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Contextualizing and Integrating Practices: Reclaiming Authenticity Lost from Translating Workplace Engineering Practices into K-12 Standards

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Keywords

engineering practices, contextualization, NGSS, workplace, interviews, standards

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Contextualizing and Integrating Practices: Reclaiming Authenticity Lost from Translating Workplace Engineering Practices into K-12 Standards

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Abstract

K-12 students need to become familiar with engineering because 21st-century careers integrate engineering practices across all science, technology, engineering, and mathematics (STEM) fields. While the Next Generation Science Standards (NGSS) emphasize learning real science and engineering practices, further work is needed to authenticate engineering for K-12 education. The NGSS are presented in a way that merges a single general practice with a core disciplinary idea and cross-cutting concept. Based on this framing and underlying epistemology, NGSS engineering practices are often implemented as overgeneralized, isolated, and largely context-neutral. Yet, in the STEM workplace, practices are rarely done in isolation from one another. Research is needed to better understand the integrated use of NGSS practices in STEM workplaces in order to make these practices more visible and accessible for use in K-12 classrooms. We conducted semi-structured interviews with 22 entry-level employees and managers in STEM-intensive workplaces. Using emergent and *a priori* coding, we identified how NGSS practices and contextual features are situated and connected in the STEM workplace. Our findings suggest that by adding rich contextual features, practices become more interconnected and reflective of authentic engineering in the STEM workplace. This process will enable educators to interpret K-12 engineering standards in an authentic way that supports deep engagement in learning engineering.

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Introduction

To encourage students to consider engineering-related careers, they need to engage in K-12 learning experiences that reflect real-world engineering practices, thereby authentically introducing students to engineering as a discipline. The Next Generation Science Standards (NGSS) were designed to integrate knowledge and practices of science and engineering, but presently, the structure and content of NGSS engineering practices do not adequately reflect workplace practices.

The NGSS were organized to connect learning across science and engineering practices, disciplinary core ideas, and cross-cutting themes through a multidimensional framework (NGSS Lead States, 2013; Tekkumru-Kisa et al., 2015). In addition, NGSS provides the groundwork for enabling students to learn core disciplinary ideas that reflect complex learning progressions and follow students' conceptual development and changes in thinking over time (Manz, 2014; Schwarz, 2009). Although the NGSS framework defines science and engineering practices that are important for students to learn, they do

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not specify meaningful contexts (not intrinsic to the practices) for instruction that reflect authentic use in research and industry (Ford, 2015). This ambiguity can lead to the practices being interpreted as oversimplified individual actions for students to do in order to learn a particular core disciplinary idea, making the practice seem like rote performance as a means to attain skills (Windschitl et al., 2007). Like the scientific method in K-12 instruction, such oversimplification risks making it difficult for students to (1) recognize differences between school science and engineering focused on learning and authentic practice, (2) develop science, technology, engineering, and mathematics (STEM) identities, and (3) foster an interest in STEM careers (Berland et al., 2016).

The NGSS were the first national standards to integrate engineering education at the K-12 level and it is especially important to consider what practices NGSS constitute as engineering and where these practices fall short. This paper explores what is lost when translating real-world STEM practices into K-12 standards and provides suggestions for how standards can be interpreted and applied in more authentic ways to better reflect STEM workplaces. We will present NGSS practices and other researchers' critiques, explore NGSS practices as they are experienced by scientists and engineers in authentic workplace settings, and analyze the ways these practices are integrated and contextualized. To do this, we posed the following research questions: (1) In what ways are NGSS science and engineering practices situated in the STEM workplace? (2) How are NGSS science and engineering practices connected and reified within STEM workplace contexts? Our findings illustrate what is lost when translating real-world STEM practices into K-12 standards by highlighting their use in the STEM workplace and integration within rich contexts.

Need for Authentic Engineering Experiences

Research suggests a myriad of benefits from students at all levels engaging with authentic practices because they reflect the way science and engineering are experienced in professional workplace settings (Pleasants & Olson, 2019; Strobel et al, 2013). Our definition of authenticity integrates the complexity in cognitive reasoning reflected in work that real scientists and engineers do (Chinn & Malhotra, 2002), while acknowledging that such reasoning becomes complex largely because the work is situated in authentic contexts (real-world or future professional situations), tasks, impact, and/or personal value (Lottero-Perdue & Brickhouse, 2002; Strobel et al., 2013). Students who engaged in scientific practices that are linked to authentic problem-based science reasoning developed more advanced investigation, analysis, sophisticated mathematical models, argumentation skills, as well as epistemological beliefs about science and engineering (Kuhn et al., 2017; Langman et al., 2019). In addition, when students participated in authentic practice through citizen science and student-driven science fair projects, they felt like they became part of a scientific community, fostering inclusion and persistence in STEM (Koomen et al., 2018). After working in authentic science and engineering partnerships, students also found that science was more accessible to them as a future career (Olitsky et al., 2018; Strobel et al., 2013).

Benefits to authentic science and engineering are essential for post-secondary learning as well. For college engineering majors, cooperative learning opportunities (co-ops) provide work experiences that tie into degree programs and also show a variety of benefits for students including skill development, improved interest, better content knowledge, and higher starting salaries upon employment (Kotys-Schwartz et al., 2011). Additional opportunities for learning that connect workplace practices to education include capstone projects, undergraduate research, competition teams, and field trips, among others (Kotys-Schwartz et al., 2011). There are many efforts to introduce authentic engineering experiences prior to post-secondary so that more students can develop a foundation and interest in engineering-related careers (e.g., Kilgore et al., 2007; Lachapelle & Cunningham, 2014; Langman et al., 2019). To improve access and equity to authentic engineering practices for all ages, it is essential that standards are presented in a way that they can be taken up by teachers to support authentic learning in K-12 settings.

Background on K-12 Engineering Standards

Researchers have been exploring ways to effectively teach science and engineering as proposed in the Framework for K-12 Science Education and the NGSS (National Research Council, 2012). For example, extensive research on modeling and argumentation provides guidance for teaching in ways that are authentic while still supporting student learning (e.g., Bricker & Bell, 2008; Etkina et al., 2006; Hestenes, 1987; Zwickl et al., 2015). Research has also explored connections across the dimensions of NGSS (Edelson, 2001; Fick, 2018); yet, much of this research focuses on a single practice in classroom contexts rather than the intersections of practices with other practices reflective of authentic contexts outside the classroom. While we recognize the importance of science and engineering instruction across the three dimensions of NGSS and that each dimension is rarely separated from others, we focus this investigation on descriptions within and between science and engineering practices as this area has been understudied, especially for engineering.

