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ISEE's Framework of Six Elements to Guide the Design, Teaching, and Assessment of Authentic and Inclusive STEM Learning Experiences

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Abstract

It seems intuitive that effective learning experiences in science, technology, engineering and mathematics (STEM) should be inclusive and should mirror authentic STEM as practiced by professionals. However, it is less intuitive what an authentic, inclusive STEM learning experience (AISLE) should look like or include. Over the course of 20 years, the Institute for Scientist & Engineer Educators (ISEE) has grappled with this question, developing and refining a framework of six key elements of authentic and inclusive STEM learning experiences. Here, we present this framework, which grew from an exploration of what "scientific inquiry" means in the context of teaching and learning, and expanded to include practices and norms that are valued in engineering fields. ISEE's framework is the cornerstone of its Professional Development Program (PDP), which trained early-career science and engineering professionals to teach STEM effectively, primarily at the college level, from 2001-2020. In addition to presenting the six elements of this framework, we describe how PDP participants implemented the elements, and we provide recommendations for putting the elements into practice through the design, teaching and assessment of STEM learning experiences.

Keywords: activity design, authentic STEM education, equity & inclusion, inquiry, professional development

1. Introduction

For over three decades, national calls for reform in science, technology, engineering, and mathematics (STEM) education have stressed the importance of providing classroom experiences that mirror the ways in which STEM disciplines are practiced by professionals. With goals that included improving science literacy in the U.S., major reports focused on teaching through "scientific inquiry" in K-12 settings (e.g., American Association for the Advancement of Science [AAAS] Project 2061, 1989; National Research Council [NRC], 1996, 2000). These reports advocated for a shift away from presenting STEM topics as collections of facts to be memorized, as well as a shift away from teaching STEM experimentation and innovation processes as lists of prescribed steps to be undertaken in a specific order. Instead, these reports encouraged active engagement of learners' curiosity and creativity.

Further reports focused on making improvements to *undergraduate*-level teaching and learning as a means of increasing equitable access to STEM education and careers in the U.S. and bolstering the STEM workforce (e.g., Project Kaleidoscope, 2006; President's Council of Advisors on Science and Technology, 2012; National Academies of Science, Engineering, and Medicine, 2017). These reports emphasized not only scientific inquiry, but also the importance of discovery-based research and research-like experiences in undergraduate STEM education.

Many of these reports influenced the Professional Development Program (PDP; Hunter et al., 2010), which we developed and ran from 2001 through 2020, first through the Center for Adaptive Optics (2001-2010) and later through the Institute for Scientist & Engineer Educators (2010-2020). Through the PDP, we trained future educators of STEM undergraduates and professionals; most PDP participants were graduate students and postdoctoral researchers in science and engineering fields. Over the course of 20 years, we trained over 600 participants, many of whom returned for multiple years of PDP training. A major theme of ISEE's programs, including the PDP, was "inquiry". PDP training included multiple intensive workshops in which participants experienced one of two "model" inquiry activities as learners, and then reflected on the design and implementation of those activities. PDP participants were then supported in designing an inquiry activity of their own in collaboration with a small team of fellow participants. This was followed by a practical teaching experience in which PDP participants taught their activity with their team and assessed their learners. Finally, PDP teams debriefed their experience together, reflecting on what they gained.

We developed the PDP's first model inquiry activity with expertise and collaboration from members of the Exploratorium's Institute for Inquiry[1]. In this model inquiry activity, learners (in this case, PDP participants) observed puzzling phenomena involving light sources and shadows. They generated questions about the phenomena, designed and conducted experiments to explore answers to their questions, and presented their findings about the nature of light to a larger group of participants. To complement this science-based activity, we later developed a second, engineering-oriented inquiry activity based on an activity that had been designed by PDP participants (Morzinski et al., 2010). In this second activity, PDP participants brainstormed goals a scientist might have for imaging a range of phenomena, such as features of a hurricane or aspects of a sunspot. Then they designed solutions — optimal methods of sampling images of those phenomena — to meet the requirements needed for their science goal. Toward the end of the activity, they presented their sampling solutions to other participants. Each of these activities ended with a "synthesis" in which instructors summarized the STEM content learning outcome of the activity as well as

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[1] https://www.exploratorium.edu/education/ifi

the primary STEM practice (e.g., designing scientific investigations or defining requirements of an engineering solution) that learners were expected to learn more deeply through the activity. During the syntheses, instructors referred directly to learners' findings and accomplishments with respect to the main content and practice goals of the activities.

These activities involved PDP participants in the process of learning new concepts through scientific inquiry and engineering design (which we also called "inquiry" in the PDP community). However, they were just two examples of inquiry activities. As we supported PDP participants' creativity in designing their own activities, we found that we needed a clearer description of what an inquiry activity should look like or include. Descriptions of inquiry in the literature were not necessarily aligned, nor did they provide concrete guidance on how to implement inquiry in the classroom. Some descriptions of inquiry emphasized asking questions (e.g., describing inquiry as a process that involves "inquisitiveness" and "curiosity"; NRC, 2000). Some descriptions highlighted the importance of the processes or practices of STEM in inquiry, e.g., describing STEM disciplines as "ways of thinking and doing, as well as bodies of knowledge" (AAAS Project 2061, 1989). One study emphasized learner ownership, analyzing how much or little guidance was given to learners as they engaged in STEM practices through inquiry activities (Buck et al., 2008). All of these ideas (and more) seemed important.

Adding further complexity to the challenge of designing an inquiry activity was the PDP community's growing focus on assessment-driven activity design. This approach draws from Wiggins & McTighe's (2005) "backward design" process and involves first articulating desired learning goals, then defining acceptable evidence that learners have reached those goals, next considering how that evidence will be elicited, and finally designing instruction. Our community was interested in assessing learners' understanding of STEM concepts as well as their proficiency with STEM practices, and integrating opportunities for assessment into the activities they designed.

