexts in and around the university classroom as well as in professional scientific research. Each of us were motivated by a shared belief, fostered in the PDP, that STEM skills are as much a part of science as scientific content, and that too many aspiring scientists are expected to simply “absorb” skills during their education, when they could be taught explicitly. In addition, we all drew on concepts of inquiry-based learning and backward design when deciding how to pursue projects involving STEM practices.

Panel discussions at the conference on Advancing Inclusive Leaders in STEM in May 2022 revealed further and perhaps more subtle areas of alignment in our teaching and learning paradigms, which we believe highlight important lessons for the teaching and learning of STEM. First, all of us identified that explicitly teaching authentic STEM practices is itself a valuable equity intervention, because of its positive impacts on levels of preparation, self-confidence, and sense of STEM identity. Secondly, we all felt that the concept of teaching *authentic* STEM practices, rather than “idealized” or “contrived” versions of STEM practices, was vital. The true nature of STEM work is messy, circuitous, and relies heavily on collaboration and iteration, in contrast to the mythical image of a lone genius patiently applying “the” scientific method which is sometimes presented. Finally, the authors all described the importance of a certain sense of “psychological safety” or “acceptance of failure” in their experiences teaching and learning STEM practices. Overall, we feel that integration of authentic STEM practices into the broader field of STEM and STEM education is vital for the future of the field, and that PDP principles like those identified in this paper provide a structure to make such interventions both equitable and effective.



Integration of authentic STEM practices in real-world education and research environments: Lessons from the PDP

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Figure 4: Panel introduction slide at the ISEE conference on Advancing Inclusive Leaders in STEM.

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