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Within the Framework for K-12 Science Education (National Research Council, 2012), scientific practices and corresponding engineering practices are described as: (1) asking questions; (2) developing and using models; (3) planning and carrying out investigations; (4) analyzing and interpreting data; (5) using mathematics and computational thinking; (6) constructing explanations; (7) engaging in argument from evidence; and (8) obtaining, evaluating, and communicating information. The NGSS present engineering practices in line with each of the above scientific practices; though the relationship between science and engineering is complex and varied (Purzer et al., 2015). For example, asking questions in science aligns with defining problems for engineering though these may be used in different ways. For example, students may ask questions about why light bends in certain materials or define a problem of how to bend light to improve an optical device like a camera lens or telescope. Engineering was included in NGSS for two important reasons: to reflect aspects of the world created by humans and also as a way to better integrate engineering and technology with science (National Research Council, 2012). Our coding scheme (discussed in the methodology section) articulates descriptions for each NGSS practice as it is used for both science and engineering, based on the NGSS Lead States, Appendix F of the NGSS (NGSS Lead States, 2013), and the National Research Council (2012) since this is how the practices are typically presented to teachers.

Recently, Advancing Excellence in P-12 Engineering Education (AE3) and the American Society for Engineering Education (ASEE) developed the Framework for P-12 Engineering Learning to enhance the quality of P-12 engineering education nationally (Strimel et al., 2021). Many of the concerns that researchers noticed regarding the NGSS engineering practices are addressed in this new framework. Like the NGSS, the P-12 engineering framework proposes a three-dimensional model of learning, yet the P-12 framework is designed to integrate engineering habits of mind, engineering practices, and engineering knowledge. The goal of the framework is to develop engineering-literate students who can communicate, think, and act as engineers. Each piece of the framework includes rich contextual features that enhance the complexity of reasoning that students develop. For instance, the practice of engineering design includes considering "clients' objectives or users' needs while satisfying a specified set of constraints." This added context and level of detail means that the framework focuses more on depth over breadth. The engineering knowledge dimension also specifically mentions the interdisciplinarity of knowledge and the need for integration. The A3E and ASEE Framework for P-12 Engineering and Learning presents standards in a way that emphasizes complexity and authenticity, rather than oversimplifying the inquiry experience for students.

While the NGSS were developed to reflect authentic practice, there have been some critiques from engineering education researchers on how well these practices reify engineering that takes place in design-intensive, client-driven workplace settings (Crismond & Adams, 2012; Cunningham & Kelly, 2017). This paper will highlight the complex ways that practices move beyond their articulation in the NGSS toward the more authentic vision introduced by the A3E and ASEE Framework.

Theoretical Framework: Situated Authenticity

The goal of this study is to reclaim the complexity lost in the NGSS practices by exploring the situated authenticity of science and engineering in STEM workplace contexts. Framing our study through situated authenticity allows us to focus on the cognitive reasoning that real scientists and engineers find valuable in their jobs (Chinn & Malhotra, 2002) while determining the complexity of their work as it is situated in authentic contexts (real-world or future professional situations), tasks, impact, and/or social norms (Lottero-Perdue & Brickhouse, 2002; Strobel et al., 2013).

Scientific inquiry in school rarely reflects scientific reasoning used in workplace contexts. As Chinn and Malhotra (2002) note, such school inquiry can even be antithetical to authentic epistemology. Simple school inquiry only allows students to use a narrow range of reasoning, mostly focused on control of variables (Wood, 2015). For instance, students may notice that making one change in a variable affects the outcome of their study. Whereas reasoning in STEM workplaces requires a range of reasoning skills from determining unobservable effects on results, evaluating the accuracy and quality of data, identifying sources of error, etc. (Chinn & Malhotra, 2002; Holmes & Bonn, 2013; Hu & Zwickl, 2018; Walsh et al., 2022). The disconnect between scientific reasoning in school and workplace contexts is also true of broader disciplinary literacies (including situated ways of reasoning, reading, writing, speaking, drawing, and acting like scientists or engineers), reflecting the practices of the professions (Silvestri et. al., 2021).

Our theoretical framework focuses on authenticity from the perspective of learning reasoning skills that are situated within different communities, whether that is a community of a class and teacher or an engineer and their colleagues. In their research critiquing NGSS engineering practices, Cunningham and Kelly (2017) describe the differences between authentic engineering as having epistemologies that better reflect knowledge valued in the STEM workplace as compared to the underlying epistemologies ingrained in NGSS practices. They define epistemic practices as being socially constructed through interactions, contextual, and situated within particular disciplines and cultures, with shared tools and communication (Cunningham & Kelly, 2017). In fact, our thoughts, values, and beliefs are entangled within engineering and design products and practices (Bucciarelli, 2003). Since learning takes place within communities and is negotiated

based on what a community values, it is important to consider what knowledge is valued and how these values influence the work of scientists and engineers. In science and engineering, when students engage in epistemic practices, they should learn what scientists and engineers do and value (Jimenez-Aleixandre & Crujeiras, 2017). Yet, what counts as knowledge (epistemologies of science and engineering) is different in different social groups and is especially different in NGSS practices and how they are presented (Jimenez-Aleixandre & Crujeiras, 2017).

This research is further guided by the theory that knowledge of science and engineering practices is socially embedded in the situated context where they take place. As Buciarelli (2003) states,

> …to explain the world we have to pay close attention to who, in this case engineers, is doing the explaining—their predilections and presumptions, the traditions they draw upon, the way they describe the world they live in. It is not enough to study propositions, facts, abstract and in themselves alone; context matters. (p. 6)

Thus, transferring practices from authentic STEM workplaces into K-12 classrooms requires an understanding of how practices are situated in the workplaces in the first place. Our study explores the knowledge and competencies that are valuable for individuals as they transition from being a student to being a scientist or engineer. By investigating salient features reflected in substantive contexts for practices as they are situated in authentic settings, our research intends to provide a lens for interpreting practices and makes them transparent and accessible to educators.

Methodology

Our research uses interview data from scientists and engineers at a critical point in their career transitions where they are typically aware of and reflective of their own practices and education (Collins & Green, 1992; Mody, 2015). Using a semi-structured approach, the research team conducted 22 interviews with entry-level new hires (within two years of being hired) and managers who worked in optics and photonics companies in the northeastern United States. Optics and photonics, the science and application of light, is a valuable field for conducting research since employees come from a variety of science and engineering disciplinary backgrounds. Interviews included open-ended questions related to the skills participants felt were most valuable and structured questions focused on particular contexts informed by theories of situated learning (situations, tools, and people). Interviews were transcribed and coded using NVIVO qualitative analysis software through a multi-stage coding process using both emergent and *a priori* approaches (Saldaña, 2013).