To help PDP participants navigate multiple definitions of inquiry and the challenge of implementing these ideas through an assessment-driven activity design process, we developed our own framework to describe what a PDP STEM learning experience should include. Our goals were to support PDP participants in designing *authentic* STEM learning experiences that parallel the ways in which STEM professionals practice their disciplines, and *inclusive* STEM learning experiences that engage learners of all backgrounds. We expanded our framework to go beyond the term "inquiry", which can be seen as science oriented, to encompass the norms and practices of other STEM fields such as engineering. We acknowledge that within the PDP community, the term "inquiry" is still used widely and is applied to engineering as well as science. (This can be seen in other papers in this collection.) However, we now use the phrase "authentic and inclusive STEM learning experience" to describe the kind of activity PDP community members were trained to design and teach.

Our framework comprises six key elements of authentic, inclusive STEM learning experiences (AISLEs). In a well-designed and well-taught AISLE, learners will:

- Element 1: Learn challenging aspects of a specific STEM practice
- Element 2: Learn challenging aspects of a specific STEM concept
- Element 3: Use STEM practices and concepts in an interdependent way
- Element 4: Generate and use evidence to support STEM ideas and actions
- Element 5: Exercise agency in learning and applying STEM concepts and practices

- Element 6: Productively participate with peers in the social aspects of doing STEM and constructing new STEM understandings

These six elements were developed and refined over two decades, drawing from research as well as from our expertise as professional developers, scientists, engineers, and educators. These elements were put into practice year after year: we used them to guide PDP participants' design and teaching of STEM learning activities, and their assessment of learners. We emphasize that our framework was developed and refined in large part *through practice*, as opposed to being an entirely theory-based framework, which must then be adapted by practitioners.

In Section 2 below, we describe each of the six elements in our framework, including how they overlap with research on inquiry, authentic STEM, inclusive STEM, and positive outcomes for learners. We describe how PDP participants have implemented the six elements and give recommendations for putting the elements into practice. Then, in Section 3, we describe in more concrete terms how educators can incorporate the six elements of our framework into the design of a STEM activity, using an assessment-driven approach. We elaborate on considerations for designing both content-based and practice-based learning outcomes for an activity and designing associated rubrics. We then outline a loose activity structure and recommend an order in which to design the components of an authentic, inclusive STEM learning experience.

2. ISEE's framework of six elements for AISLEs

2.1 Element 1: Learning challenging aspects of a specific STEM practice

Within ISEE and the PDP community, we use the phrase "cognitive STEM practices", or more simply "STEM practices", to describe the reasoning processes that scientists and engineers use to understand the natural world and to solve problems. Examples of foundational, or "core", practices include: generating explanations or designing experiments in science, and defining requirements in engineering. Further discussion of core practices in both science and engineering, including an acknowledgment that scientists and engineers may engage in these practices interchangeably, is provided in Section 3.2 below.

Practices, which in the literature are sometimes called processes, competencies, or reasoning skills, are emphasized in essentially all STEM education standards. For example, the Next Generation Science Standards (NRC, 2013) call for the integration of eight core practices in K-12 science curriculum (see Box 1 for a description of the importance of practices in science). Learning STEM practices is increasingly a key component of undergraduate-level standards, as well. For example, in biology, "applying the process of science" is a core competency expected of all biology undergraduates (AAAS and National Science Foundation, 2011) and is considered foundational for future physicians (American Association of Medical Colleges and the Howard Hughes Medical Institute, 2009). Learning STEM practices may enhance the performance of underrepresented minorities in STEM undergraduate programs (e.g., Dirks & Cunningham, 2006) and has been shown to positively affect undergraduates' STEM identity, motivation, and achievement (e.g., Hazari et al., 2010; Starr et al., 2020). Practices are also highly valued in the STEM workforce because they enable individuals to become more independent investigators and problem solvers (Seagroves & Hunter, 2010).

Box 1: Understanding how scientists work

The idea of science as a set of practices has emerged from the work of historians, philosophers, psychologists, and sociologists over the past 60 years. This work illuminates how science is actually done, both in the short term (e.g., studies of activity in a particular laboratory or program) and historically (studies of laboratory notebooks, published texts, eyewitness accounts). Seeing science as a set of practices shows that theory development, reasoning, and testing are components of a larger ensemble of activities that includes networks of participants and institutions, specialized ways of talking and writing, the development of models to represent systems or phenomena, the making of predictive inferences, construction of appropriate instrumentation, and testing of hypotheses by experiment or observation.

…a focus on practices (in the plural) avoids the mistaken impression that there is one distinctive approach common to all science—a single "scientific method"—or that uncertainty is a universal attribute of science. In reality, practicing scientists employ a broad spectrum of methods, and although science involves many areas of uncertainty as knowledge is developed, there are now many aspects of scientific knowledge that are so well established as to be unquestioned foundations of the culture and its technologies. It is only through engagement in the practices that students can recognize how such knowledge comes about and why some parts of scientific theory are more firmly established than others.

Excerpted from NRC (2012), pp. 43-44; see also references therein

Practices are difficult to teach, and are rarely taught formally in the classroom. A well-designed STEM learning activity may engage learners in many STEM practices, but within the PDP, we advocated for an explicit focus on teaching and learning one core practice in particular. That is, PDP participants did not attempt to teach in depth about generating research questions, designing experiments, and explaining results all in one six-hour lab. While learners might engage in each of these practices in a PDP-designed activity, a PDP team would choose one core practice to focus more attention on in terms of teaching and assessing learners. This core practice might be particularly important and relevant to the disciplinary area of their activity, while also being transferable to other contexts. The team would delineate challenging aspects of the practice, often drawing from education research to do so. They designed their activity to provide opportunities for learners to engage in and receive feedback on those specific aspects of the practice.

We strongly encouraged PDP participants to round out a STEM learning activity with a component in which learners reflected on their understanding of the core practice that the activity focused on. In that component, learners could reflect on how they used the practice during the activity, what they learned about it and/or might still need to learn, and how they could apply the practice in different contexts. This required that learners disentangle the practice from the content or concepts that they learned, so that they could identify the generalizable aspects of the practice they engaged in, which they could apply beyond the activity — to other content, for example. For this reason, we made sure that PDP participants could also disentangle content from practices, so that they in turn could support their learners.