Research Setting

Participants included recently hired employees and managers in optics and photonics companies in the northeastern United States. Optics and photonics reflect a diverse range of applications and connections across disciplines that impact a myriad of industries such as health, computing, security, and communication among others (National Research Council, 2013). For example, medical technicians and doctors need a basic understanding of optics and photonics to interpret medical images and use techniques such as interventional radiology. A microsystems engineer needs to be able not only to work with electrons and circuits, but also to manipulate and guide light to carry information across circuits. The field of optics and photonics advances other fields of research and technology. For instance, photonics is shifting technologies from reliance on electrons to light allowing devices to send more information at greater speeds and across greater distances, while using less energy. Optics and photonics are not commonly taught in high schools as a standalone subject but are present within physics. Occasionally, companies can hire people with specific degrees in optics and photonics; however, they tend to leverage students with backgrounds in physics, chemistry, mechanical engineering, electrical engineering, computer science, or other STEM areas. Even for students who do not pursue STEM careers, simply becoming aware of the pervasiveness of optics in our everyday life (e.g., the myriad optical components in cell phones including screens, cameras, filters, and fingerprint identification) holds value in their understanding of the changing role of science, technology, and society. Since many cutting-edge developments in science and engineering are linked to optics and photonics, it is particularly valuable as the workplace context for our study.

Participants

Our study examined data from 22 interviews with nine new hires (within two years of being hired) and 13 managers. New hires included those entering both technician- and engineering-type positions, with the technicians typically entering with high school diplomas or associate's degrees and the engineers often entering with bachelor's or master's degrees. Approximately 22% of our participants were female; specifically, 18 were male (seven new hires, and

11 managers) and four were female (two new hires and two managers). According to the Society of Photo-Optical Instrumentation Engineers (SPIE) 2018 Salary Report, women make up 19% of all employees in the field of optics and 16% of full-time workers in optics so we adequately represent gender in the field (SPIE, 2018). Of our participants, three are from traditionally underrepresented racial and ethnic backgrounds, which will not be disclosed to maintain participant anonymity.

Data Collection

Each interview was semi-structured, starting with an open-ended discussion of what makes someone successful in their company and what areas they wish they (for recent hires) or their employees (for managers) could improve. Interviews were designed to include a combination of ethnographic questions such as descriptive questions to understand science practices in detail, structural questions to determine the kinds of situations or activities that an employee participates in, and contrast questions to examine the underlying meaning of each employee's perspective (Spradley, 2016). Specifically, participants were asked to describe mathematics, physics, and communication competencies they use or expect on the job. For each type of competency, participants were asked to provide examples of situations and tools used as well as what aspects they experienced (or expected) prior to hiring and what they learned (or trained for) after starting the job. Additional questions addressed academic preparation necessary for positions in their company, processes for advancement, hiring practices, and training opportunities. Lastly, participants were asked to consider cultural fit and other influences of entry and success on the job by comparing situations where someone fits or does not fit well at their company. The overarching goal of the interviews was to explore the authentic competencies and scientific practices that employees used on the job.

Data Analysis

Interviews were transcribed and coded using NVIVO qualitative analysis software through a multi-stage coding process with both emergent and *a priori* approaches (Creswell & Creswell, 2017; Saldaña, 2013). Emergent coding was essential to identify competencies that participants found valuable and their underlying contexts, as well as themes across *a priori* coded findings. Emergent structural coding was used to organize and connect multiple emergent competencies to determine their presence as well as explore the underlying organization and hierarchies between each code (Jackson & Bazeley, 2019; Saldaña, 2013). *A priori* coding was based on NGSS and supplemented by Epistemic Practices of Engineering (EPE) (Cunningham & Kelly, 2017; NGSS, 2013), to reflect both NGSS and suggested considerations for a more balanced consideration of engineering practices (Cunningham & Kelly, 2017). While we use both science and engineering definitions of practices in our coding, our participants work with both types of practices in engineering-focused, client-driven companies. Both types of practices emerged from our data in a complementary way, often with science practices serving to support the development of engineering practices and vice versa.

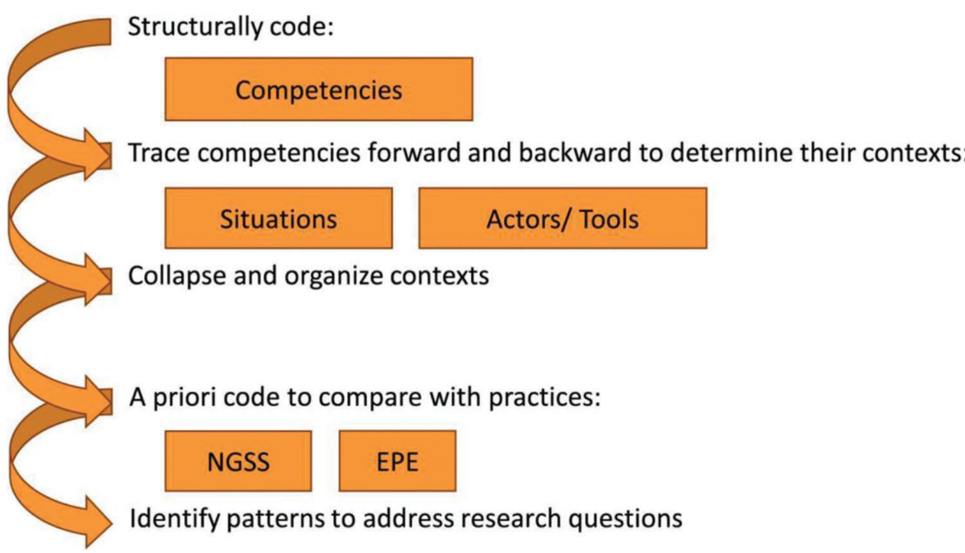

Figure 1. Methods flow chart showing the coding process. Codes used are in orange boxes and actions performed with those codes are written in text above each.

To analyze the interviews, at least two coders separately applied an emergent structural coding framework to identify competencies that participants found valuable on the job. Each of these codes was then traced forward and backward in the data to determine the underlying contextual features including the related task, purpose, actors, and tools. Instances where not enough detail was provided were not included for further analysis (e.g., if a participant mentioned needing a competency without adding an example or explanation for why it was valuable on the job). Despite this inclusion criterion, each participant described multiple competencies with enough contextual details, so that each participant is represented in the data sample. Next, coded competencies were merged when contexts were similar across interviews. Merging allowed us to look for connections, articulate patterns, and gain a deeper understanding across multiple contextual features.

Using emergent codes for competencies and their underlying contextual features, at least two coders then applied the NGSS practices and EPE as *a priori* codes. EPE codes were coded throughout and are further examined in our findings for cases when contexts did not connect to multiple NGSS practices as a way to assess other potential practices that intersected in emergent findings. At least four researchers discussed each coded instance and refined our interpretation of the *a priori* codes until we reached interrater agreement. These discussions also served as a basis for developing broader themes from the data. Themes emerging from the data emphasized the underlying contexts when participants discussed valued skills and competencies and the intersections of practices across these contexts. As an additional way to visually understand and interpret findings, we used Gephi software to create maps that illustrate connections between practices across different contextual features and themes. Figure 1 illustrates the methods used for this study.