2.1.1 Recommendations for putting Element 1 into practice

Learning challenging aspects of a specific STEM practice can be supported by designing and teaching learning experiences in which learners:

- Perform challenging aspects of one core STEM practice, rather than simple aspects of multiple core practices
- Practice, get feedback, and reflect on aspects of the STEM practice in a way that separates the practice from content and is generalizable to other contexts (such as other content)

2.2 Element 2: Learning challenging aspects of a specific STEM concept

All STEM fields have core, or foundational, concepts — concepts that have broad explanatory power, or can explain many phenomena, and are tied to “big ideas”. In the K-12 arena, the Next Generation Science Standards (NRC, 2013) are intended to guide science curriculum nationally. These standards include both content and practices, and identify core concepts that apply to multiple STEM disciplines. Examples include the concept of natural selection in life sciences, and the concept of conservation of energy in physical sciences. In higher education, there has also been an increasing movement to establish “standards”, which delineate the core concepts learners are expected to understand as a result of their coursework. For example, five core concepts in undergraduate biology have been published as a result of a long process of building consensus from faculty members across the country (AAAS and National Science Foundation, 2011; see Box 2). These core concepts are intended to be used to establish learning outcomes for courses, and also to tie “units” of study within a course (such as activities designed by PDP teams, or AISLEs more generally) to a larger framework of important concepts. This can be achieved through a flow-down from course learning outcomes to activity-level learning outcomes.

In the PDP, the starting point for designing a learning activity was for participants to identify a core concept that they would teach their learners. Participants considered what it would mean for learners to demonstrate a deep understanding of the concept – an understanding that would allow them to apply the concept in a new context. From years of experience, PDP developers identified that the most important part of establishing a content goal was the careful articulation of an “assessment prompt” (also see Section 3.1). PDP participants then created a series of activity components that mirrored authentic research and innovation environments, in which their learners could use the concepts to explain a phenomenon, make a prediction, or design and/or support a solution. They planned for the varied amount of experience their learners might have with the concept, anticipating potential misconceptions and/or non-intuitive aspects of the concept that might be challenging for learners. PDP teams then prepared to facilitate learning as learners constructed their own ways of understanding the concept.

2.2.1 Recommendations for putting Element 2 into practice

Learning challenging aspects of a specific STEM concept can be supported by designing and teaching learning experiences in which learners:

- Gain an understanding of challenging and assessable aspects of one core STEM concept
- Gain an understanding of specific aspects of a core STEM concept that may be applied to different contexts
- Use this core STEM concept in a setting that mirrors an authentic scientific or engineering situation

Box 2: Core concepts to guide undergraduate biology education

Participants in the Vision and Change in Undergraduate Biology Education national conference in 2009 *agreed that all undergraduates should develop a basic understanding of the following core concepts*:

- *Evolution*
- *Structure and function*
- *Information flow, exchange, and storage*
- *Pathways and transformations of energy and matter*
- *Systems*

Excerpt in italics from AAAS and National Science Foundation, 2011, pp. 12-14. See the report for a full description of each concept.

2.3 Element 3: Using STEM practices and concepts in an interdependent way

In ISEE's definition of AISLEs, learners' engagement in cognitive STEM practices is motivated by conceptual understandings, and vice versa – core concepts are learned by using STEM practices. Teasing apart content and practices (as described above) is an important part of teaching and assessing STEM. However, in the actual learning experience, they are interwoven. As in authentic scientific research or engineering innovation, STEM practices are employed in order to learn or design something.

The intertwining of content and practice learning is an important element of effective teaching. Some studies (e.g., Norman & Schmidt, 1992; Kvam, 2000) have demonstrated that engagement in "active" and "problem-based" learning can enhance long-term retention. Furthermore, instructional strategies that involve learners in collaborative projects and STEM practices can improve learners' motivation, self-direction, and their ability to transfer concepts to new problems.

Within the PDP, we defined several points in a learning experience that are key to weaving together content and practices. A well-designed activity starts with a component in which learners raise "how" or "why" questions that are related to a core concept and that can be further addressed by engaging in STEM practices. Learners then investigate or design something in order to explore an answer to their question or a solution to the problem they defined. This investigation or design process allows them to learn about and apply the core concept. Finally, learners explain what they found out through their investigation or design. Content and practices are woven together throughout an activity designed in this way, and the three main phases of the activity (raising questions, investigation, explanation of new results or understandings) are linked. See Section 3.3 below for further recommendations on how to structure an AISLE.

2.3.1 Recommendations for putting Element 3 into practice

Using STEM practices and concepts in an interdependent way can be supported by designing and teaching learning experiences in which learners:

- Raise questions that are related to concepts (from Element 2) that they later explore or apply
- Use STEM practices (the core STEM practice from Element 1 as well as other practices) to come to their own understanding of the content that relates to their question
- Explain their findings or solution using their understanding of the content, rather than simply restating the content

2.4 Element 4: Generating and using evidence to support STEM ideas and actions

Supporting one's findings or solutions with evidence is at the heart of science and engineering. Scientists use evidence and reasoning to generate explanations of natural phenomena, and engineers use evidence to support design choices. Constructing evidence-based explanations (or "arguments") is part of formal scientific communication, as well as part of the informal daily practices of professional scientists and engineers. They use evidence to make sense of things, justify their actions, and persuade others about the importance of their results.

The process of using evidence to support explanations is particularly important because explanation plays a major role in constructing new scientific knowledge (see, e.g., Knorr Cetina, 1999). Some studies (e.g., Nussbaum et al., 2008) have found that teaching students about explaining can improve their ability to learn science. Furthermore, the social aspect of talking with others to build understanding together has long been known to be an important aspect of the learning process (Vygotsky, 1978; this is also relevant to Element 6 described below).

In a well-designed STEM learning activity, learners work with existing data, materials, or simulations, or generate their own. They decide how to use this information as evidence as they develop a new scientific understanding or engineering solution. For example, learners may need to analyze data, weight measurements, and/or determine errors. They use this as evidence to justify their choices as they investigate phenomena or design solutions. Learners then decide how to convey this evidence as they share their new understandings with others via explanation.