Findings

The findings in this paper are divided into two sections, each relating to the two research questions posed. In the first section, we use qualitative vignettes and quotes to illustrate two examples of rich contextual features of situated science and engineering practices. In the second section, we use tables and maps to visualize connections within and across NGSS practices reflected in each of the examples introduced in the first findings section. While we list several ways that the practices intersect, we specifically highlight the most prevalent intersection for each example.

NGSS Science and Engineering Practices Situated in the STEM Workplace

To address research question 1, we explored how employees describe the science and engineering they value and practice. We specifically highlight two examples with different contextual features (based on specific situations, actors, and tools) that illustrate and compare practices prevalent in the STEM workplace.

Example 1: Client-Driven Parameters and Constraints in Optical Design

The optics and photonics industry relies on several companies coming together as part of an ecosystem or supply chain. For instance, one company might design the laser that tests an optical device, another makes the glass, and yet another company makes the tool that cuts and shapes the glass. Each of these companies can be considered a client or supplier for the other. Clients also might be a research lab, aerospace designer, or medical facility that uses the finished product. All of these clients have additional constraints based on material, cost, time, and size, among others. Such interconnectedness and dependencies mean that certain constraints and parameters must be set and adhered to along each step of the design and manufacturing process. Competencies like designing within parameters and constraints, reading and interpreting schematics, and testing designs and products based on evidence are valued competencies within such a client-driven context. Vignette 2 shows the importance of taking into account parameters and constraints as a critical aspect of client-driven design.

Vignette 1: Attending to parameters and constraints

When making optical lenses, James explains that plastic is affected by thermal conditions, even as small as the heat from holding a part in his hand. Because he works in a small company, James both makes and tests parts. When testing, he has to check surface roughness ensuring that it is below a certain amount based on the client's specifications. Optics is different from James' previous manufacturing experience since it requires more careful attention to details. For instance, even if what he is making seems clean, it could be dirty on an optical level. James uses solvents and chemicals, and even toilet paper, to avoid scratching the surface of a lens. He uses special techniques to avoid adding even his own fingerprints. James never rushes because the equipment is so expensive. James also does his own quality control so he knows if he is making good parts that the client will not have to ship back.

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In Vignette 1, James accounted for a variety of parameters in designing and testing based on client specifications. Some employees need to take these upper limits for tolerance a step further by taking time and cost into consideration in different ways depending on client needs. While James needed more focus on precision and the cost of making a mistake, others might need to consider scale and be less precise in order to save a client money if slight irregularities do not inhibit performance based on the client's goals.

Using parameters and constraints when designing and making means that employees must make decisions that result in different courses of action for different constraints. For example, one employee explains that you have to consider the context of the lens that you are designing and determine clients' specific parameters from that context. She describes:

> You have to design for that specific projector, like different parts of the design have to fit in it and stuff like that. Usually, they [the clients] know where they want the image to be; so they know the project and so I figure out the rest and design the lenses.

In this case, the client's parameters were taken into account in the initial design phase of the project influencing decisions about the entire design and manufacturing process.

Parameters and constraints are often communicated visually through schematics and design specifications, so reading and interpreting these is an important task within the client-driven parameter contexts that new employees face. Employees design and make products with reference to such schematics, but also need to question and communicate based on these visualizations. Reading and interpreting data are critical for a variety of tasks such as representations for fringes and waves indicating radius and location of curvature, also more generally as a comparison for assessment and troubleshooting.

Testing is also influenced by parameters and constraints set by clients and conditions. Employees test designs and products based on evidence. Such evidence can come from optics bench work and metrology data but can also be in the form of models and simulations. For instance, Zemax software allows employees to develop tests to ensure these parts meet clients' parameters and constraints. Employees use virtual prototypes in Zemax to design a physical test bench in order to collect data. The prototype also helps employees interpret data in light of clients' expectations. Clients and conditions influence the prototype design, which is then used to collect evidence virtually and determine what data should be collected physically. This then enables science experiments that evaluate where performance of a piece is meeting expectations or falling short and diagnose how to fix deficiencies.

Example 2: Rhetorical Situations and Developing a Shared Language for Engineering

Contextual features centered on communication were essential for new hires in optics and photonics workplaces. Such rhetorical situations are based on variables such as time, people involved, environment, tools, and purpose. For example, an employee may need to elicit information from a client while being persuasive for the purpose of determining the cost and time it will take to make a specific part in order to make a profit while maintaining a future relationship with the client. Moreover, managers emphasized the importance of communication and the need to screen for a job applicant's interpersonal skills to work in such rhetorical situations. Competencies in rhetorical situations include writing clear and concise e-mails to customers, getting along with employees of different educational and cultural backgrounds, and keeping a detailed and accurate record of work with specific tools and machines among others. Vignette 3 illustrates the need not only to communicate well overall, but to adapt communication while ensuring mutual understanding to meet the needs of a variety of people.

Vignette 2: Adapting communication for mutual understanding

> *Sarah, an optical engineer, works closely with clients to develop specifications for custom projector designs. She talks with people who do not have technical backgrounds and they use words that do not mean what they mean to her. In these situations, Sarah must translate and figure out the client's actual meaning. She also needs to talk about technical optics in a general way for sales people who do not know optics, and often whose first language is not English. Sarah breaks down math and physics into small digestible bits and relies on a lot of drawings. Sarah also adapts her communication for other situations and people. Once she realized that her boss does not read past the first two sentences of an e-mail, Sarah started writing him shorter e-mails. She has learned to adapt her communication practices until she understands others and gets her point across.*

Like Sarah demonstrated in Vignette 2, one rhetorical situation that new employees commonly faced is communicating information to others on how machines work, processes for methods used, and any solutions to problems. Such informative rhetorical contexts include competencies such as documenting information for colleagues to help with shift changes on a given machine. Written documentation also included thorough lab notebook records that help an employee look back at a

later time in order to replicate or compare previous work. Some companies systemize the processes in informative rhetorical situations by having employees upload processes and solutions to a server. This allows information to be documented and shared broadly across the organization. As one employee explains, for example,

> …there are bar codes all over it. So we scan stuff…type in your run time and then so on. Not only does that help keep track of where the part is but also helps a sales engineer quote stuff. So say a part takes 12 hours to run, now the sales engineers know that.

Other companies rely on informative rhetorical contexts when training new hires by having them rotate with more experienced employees or those working in different divisions of the company. More experienced employees are asked to share knowledge with recent hires, teaching them how machines and tools work and the processes they use. New hires then must learn how to ask questions that elicit such information.

A second common rhetorical situation involved eliciting information from and conveying information to others (colleagues, supervisors, other departments, and clients) in order to persuade, explain, or build consensus. Such information is elicited throughout the design and manufacturing process. One manager explains the importance of asking questions and having the confidence needed to elicit information:

> A lot of people have the problem where if they speak up and they ask a question, that identifies a gap in their knowledge which they feel that brings them down a rung in other people's eyes. But really, that's something that we value here is the ability just to ask a question.