In a learning activity designed by PDP participants, learners would be encouraged to go beyond simply noticing a data trend and instead construct an understanding of what the trend implies or why it may have arisen. In engineering contexts, learners would justify their design choices rather than simply “guessing and checking” possible solutions. Each activity designed by PDP participants offered an opportunity for learners to explain their new understandings in a culminating task in which learners used evidence to justify their findings (e.g., reporting findings through a poster presentation or a written abstract; this is also relevant to Element 6 described below).

2.4.1 Recommendations for putting Element 4 into practice

Generating and using evidence to support STEM ideas and actions can be supported by designing and teaching learning experiences in which learners:

- Generate their own evidence and/or define what counts as evidence
- Use their own evidence to support an explanation of their new understandings

2.5 Element 5: Exercising agency in learning and applying STEM concepts and practices

Learner agency is a key aspect of authentic STEM learning experiences and has been linked to many positive outcomes in terms of learners’ grades, motivation, and enjoyment of STEM activities (e.g., Black & Deci, 2000). Definitions of learner agency vary, but a definition that aligns well within the PDP community is “students’ capacity to act in ways that exhibit their own choices in their learning, informed by their beliefs and careful consideration, self-regulation, and self-reflection about their ability to control and take ownership of their own learning” (Moses et al., 2020). Studies have found benefits to instruction that provides some structure yet still allows students to act autonomously and self-regulate (Rainer & Matthews, 2002). This matches what the PDP community learned through years of practice. That is, instructors can have specific goals while still providing a learning experience in which learners exercise agency. The PDP community considered the ways in which an activity is designed as well as the moment-to-moment interactions between instructors and learners during teaching (facilitation), often considering ownership, and the extent to which learners had choice in how they worked through challenging aspects of the activity.

Creating STEM learning activities that provide learners with opportunities to exercise agency is challenging, and instructors generally have limited or no models to draw from. There is a long history of teaching “cookbook”-style lab activities, in which learners are given step-by-step instructions; these types of activities continue to dominate lab experiences. For example, Buck et al. (2008) examined the amount of self-direction learners had over “characteristics of inquiry” in 386 laboratory activities, many of which were self-described as “inquiry-based”. Buck et al. analyzed how these activities engaged learners in STEM practices such as raising questions or conducting investigations. They found that most of the activities they analyzed were heavily guided, rather than allowing learners to make choices about how to proceed.

Science curricula also commonly incorporate STEM practices in such a simplified way that they do not provide an opportunity for learners to exercise agency in an impactful way. Relevant to Element 1, Chinn and Malhotra (2002) examined how learners were engaged in STEM practices in a large sample of science curricula, and found that most curricula do not engage students in authentic STEM practices, but rather "simple tasks" (see further discussion of this in Section 3.2.2 below). Finally, agency can be constrained by imposed structures, such as norms of the learning environment and instructor-learner power dynamics. Significant research has been done in K-12 settings that illuminates power dynamics between instructors and learners, and how actions by teachers maintain authority relationships that constrain learner agency (e.g., Hogan, 2002; Reinsvold & Cochran, 2012).

In designing for learner agency, PDP participants were encouraged to focus on the STEM practice and the STEM concept that their activity emphasized. PDP participants considered ownership in relation to their learners' use of the core STEM practice, including how challenging it would be, and whether their learners would have choices to make as they performed the practice. For example, for the STEM practice "using evidence in explanations," determining what makes appropriate and sufficient evidence to support an explanation is an opportunity for learner agency. To leverage this, an activity can be carefully designed so that learners must decide amongst multiple good possibilities for evidence and multiple reasonable explanations.

The PDP's focus on learner agency in relation to performing STEM practices aligns with research related to self-determination theory. For example, Stefanou et al. (2004) studied the kinds of choices students are provided with in classroom activities. Their study showed that instructors need to go beyond allowing students to make organizational choices (e.g., choosing roles of group members) or procedural choices (e.g., choosing materials) to give students "cognitive autonomy," such as choosing their own approach to a problem or finding multiple solutions. Equally important in the PDP was designing activities in such a way that learners came to their own understanding of the core concept and developed the empowering feeling of "I figured it out myself." A significant amount of effort in the PDP went to training participants to design ways for learners to ask their own questions related to the content goal, figure out a way to investigate their question, and come up with their own way to explain their findings.

In addition to using an agency lens to design the structure of an activity, the PDP community considered the moment-to-moment interactions between instructors and learners ("facilitation"), and how they impact learners' agency. There have been many studies analyzing teacher discourse practices such as verbal prompts, guiding cues, and follow-up questions, which have linked these practices to improved content understanding and engagement in STEM practices (e.g., McNeill, 2009). For example, McNeill analyzed videotaped lessons and found that the highest performing classrooms were those in which students were given more authority and independence through teacher discourse. Black & Deci (2000) studied undergraduate organic chemistry courses and measured students' perception of their instructor's facilitation, finding that students' perceived autonomy (e.g., "I feel that my instructor provides me some options and choices" or "My instructor listens to how I would like to do things") was significantly correlated with average course grade as well as students' interest and enjoyment in the class. In a study of undergraduates in research experiences, Ball (2009) recorded and analyzed hundreds of hours of interactions between mentors and interns, and found a correlation between discourse patterns of mentors and instances of reasoning and self-initiative taken by the interns. For example, when mentors' discourse positioned the mentor as the expert "knower", intern self-initiative was constrained; however, when mentors' discourse positioned mentor and intern as co-investigators, intern self-initiative was promoted.

PDP participants read about and discussed research such the studies described above, analyzed vignettes (see example vignette and discussion of facilitation strategies in Ball et al., 2022), and had an extended opportunity to facilitate learning in their practical teaching experience. This aspect of the PDP was an eye-opener for many participants, who often found it took great control to avoid giving direct answers or step-by-step instructions, which learners are used to and expect. A much more thorough description of facilitation training in the PDP is provided in Kluger-Bell et al., 2022.