Persuasive contexts for eliciting information can include skills such as learning the needs of another person in order to decide what and how much information to provide in an e-mail. Persuasive rhetorical situations are especially common when employees work with clients to facilitate conversations that determine designs, limitations and tolerances, and costs of manufacturing based on material and time needs. Persuasive contexts also determine what visual design forms an employee should use, how to keep in mind people's preconceived ideas, and how to anticipate different levels of understanding when giving presentations or guiding conversations. This then allows the employee to find common ground, build consensus, and/or persuade others.

Less structured communication involving interpersonal contexts was also important in the optics and photonics workplace. Navigating social norms is essential when people of different educational backgrounds, races, cultures, genders, ages, and roles make up a company. Interpersonal practices included company presentations, writing work instructions for others, e-mailing colleagues, calling clients, and asking questions of supervisors. For example, many managers mentioned the importance of employees learning to send concise (less than a couple of paragraphs) e-mails that are clear and convey messages effectively to co-workers to ensure that they read and understand. As one employee explains,

> When you talk to customers you've got to know how to kind of read them and reading if they're understanding you. Again, a lot of what we do is very technical and people may or may not need to necessarily understand how our local interferometer works, but how does measuring thickness get them what they need. So it's about being able to, not dumb it down, but make it understandable.

Employees recognize the value in clear, but efficient written communication and note that in cases where this is not possible, a phone or virtual call is typically better. Employees talk with existing and potential clients throughout the design and manufacturing process to meet their needs; yet problems can arise when interpersonal communication breaks down. For example, one employee discussed issues with engineers not respecting the skills of technicians in making design changes based on the tools required. Knowing how to respectfully ask questions that value the contributions and expertise of people in different roles is a valuable skill that can lead to better teamwork and improved productivity.

Intersecting Practices Represented in STEM Workplace Contexts

To address research question 2, we explored how NGSS practices are represented within how employees describe the science and engineering they value and practice. In this section, we highlight the most prevalent intersection patterns across the two examples from the first findings section: (1) measuring and interpreting results: client-driven parameters and constraints; and (2) eliciting information from others: rhetorical situations.

One way the NGSS practice of planning and carrying out investigations was reified in industry occurred when an employee set up an experiment to explore lateral color and focal length of a lens. In doing this experiment, the employee

needs to take measurements using mathematics and computational thinking. Once the data are collected, the employee will need to analyze and interpret data. This experiment was also done using aberration theory that involves the practice of developing and using models. Furthermore, the experiment using models is done in order to determine the causes of distortion in the lens, and so reflects the engineering practice of designing solutions. When a meaningful context in the workplace is apparent, we can better understand the multiple science and engineering practices people use and how these intersect. This findings section on intersecting practices illustrates some of the ways practices cluster and intersect as shown in Figures 2 and 3.

Measuring and Interpreting Results: Intersecting Practices within Client-Driven Parameters and Constraints

The NGSS practices (and EPE) with contextual features focused on client-driven parameters and constraints are shown in Figures 2 and 3. Client-driven parameters and constraints appear much more prevalent and essential to engineering practices. Measurement (C2) and interpreting results (C3) were both situations involving multiple NGSS practices and EPE in which clients or circumstances in the context of the tasks determined the decisions that employees needed to make. Because measuring also involves mathematical reasoning, precision, problem-solving, discerning of use and structure, using tools, and repetition, measurement is also critical for integrating mathematics in science and engineering instruction.

Measurement tasks are tied to client-driven parameters and constraints. A client's needs can influence what needs to be measured, what tools are appropriate for the task, what tolerances and fits (functional limits of accuracy) are necessary, and what testing is required to evaluate results. For example, an employee needs to make decisions based on the allowable tolerances when using white light scattering to determine surface roughness. In some cases, surface roughness may have strict requirements so that light reflects evenly across the surface such as making a lens for a telescope. In other cases, surface roughness may not have as much influence over the object's function such as in the cover for a reading light inside an airplane or car. In the latter case, a company may need to produce many of the same light cover and expecting measurements that are more accurate than necessary would slow down production and cost more for the client unnecessarily. In one case, a recent hire explains how a client's needs can influence the measurements that will determine whether those needs are met.

> So a customer comes to us with a set of specifications, what they need their system to do. And then, I work with the optical designer and the mechanical engineer to develop what we call test bench of how we actually intend to make sure

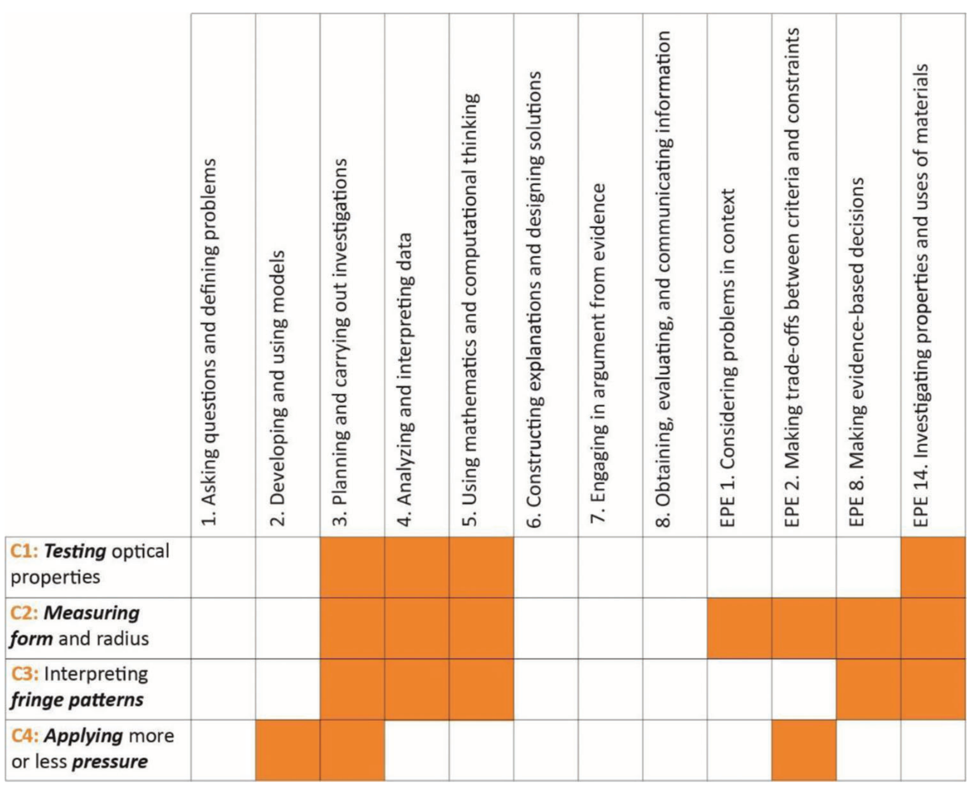

Figure 2. NGSS practices and EPE featuring client-driven parameters and constraints (orange).