2.5.1 Recommendations for putting Element 5 into practice

Exercising agency in learning and applying STEM concepts and practices can be supported by designing and teaching learning experiences in which learners:

- Ask their own questions about given phenomena and/or define problems to be solved
- Have choice in how to investigate their own question and/or design their own solution
- Make choices about how to use challenging aspects of STEM practices
- Come to their own understanding of content
- Have choice in how they explain their findings

2.6 Element 6: Productively participating with peers in the social aspects of doing STEM and constructing new STEM understandings

An authentic and inclusive STEM learning experience not only provides opportunities for learners to assert ownership and agency as individuals, but also gives learners practice with the *social* norms, values, and ways of thinking that are prevalent in STEM. Well-designed STEM learning activities mirror the ways that knowledge is collaboratively generated and revised in the professional environment. For example, a learning activity on marine ecology could focus on the practice of generating a scientific explanation (relevant to Element 1), giving students experience with using the particular types of evidence used to support explanations in this field (Element 4). The activity could also include a discussion of the norms for giving feedback or asking questions during presentations in this field. Furthermore, the activity could give learners practice with presenting their findings and giving each other feedback in a context that parallels how this is done in professional settings.

In the PDP, participants designed learning activities in which learners co-constructed knowledge. Learners worked together in small teams that enabled collaborative exploration, similar to professional STEM teamwork. PDP participants assessed their learners by requiring learners to share their findings in ways that aligned with the ways in which STEM professionals share their knowledge and innovations. For example, learners in a PDP-designed activity might present their new content understandings via poster presentations rather than by filling in a worksheet.

Learners benefit from working together, building on each other's ideas, and being acknowledged for their contributions (just as professionals do), in part because these activities provide opportunities for recognition. Carlone & Johnson's (2007) research showed that recognition by others has a particularly strong influence on learners' science identity (whether they see themselves as a "science person"). Furthermore, science identity and engineering identity have been linked to learners' interest in science and engineering careers, respectively (e.g., Hazari et al. 2010, Godwin et al. 2016). Starr et al. (2020) found that recognition may be especially important for learners who belong to groups that have historically been marginalized in STEM. Furthermore, Starr et al. found that peer recognition had at least as strong an effect as recognition from instructors on learners' STEM identities. Giving learners experience with both the formal and informal social interactions that are common in STEM is therefore an important aspect of authentic and inclusive STEM learning activities.

2.6.1 Recommendations for putting Element 6 into practice

Productively participating with peers in the social aspects of doing STEM and constructing new understanding can be supported by designing and teaching learning experiences in which learners:

- Contribute, explain and justify their ideas to peers
- Explain their findings in a way that is similar to authentic STEM reporting
- Perceive that they are working in much the same way that STEM professionals do
- Have opportunities to get recognition from both peers and instructors for their contributions

3. Incorporating the framework into assessment-driven activity design

In this section, we describe how educators can use an assessment-driven approach to weave the six elements of AISLEs into a STEM learning activity. The activity design method that we trained PDP teams to use, which began with articulating learning outcomes, is used here as a model. Below, we discuss how to design content learning outcomes and practice learning outcomes, and then we describe a loose activity structure that can incorporate the six elements, and finally we outline a recommended approach for designing a complete AISLE.

3.1. Articulating content learning outcomes

In ISEE's definition, a well-designed STEM learning activity has an intended learning outcome that includes (or is part of) a core concept. From many years of experience, the PDP community learned that the most effective driver of activity design is an "assessment prompt" that elicits learners' understanding of the core concept (Hunter et al., 2022). This "assessment prompt" is delivered near the end of activity, during the Culminating Assessment Task (see Section 3.3). It is crafted in such a way that learners will need to explain a phenomenon or to design an engineering solution *using* the core concept. For example, the assessment prompts for the activities described in Section 1 were:

- Use the ray nature of light to explain the phenomena you investigated. Use evidence from your investigation to support your explanation.
- Explain how to determine the design specifications that adequately sample a signal. Support this explanation with an example of your team's goal, requirements, and specifications.

Carefully crafting an assessment prompt and corresponding rubric (in addition to crafting a practice goal and rubric, discussed in Section 3.2) is the first step in designing the activity itself.

3.1.1 Challenging aspects of core concepts

Identifying a core concept, and what it looks like when a learner understands it, is challenging for all educators. However, there are many helpful resources on this front. There is a significant body of research on how learners gain deep understanding of challenging STEM concepts, for example through a developmental process of "conceptual change" (e.g., Posner et al., 1982; Duit & Treagust, 2003) over the course of an individual person's lifetime. Some schools of thought focus attention on "misconceptions" or "alternative conceptions." A newer theoretical perspective includes the identification of "threshold concepts" that, once understood, transform perception of a given subject. Some threshold concepts overlap with "troublesome knowledge" that may be counterintuitive or particularly difficult to master. An instructor can look to both threshold concepts and troublesome concepts to identify what a curriculum should focus on (Meyer & Land, 2003).

There is also rapidly growing research that combines knowledge about teaching and learning in general with discipline-specific knowledge, through Discipline-Based Education Research (DBER; see for example NRC, 2012). For example, one study surveyed 75 faculty members and 50 undergraduates to identify core concepts in biochemistry and the particular difficulties that students have in understanding them (Loertscher et al., 2012; see Box 3). Many researchers have also developed "concept inventories" — validated tests that are typically a set of multiple choice questions with one correct answer and several incorrect answers that are based on common misconceptions ("distractors").

The limited time period of PDP training excluded the possibility of discussing learning theory around conceptual understanding in detail. However, we encourage STEM educators to explore this literature, as they may find it very useful in identifying concepts that make appropriate learning goals. Scanning the literature for misconceptions, alternative conceptions, troublesome knowledge, etc., can also be very helpful in identifying when a learner understands a concept versus when the learner has not yet achieved understanding.