Figure 3. Intersection of NGSS practices (red) and EPE (orange) featuring client-driven parameters and constraints (yellow). Note that larger circles represent a greater number of references to each practice across data.

> that these systems meet the specifications. Because in optics, there's an adage that you can't make it if you can't measure it…So it's different from a traditional kind of QA [quality assurance] where it's—does this thing have a scratch on it? No. It's—does this thing actually do what it's been designed to do? What you've said that it's going to do.

Knowing the client's specifications as well as what influence a material property or design feature can have for a specific function influences the measurements taken.

Effective measuring is paramount to planning and carrying out investigations, analyzing and interpreting data, and using mathematics and computational thinking. Though these are only three of the NGSS practices, measurement becomes much more prominent when EPE are also considered. EPE specifically takes into account parameters set by clients and conditions such as considering problems in context and making trade-offs between criteria and constraints. Moreover, EPE includes making evidence-based decisions, which is important for taking and using measurements. NGSS practices integrate evidence in the data collection stage and for making arguments, but not necessarily for deciding other courses of action. Additionally, EPE includes the practice of investigating properties and uses of materials that is essential in client-driven contexts, especially measurement. Much of measurement in the workplace is connected to the function of specific materials. An employee might select a particular type of glass based on its properties and the measurements needed to make a product function well for a particular purpose. For instance, interpreting fringe patterns when setting up an interferometer so that two reflections of light bend at a certain angle involves an understanding of the material properties for reflecting light. Taking and using such measurements would be impossible without considering the reflective properties of the material.

Eliciting Information from Others: Intersecting Practices within Rhetorical Situations

The NGSS practices identified with rhetorical contextual features are shown in Figures 4 and 5. Reading blueprints that obtain information from others in order to interpret, design, make, and evaluate results (R1) involved a substantial number of science and engineering practices. Reading blueprints is embedded in a rhetorical context since they are living documents that facilitate conversations across the company and over time. Another rhetorical situation for obtaining information from others where multiple NGSS practices intersect is taking initiative in asking questions (R8). Asking questions integrates more than just the NGSS practice 1 "asking questions and defining problems." With contextual clues, asking questions also relates to constructing explanations, engaging in argument from evidence, and the practice of obtaining, evaluating, and

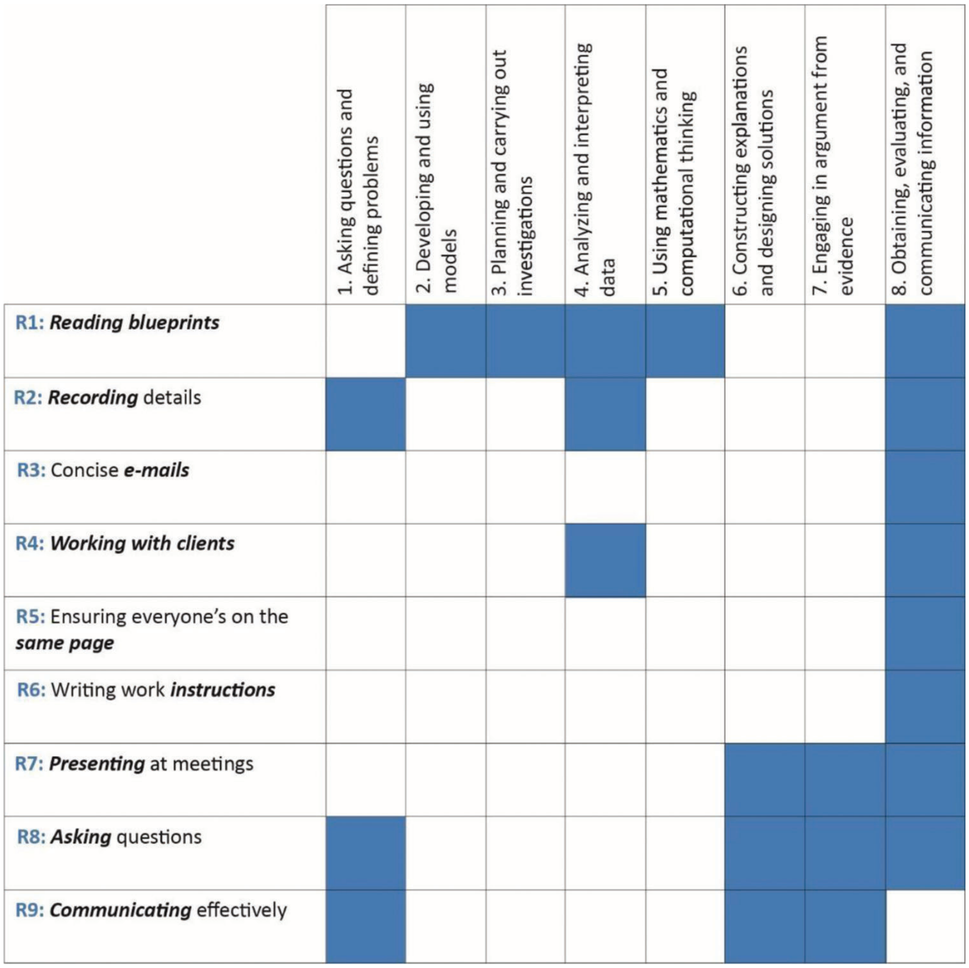

Figure 4. NGSS practices featuring rhetorical situations (blue).

communicating information. Each of these practices is social and asking questions of others can help employees position their results and designs for others to understand and use.

Eliciting information, verbally or via artifacts, is critical for working with clients as well as for working with people of different roles and expertise. For instance, someone creating a new design software needs to know what information to obtain from the software users to design a part and those who use physical tools to manufacture the part so that the designer knows what specifics are needed and the most efficient ways to create the software. Because of these needs, the software designer needs to know how to ask appropriate questions and the specific social norms and expectations for asking others within the company. Eliciting information also means asking questions and having conversations that others (clients or employees with different roles) can follow and understand. One manager emphasizes the necessity for hiring employees who can initiate and support conversations with others when he explains,

> A lot of times they [clients] are willing to share, "Here is what I'm hoping to accomplish"…So [employees] need to be able to understand how this is going to fit into the whole experiment…By talking about the experiment they learn, "Oh, you're going to need a very, very focused wavelength. You can't have one that's fluctuating."

Sometimes, the need for eliciting information effectively involves an additional need for visualization in the form of diagrams or figures that can help communicate complex information. In one case, an employee describes how communication can break down when clients do not understand 3D mathematics. She discussed how it was her responsibility to find a way to visualize the mathematics so that it is more understandable in order to have conversations with clients to determine their specific needs for projection systems used in amusement park rides.

One employee says,

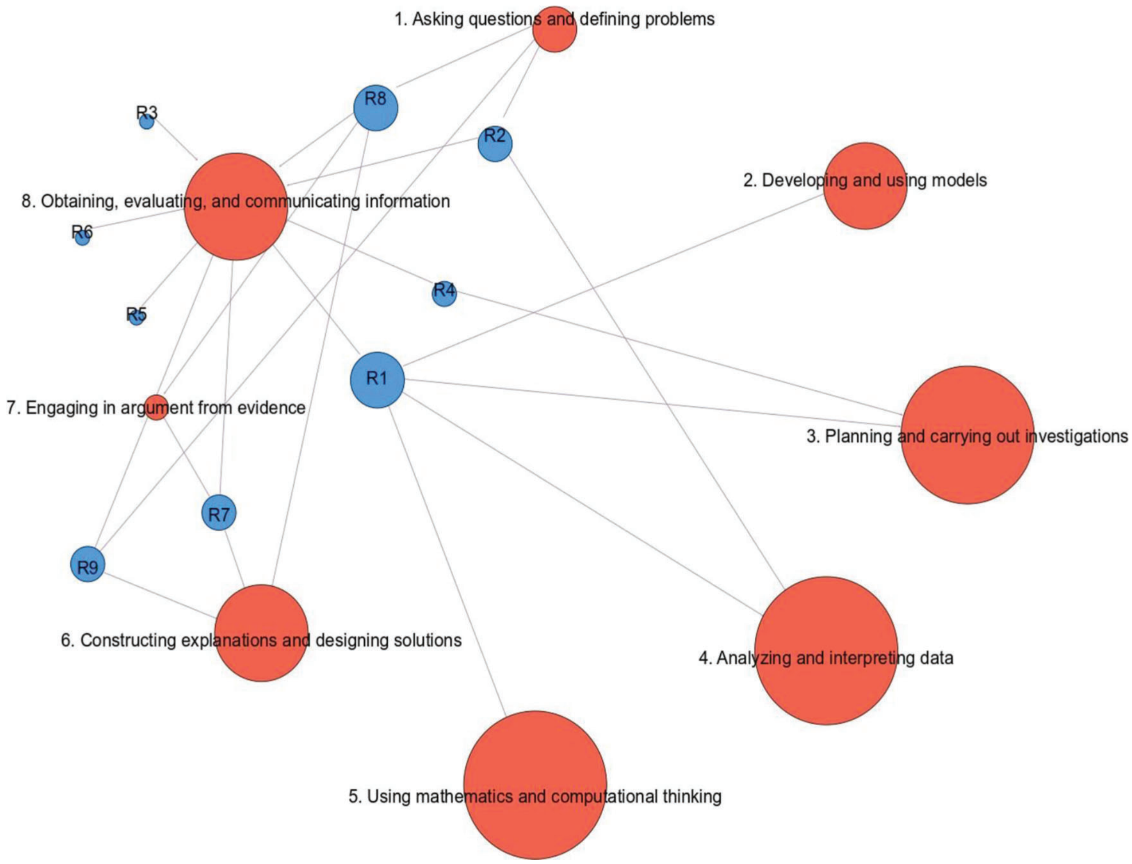

Figure 5. NGSS practices (red) featuring rhetorical situations (blue).

> Because we try them all out with our hands, like "Just picture this thing that I'm doing right now." And it's a lot easier when you can actually draw on it. The thinking in 3D thing is one of the biggest challenges for the whole projection area. It's hard for everyone. It's hard for us, it's hard for sales talking to the customers. It's easy when it's a flat plane but once you get curved surfaces that you want to project on, your mind just breaks a little bit.

In this example, eliciting information in rhetorical situations involved both verbal and visual communication of science and mathematics. The rhetorical situation was a part of doing science and mathematics in social contexts.

Multiple NGSS practices take place within rhetorical contexts, whether communicating within a company or with clients. In eliciting information from others, the NGSS practice *asking questions and defining problems* is embedded in a context where engineers and scientists communicate for specific purposes. As one recent hire recalls,

> …there's this one instance where the customer's having problems with our system that we built for him, and when they described the problem that they were having…they didn't tell us how the whole system worked, they only told us how they wanted this one component that we make for them works… The more and more we dug, the more we just couldn't find anything. And then, eventually, they started telling us more and more about their system.

In this case, the new hire was not working independently to ask questions and define problems. Rather, the employee needed to do this in a rhetorical context with the client. The employee also discussed contexts involved in the practice *obtaining, evaluating, and communicating information* when explaining that presenting at meetings involves not only communicating findings persuasively, but anticipating and adapting to the communication norms of others (e.g., not using the color red in graphs where people may interpret those data as negative). Employees need to not only explain their findings, but also understand the communicative context and competencies (e.g., knowing the audience) involved in this practice.

Intersecting Practices across Workplace Contexts

When looking across workplace contexts, it is clear that multiple NGSS science and engineering practices are prevalent though not all of them are used for the same situated tasks. Client-driven parameters and constraints tend to involve

practices of planning and carrying out investigations, analyzing and interpreting data, and using mathematics and computational thinking. Such contexts also play a role in helping employees determine what evidence they need to make decisions, what design considerations to prioritize, and what materials and tools to consider, aspects not necessarily emphasized in the NGSS practices though included in the EPE. Rhetorical situations involve several NGSS practices including asking questions and defining problems, constructing explanations and designing solutions, engaging in argument from evidence, and obtaining, evaluating, and communicating information. Our data emphasize how prevalent rhetorical situations are in the workplace and how intrinsically connected they are to multiple competencies.

Discussion

Our study explored science and engineering practices within professional STEM contexts in order to replace the authenticity lost from the original translation of workplace inquiry into K-12 standards. We interviewed recently hired entry-level employees and managers to investigate the science they do and what they find valuable for success. We coded and thematically analyzed these data to address the questions: (1) In what ways are NGSS science and engineering practices situated in the STEM workplace? (2) How are NGSS science and engineering practices connected and reified within STEM workplace contexts? These questions allowed us to explore science and engineering practices and understand how they might best be interpreted and applied in ways that better reflect authentic use for teaching and learning.

Our findings from this study suggest that multiple NGSS science and engineering practices are present in the STEM workplace, often with intersections of several practices together. The intersection and contextual features of situated practices are highlighted in two examples reflecting: (1) client-driven parameters and constraints and (2) rhetorical situations. Our results show that authentic science and engineering practices are not isolated and that they intersect within complex situations. This is consistent with Bucciarelli's (2003) claim that complete independence of tasks from each other is not possible. Integrating the contextual features of these complex situations will make national standards more authentic in K-12 science and engineering instruction.