Before beginning to design the structure of their activity, each PDP team was charged with identifying aspects or "components" of the core concept that learners could develop understanding of. PDP teams worked with these aspects to develop dimensions (sometimes called criteria) of a rubric. Furthermore, they were expected to identify what would count as evidence that a learner understood (or did not yet understand) each aspect of the concept. Having done this, PDP teams could then develop quality definitions (levels of understanding or achievement) for their rubrics, and generate examples of what student work (or "artifacts") might look like. Investing significant time in iterating on an assessment prompt, rubric, and example artifacts positioned PDP participants to efficiently move forward with designing their activity. This prepared them to assess their learners' understandings, and plan for ways to facilitate learners through challenges or misconceptions.

Box 3: Difficulties students have related to core concepts in biochemistry

In a study involving 75 faculty members and 50 students, Loertscher et al. (2012) found common difficulties students have in learning core concepts in biochemistry. Some examples (p. 522-523) include:

- **Equilibrium:** challenges came "*largely from an everyday use of the term equilibrium to mean 'balanced' or 'just right'.*"
- **Intra- and Intermolecular Interactions:** "*Students could name the interactions, and some could discuss the role of polarizable electron clouds in these interactions, but they struggled to make generalizations about the electrostatic basis of the interactions.*"

3.2. Articulating practice learning outcomes

PDP teams were expected to articulate a practice learning outcome as well as a content learning outcome for their activity. They designed "practice rubrics" that would enable them to measure their learners' progress with the practice learning outcome. In designing practice rubrics, PDP teams also considered ways to elicit learners' understandings about the practice their activity focused on and/or learners' proficiency with the practice. The first step in this process required deciding on the core practice that the activity would focus on. Here we describe several considerations that are relevant to developing a practice learning outcome and rubric.

3.2.1 Core practices

There are a number of lists of "core", or foundational, STEM practices (e.g., NRC, 2013), and though there is some variation in these lists, there is also a great deal of overlap between them. Each of the lists shares a focus on STEM practices that are used across many disciplines and embody a set of skills that scientists and engineers build upon and become increasingly sophisticated with as they progress from novice to experts in their fields. For example, core science practices often include:

- Generating questions and/or hypotheses
- Designing investigations
- Generating explanations

“Using models” is broken out as a core practice by some, but in other cases it is described within the context of other core practices — for example, using models to design experiments, or using models to generate explanations.

Core engineering practices have also been identified in several lists (e.g., NRC, 2013), and include:

- Defining problems
- Brainstorming solutions
- Justifying solutions

As with science, there is variation and overlap between engineering practices. For example, “defining requirements” is an important engineering practice, which in some cases is considered an aspect of defining problems, and in other cases is broken out as a separate practice. A good argument can be made for either way of viewing this extremely important practice, which is a key part of engineering, but is less often considered a part of science.

In the PDP, the differentiation between science and engineering was made in relation to the sets of practices used, not which discipline one might be working within. We recognized that scientists regularly use engineering practices (whether or not they identify them as such) and engineers often use science practices. For this reason, all PDP participants were encouraged to develop ways of teaching both science and engineering practices in general, though they were expected to focus on one core practice when designing the practice learning outcome for their activity.

3.2.2 Core practices and authentic STEM

One study that influenced our focus on designing STEM activities with one specific core practice learning outcome, rather than several practice goals, is that of Chinn & Malhotra (2002), who examined how learners engaged in STEM practices in a large sample of science curricula. Most of the curricula Chinn & Malhotra reviewed engaged students in “simple tasks” rather than the more challenging aspects of STEM practices, which often involve decision-making. Chinn & Malhotra presented a framework that can be used to evaluate whether learners are engaged in “authentic” STEM practices, and provided a table that demonstrates a spectrum of authentic to simple tasks. We present a few highlights in Table 1, along with our own engineering-oriented example.

In our view, STEM learning activities with multiple practice goals for learners are more likely to engage learners in simple tasks, due to time or other constraints. By concentrating on one practice learning outcome, an educator can delve more deeply into challenging aspects of that practice, giving learners more authentic opportunities to engage in the practice, and generally more authentic experiences with STEM. We reiterate that we expect learners will perform several STEM practices in an authentic, inclusive STEM learning experience; however, focusing on having them learn one of these practices more deeply can be very effective.

Table 1: Engaging in simple versus authentic STEM practices. This table includes examples of specific aspects of core STEM practices as they are carried out in authentic contexts, versus the simple ways in which they are often carried out by students in classroom activities. Examples in italics have been excerpted from Table 1 in Chinn & Malhotra (2002), pp. 180-182. It should be noted that this table shows two ends of an authentic-to-simple spectrum, and that there is a continuum in between. See the full table in Chinn & Malhotra for further examples.

Aspect of practice	As used in authentic contexts	As used in simple context often experienced by students
Core practice: Designing experiments		
Controlling variables	• *Scientists often employ multiple controls* • *It can be difficult to determine what the controls should be or how to set them up*	• *There is a single control group* • *Students are usually told what variables to control for and/or how to set up a controlled experiment*
Planning measures	• *Scientists typically incorporate multiple measures of independent, intermediate, and dependent variables*	• *Students are told what to measure, and it is usually a single outcome variable*
Core practice: Generating explanations		
Transforming observations	• *Observations are often repeatedly transformed into other data formats*	• *Observations are seldom transformed into other data formats, except perhaps straightforward graphs*
Indirect reasoning	• *Observations are related to research question by complex chains of reasoning* • *Observed variables are not identical to the theoretical variables of interest*	• *Observations are straightforwardly related to research questions* • *Observed variables are the variables of interest*
Core practice: Analyzing tradeoffs		
Optimizing a system	• Requires developing a scientific understanding of system • Requires iterations of improving and re-characterizing • Requires providing reasoning / justification for new iterations • System variables/components are interdependent and not easily co-optimized, with complex tradeoffs	• System is treated as a “black box”, or science behind how the system works is given • Procedure is given • A single system element or variable requires tuning to maximize performance, or at most two variables are easily co-optimized

3.2.3 Challenging aspects of core practices

Because STEM practices are not often formally taught, it is not necessarily easy for scientists and engineers to articulate what they are doing when they engage in practices. Education researchers have made significant contributions to the teaching and learning of STEM practices in recent years. Many studies have focused on making specific aspects of core practices more explicit, so that both instructors and learners can talk about and apply practices in the learning environment. The list of authentic tasks involved in scientific practices provided by Chinn & Malhotra (2002; see Table 1) is relevant here.

As a more specific example focused on the practice of scientific explanation, we note that without identifying what makes a good scientific argument, it is very difficult to teach, learn, and assess scientific argumentation or explanation. A large body of work supports the idea of a scientific explanation including a claim, evidence, and reasoning (CER) — this has led to a "CER framework" (e.g., Sandoval & Reiser, 2004), which at various points was used in the PDP. A variation on the CER framework that has also been identified for assessing students' scientific understanding (Ryu & Sandoval, 2012) is shown in Box 4. Armed with the four criteria listed, it becomes much easier to teach and learn the practice of scientific argumentation. For example, an instructor could identify that a student does not have a coherent chain of inferences in their explanation of a phenomenon, and then find a way to help the student find and fill gaps in reasoning.

PDP participants worked with studies such as those by Ryu & Sandoval and Chinn & Malhotra to identify specific, challenging aspects of the core practice their activity focused on that could be observed and measured. This way, PDP participants were able to design dimensions of a rubric that could be used to assess learners' proficiency with the practice.

3.2.4 Learner difficulties with core practices

Another contribution that education researchers have made in relation to teaching and learning STEM practices is to identify the difficulties that students have with particular practices. For example, a number of researchers have identified difficulties that undergraduate students have with experimental design (e.g., Dasgupta et al., 2014; see Table 2). Though it is not a complete set of all aspects of designing an experiment, Dasgupta et al.'s list of specific elements of experimental design could be very useful in diagnosing student difficulties with this practice, and several of these aspects could be a valuable focus of a STEM learning activity.

Box 4: Four criteria for assessing students' understanding of scientific argumentation

1. *Causal structure: Science is aimed at understanding the causes of natural phenomena. Consequently, students have to understand that a scientific argument should contain causal claims.*
2. *Causal coherence: Many, if not most, scientific arguments advance chains or networks of causal inferences. These chains cohere into a sensible overarching narrative.*
3. *Citation of evidence: Claims are made about data; consequently, a good argument cites the data that claims are meant to explain.*
4. *Evidentiary justification: A crucial element of an argument is the asserted relationship between claims and evidence. Good arguments explicate and justify these relationships.*

Excerpted from Ryu and Sandoval (2012), p. 494

As another example, one ISEE study looked at difficulties that undergraduate students had as they completed a summer engineering project in an internship program (Arnberg, 2014; see Box 5). The practice of defining requirements was an ongoing challenge for the interns; this was made evident when they were asked to formally communicate the results of their projects. The ways in which interns presented their work and the content of their presentations indicated that they had challenges in clearly articulating design requirements, and this may have indicated gaps in their understanding of their projects at a deeper level.

PDP participants were encouraged to learn from studies like those above and also draw from their own experiences teaching and learning STEM practices as they considered difficulties learners might have with the STEM practice they were focusing on in their activity. By articulating not only important aspects of a particular STEM practice (which could form the dimensions or criteria of a rubric), but also what it might look like when learners have difficulties or challenges engaging in those aspects of the practice (which could help inform quality definitions or levels of understanding/achievement), a PDP team could further develop their rubric for

Table 2: Difficulties that undergraduate biology students have with experimental design. This table lists four areas of difficulty that undergraduate biology students have with experimental design, excerpted from Table 2 of Dasgupta et al. (2014), pp. 272-273. Some examples of evidence of difficulty are shown, numbered as they are listed in the original table (for brevity, we have not included every example). See the full table in this paper for more examples of difficulties as well as examples of correct application.

Areas of Difficulty	*Typical Evidence of Difficulty*
1. *Variable property of experimental subject*	*a. An experimental subject was considered to be a variable.* *c. Variable property of experimental subject considered is not consistent throughout a proposed experiment.*
2. *Manipulation of variables*	*b. Hypothesis does not clearly indicate the expected outcome to be measured from a proposed experiment* *e. Independent variables are applied haphazardly in scenarios when the combined effects of two independent variables are to be tested simultaneously.* *j. Experimental subjects carrying obvious differences are assigned to treatment vs. control group*
3. *Measurement of outcome*	*b. The treatment and outcome variables are reversed* *h. There is a mismatch between what the investigation claims to test and the outcome variable.*
4. *Accounting for variability*	*b. Criteria for* selecting *experimental subjects for treatment versus control group are biased and not uniform.* *d. Decisions to* assign *experimental subjects to treatment vs. control group are not random but biased for each group.*

measuring their learners' proficiency with the practice. Furthermore, they could plan ahead for how they might help their learners overcome those challenges.

3.2.5 Understandings about STEM practices

Teaching and learning STEM practices includes both doing the practice, and holding understandings about the practice. One study of the practice of "modeling" (Schwarz et al., 2009) points out that it is not only important for students to engage in the practice of modeling (e.g., incorporating evidence or theory into a representation, or using a representation to predict or explain something), but it is also important for learners to gain an understanding of how models are used (the contexts in which models are used, what the strengths and limitations of various models are, etc.). Schwartz et al. argue that the "doing" of the practice and the underlying knowledge about a practice should not be viewed as separate learning goals – it is the integration that creates a powerful and meaningful learning experience.

Within the PDP, we did not encourage participants to spend a lot of time disentangling the doing of practices from understandings about practices. However, as noted above in Section 2.1, we did encourage PDP participants to disentangle practices from content, and to design a component into their activity in which learners reflected on the practice and how it could be used in multiple contexts (for example, applied to different content).

Box 5: Difficulties with defining requirements of an engineering problem

From a study of college students doing engineering internships, Arnberg (2014) found:

> *This qualitative study identified three key challenges that engineering interns experienced when identifying functional requirements for their internship projects – identifying constraints as functional requirements, identifying non-functional requirements as functional requirements, and not stating functional requirements in a verifiable manner.* (p. 111)

Arnberg noted that interns often focused on factors that limited solutions (usually called constraints), often losing track of what the solution must do (functional requirements), and they often stated requirements in a way that was not verifiable (e.g., stating a requirement as "user friendly").