Implications for Research and Policy: Using Contexts as a Strategy for Interpreting Practices in National Standards

Though our findings illustrate how NGSS science and engineering practices are situated in STEM workplace settings, they also shed light on some limitations in how we conceptualize the practices as a community. One consideration is that practices can change depending on the goal of a particular activity. For instance, our findings show that the NGSS practice of using *mathematics and computational thinking* looks quite different if the goal of using mathematics is to fit a theoretical equation to a set of measurements from if the goal is to take preliminary measurements in order to test the setup in an investigation. Another consideration of how practices can differ within different situated contexts is apparent in the communication-rich NGSS practices of *engaging in argument from evidence* and *obtaining, evaluating, and communicating information* where the practice of *engaging in argument from evidence* typically takes the form of students communicating with other students both aurally and visually to compare tentative models based on evidence (Windschitl et al., 2007). Yet, in STEM workplaces, an engineer may engage in argument by using a blueprint based on the client's expectations and compare these expectations with data obtained from testing a design or product. The argumentation may be mostly with the employee and a written artifact while comparing various forms of evidence, rather than between two individuals directly. Our findings support literature from research on communication across the disciplines that highlights the need for students to learn STEM communication practices as intrinsically linked with their context including the goals, audience, and tools necessary for a particular situation (e.g., Silvestri et al., 2021; Tapia et al., 2017; Wickman, 2013).

Without understanding the contexts behind authentic practice, standards may be interpreted without connections to their broader purpose outside the K-12 classroom. While our research focused on workplace contexts, further research could explore other meaningful contexts found in place-based science and engineering, community-driven science and engineering, and service learning. This research could explore how other such contexts can be used in conjunction with standards to better support students' learning.

Implications for Curriculum Design and Instruction: Using Contexts as a Strategy for Teaching Authentic Science and Engineering Practices

Integrating standards through authentic contexts would be beneficial for curriculum design and teacher professional development. Curricula could add more context or guiding questions so that teachers could incorporate locally relevant

features. Professional development could provide training on how to teach across multiple standards in ways that best reflect authentic practices in workplace contexts. For example, teachers could plan a curriculum by starting with learning goals and then adding contextual features that allow them to integrate their learning design across multiple intersecting standards. Contextual features for consideration could include the audience, client, or end-user (For whom are we engineering/designing?), the purpose of the science or engineering practices (Why are we engineering/designing?), the materials and tools to use in engineering (What materials and tools make sense for our purpose? What materials and tools should we select and why?), and an evaluation plan based on the needs of others (Do our designs make sense? How well do they need to meet our requirements/tolerances?). Including these contextual considerations in curriculum and instruction planning will allow teachers to better integrate learning across multiple practices (and other standards) as well as authenticate the standards in ways that still make sense for use in K-12 learning.

In engineering education, one type of contextualizing curricula uses the Honeycomb of Engineering Framework (Purzer et al., 2022). In this framework, the goals of engineering center on negotiating risks and benefits to problem scope with user-centered design rather than context-independent optimization. When this goal is foregrounded, as our own data and the framework suggest happens in authentic engineering, rhetorical goals related to communicating evidence, trade-offs, and alternatives provide opportunities for connecting multiple other goals within client-based and rhetorical contexts. An example of a context-rich curriculum that aligns well with this framework is the EngTEAMS unit, Ecuadorian Fisherman, for Grades 6–8 (Siverling & Moore, 2020). In this unit, students begin with defining the engineering problem including introducing the setting (San Cristobal Island in Ecuador), the client, end-users (Ecuadorian fisherman), criteria, constraints, and topics or materials students would like to learn. The students receive a letter from the client, read it, and ask questions of the client. This positions the students to then decide their own science and engineering learning goals based on negotiating risks and benefits related to designing and building an inexpensive cooker container (to cook fish). The context allows for multiple engineering, science, and math standards to be integrated and learned in a deep way throughout the unit. In a similar example, the Center for Science and Engineering School for Scientific Thought Atoms to iPhones class was developed as an interdisciplinary engineering course where high school students start with a familiar everyday object (iPhone) as a way to contextualize learning about semiconductor physics and make their own p–n junction in the lab. Again, the use of a familiar context based on student interest brings together multiple practices in an authentic and accessible way.

Context-rich storylines are also helpful for authenticating standards within K-12 learning experiences. The NGSS introduced storylines as a strategy to describe the context and rationale for performance expectations, combine multiple standards, and help students understand what they are learning and why (NGSS Lead States, 2013). In their book *Ambitious Science Teaching*, Windschitl et al. (2018) present a process for NGSS-informed curriculum design that is grounded in anchoring events. They describe anchoring events as complex phenomena, processes, or events that motivate students to develop models and explanations for what is going on. Windschitl and colleagues (2018) suggest that anchoring events help students develop deep understandings by providing complex problems for them to engage in. Anchoring events are contextualized by students' interests, their local community and place, or their lives and careers they may pursue outside of school (where our study comes in). Contextual features from STEM-intensive workplaces that also support student learning can guide anchoring events and integrate multiple NGSS practices. Our findings highlight contextual features that can be drawn upon for curriculum planning and instruction. We also highlight specific examples of how NGSS practices can intersect within contexts emphasizing these features. We propose that adding contexts to standards will allow teachers to develop anchoring events that specifically support students in learning authentic intersecting practices of science and engineering.

Limitations

While our research offers insights for how we conceptualize and contextualize NGSS practices, it is somewhat limited in its scope. Focusing on one particular STEM industry (optics and photonics) in one geographic area of the United States (the northeast) allowed us to understand practices deeply, but our findings are not necessarily generalizable across all STEM-intensive careers. Future research should examine other STEM-intensive workplace contexts as well as contexts that may be meaningful for students' interests such as place-based science and engineering learning. Additional research could investigate K-12 instruction or teacher education that emphasizes authentic contextual features found in our study, and other aspects of context around national standards. In addition to exploring NGSS practices and EPE prevalent in workplace contexts, newer research could broaden the scope of standards to include considerations from the recent A3E and ASEE Framework for P-12 Engineering Learning. Our findings also provide support for other research and curricula that contextualize science and engineering including project-based instruction, citizen science, and place-based science and engineering, among others (e.g., Aikenhead, et al., 2006; Chinn, 2007; Koomen et al., 2018).

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Conclusions

Exploring how NGSS science and engineering practices are situated in workplace contexts brings to light the complexity and connectivity of science and engineering practices absent from simplified national standards. These findings provide rich insights on authentic workplace contexts and how these are shaped by a variety of disciplinary norms and values. Alternatively, within the NGSS framework, each standard is largely context-independent. This makes sense as it allows teachers to articulate the framework in a way that works well for their own classroom context; however, there are limitations in this model when we want students to learn the goals, expectations, and values of professional STEM communities. Curricula and professional development can emphasize authentic contexts, tasks, and purposes for standards-based science and engineering practices in ways that are still locally relevant (e.g., Sezen-Barrie, 2018). By reinterpreting standards so that they intentionally consider contextual features when planning instruction, educators will be able to interpret and align standards with more authentic learning experiences for students.

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