3.3. Designing an AISLE

After designing a practice learning outcome and a content learning outcome for a STEM learning activity, as well as associated practice and content rubrics, one can design the activity itself. We developed a specific approach to doing this, but first, it helps to provide an outline of what an AISLE could look like. Incorporating the six elements of our framework into the design of a learning activity requires much thought and intention. Through many years of experience supporting PDP participants as they designed hundreds of activities, ISEE has identified a loose structure of five activity components that can help educators incorporate the elements of our framework:

1. Introduction
2. Raising Questions
3. Investigation
4. Culminating Assessment Task
5. Synthesis

These components are based on the extensive work of the Exploratorium's Institute for Inquiry, and are not meant to be rigid or contrived. Rather, these activity components help to create a flow of tasks for learners, while providing windows through which thinking and learning can be made visible to both learners and instructors.

In an authentic and inclusive STEM learning experience, learners experience these activity components as follows:

1. Learners receive the general context and the overall goal of the activity in a way that will help them keep perspective on what they are doing and why, and sets them up for an experience in which they will *exercise agency* (Element 5) while also *productively participating with peers* (Element 6). Expectations of learners and instructors are set, especially as an activity in which learners have a great deal of responsibility for their own learning may feel uncomfortable or vastly different from typical learning experiences. This is the **Introduction**, which is brief, and very different than a "pre-lab lecture."
2. Learners encounter puzzling phenomena or challenging problems that stimulate them to ask questions in their own words about the content. They are encouraged to be curious, ask questions, and brainstorm, individually and collectively. This is the **Raising Questions** component of the activity, which launches learners into an experience in which *STEM content and practices are intertwined* (Element 3).
3. Learners *exercise agency* (Element 5) by choosing questions from the Raising Questions component — related to the content goal of the activity — to deeply investigate in small teams. They are empowered to *productively participate* (Element 6) with their peers as they make decisions with their teams about how to investigate the *content* (Element 2). They use many STEM practices, but get experience with, and feedback on, challenging aspects of *one core practice* (Element 1). Learners spend significant time in this **Investigation** component *generating evidence* (Element 4) to support possible explanations or design solutions.

4. After generating a lot of evidence and ideas, learners shift to *deciding what evidence from their investigation counts towards explaining a phenomenon or justifying a design* (Element 4). They move from gaining understanding to demonstrating their understanding of a concept in a task that *gives them practice with authentic social aspects of participating in STEM* (Element 6). They continue to learn as they present their work, engage in dialogue, and receive both feedback and recognition from peers and instructors. This is the **Culminating Assessment Task**.
5. Finally, the entire group comes together to reflect on the knowledge generated and processes used to generate it. Instructors *make connections to the core concept that learners learned* (Element 2) and the core practice they gained experience with (Element 1). Learners process what they accomplished and learned in a way that can be applied to different contexts. This final component of inquiry is referred to as the **Synthesis**.

From the learner's perspective, these activity components are not necessarily strictly separated and can sometimes overlap with each other. This list of components is not meant to be taught to learners, but instead is a professional development tool to help instructors design an AISLE. The components create a structure in which educators can integrate the elements of our framework in their own way. Though these activity components are not the only way to design an effective STEM learning activity, they have proven to be extremely useful to the PDP community.

3.3.1 An Assessment-Driven Approach

The PDP included many sessions and tools to help participants design their activities using an assessment-driven design approach, which are beyond the scope of this paper, but which are briefly described below (see fuller description in Hunter et al., 2022).

In order to follow an assessment-driven approach to designing an AISLE, we advocate for designing the Culminating Assessment Task early in the process. This activity component incorporates the assessment prompt (already carefully crafted; see Section 3.1 for more on assessment prompts) to create a way for learners to report on their findings. Examples of Culminating Assessment Tasks include poster presentations or a small group discussion in which learners report their findings as they would in a lab group meeting. Designing the task involves outlining the structure and timing of this part of the activity, as well as roles of instructors and peers. The Culminating Assessment Task is a good opportunity for learners to receive recognition for their contributions, but without careful design can inadvertently lead to disparities in who gets recognized.

Next, the Investigation component of the activity can be designed. At this stage, it is important to consider what kinds of investigations learners could engage in that would lead to an understanding of the content goal. Investigations should also lead directly to learners being able to complete the Culminating Assessment Task. (Note that the Culminating Assessment Task should not be a new application of content knowledge, but instead a sharing of how learners used the content to explain, design, or predict something during the Investigation.) A key part of designing the Investigation component is incorporating the core STEM practice in a way that will challenge learners and provide opportunities for learner agency in how to use the practice. Practical considerations come into play, as well, such as what data or equipment learners might need to access during their investigations, and what data or equipment should not be made available, e.g., due to safety issues or due to the fact that it might lead learners astray from the content of the activity. Allowing more than one possible investigation path that will lead to the desired content understanding is important for fostering learners' agency.

The next step is to design the Raising Questions component of the activity. Here, the activity designer considers how to elicit questions from learners that are relevant to the content they will investigate and, ideally, naturally lead into investigations. This can be done in many ways, such as demonstrating puzzling phenomena or design challenges to learners with physical materials, images, or data.

Lastly, the Introduction and Synthesis of the activity can be designed. While this design approach flows mostly backward through the activity, it is goal-driven, ensuring that the components of the activity are linked by the content and naturally flow toward the content goal. This method of designing an AISLE has been very successful in the PDP. Several AISLEs designed by PDP teams are highlighted in other papers in this collection.

Beyond designing an activity, preparing to teach the activity is also crucial. Preparing for the moment-to-moment interactions that facilitate learning is especially important. Although a discussion of facilitation is beyond the scope of this paper, Kluger-Bell et al. (2022, in this volume) present considerations including how to make learners' thinking accessible, how to help learners progress toward the learning outcomes of an activity while fostering agency, and how to support equitable and inclusive collaboration between learners. We recommend Kluger-Bell et al.'s paper for those who are interested in learning more about facilitation or how to train facilitators through professional development.

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