DISSERTATION

ADVANCING EQUITY IN MIDDLE SCHOOL SCIENCE: THE ROLE OF CLASSROOM CULTURES AND CURRICULAR STRUCTURES

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ABSTRACT

ADVANCING EQUITY IN MIDDLE SCHOOL SCIENCE: THE ROLE OF CLASSROOM CULTURES AND CURRICULAR STRUCTURES

This dissertation explores the role of classroom culture in shaping equitable student experiences and outcomes in science education, and examines how curricular structures might further reinforce equity. Here, equity in science education means supporting student identification, belonging *and* learning in science, with particular attention to disrupting historical patterns of inequity that have created barriers to participation for students from historically marginalized populations. Classroom culture is a critical component of equity because it shapes student experiences and opportunities within science and determines whose voices, experiences, epistemologies, and cultural connections have credence within science learning. For their part, curricula shape how students interact with science content and serve to expand or constrain the breadth, depth, and rigor of the content that students experience. The study outcomes are student interest and belonging, both of which are critical for broadening participation in science because they are associated not only with improved learning, but also with meaningful participation in classroom science communities, course-taking patterns, and career decisions.

The first two papers in this dissertation draw on large-scale survey data from 847 middle-school students in more than 30 OpenSciEd classrooms across the country. We use hierarchical linear modeling with students nested within classrooms to examine the extent of classroom-level variation in classroom culture, and how key features of equitable science classroom cultures relate to student interest and belonging in science. In both cases, we find significant classroom-level variation in culture, suggesting that classroom culture can be an important lever for equitable transformation.

The first paper explores the relationship between classrooms reflecting *collective enterprise* and *care* with student interest in science. We find a strong and consistent relationship between collective enterprise and care, respectively, with student interest. We propose that these attributes of classroom culture may bolster student interest in science by supporting relationships and by connecting with the cognitive, emotional, and values-related components of interest.

The second paper examines how classroom *epistemologies of science* relate to students' sense of belonging in science. Again we find a strong and consistent relationship between classrooms reflecting broader and more flexible epistemologies of science, with belonging in science. We consider the tensions between the science-as-practice vision of science education and the pervasive cultures of school science to contextualize the observed variation in classroom epistemologies of science. We argue that a concerted "epistemic boost" in science education may be necessary to fully realize the science-as-practice vision of science education.

Finally, the third paper uses data from 38 teacher interviews to understand aspects of the science curriculum that teachers found supported their efforts to build equitable science classrooms. While many curricula address equity through increased representation of minority scientists or through guidance for teachers around equitable instruction, I argue that the design of curricular structures has been underappreciated as a potential venue for bolstering equitable science participation opportunities for students. I propose that curricular structures designed to support deep and authentic content learning can serve double duty by structuring student learning tasks and participation in ways that reinforce equitable classroom cultures.

Collectively, these three papers contribute to the goal of expanding opportunities for students to connect with and succeed in science. They focus on valuable potential levers for equity, namely classroom culture and curricular structures. They help us to understand how relational and epistemic aspects of the classroom culture, and intentionally designed curricular structures, have the potential to expand how students understand science as a discipline, its value and relevance for their lives, and their own place within the world of science.

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Introduction

A primary goal of science education in the United States is to broaden participation in science for students from communities that have been historically minoritized within the field, including girls and students of color. Although females achieve at similar or higher rates than males in primary and secondary science classes, they are nonetheless underrepresented in many STEM majors and careers (see Voyer & Voyer, 2014 for a review; NCES, 2014). For their part, students of color experience an opportunity gap, reflected in an achievement gap in K-12 science (Carter & Welner, 2013; NCES, 2019). These discrepancies are now understood to result largely from sociocultural features of schooling, and of science as a discipline, that continue to exclude girls and students of color (e.g., Ceci et al., 2009; Su & Rounds, 2015). Transforming science instruction to disrupt these patterns is essential, both to expand opportunities for youth themselves and to improve scientific outcomes for society.

Classroom culture shapes the experiences and opportunities that students have within science: Classrooms are a key space where historical inequities can, often unintentionally, get reproduced. Classroom culture also has the potential to transform how students experience science in ways that may impact their science trajectories moving forward. Classroom culture includes the nature of the relationships and interactions between teachers and students and among peers; the kinds of participation structures that are available to students; the norms that govern the roles, opportunities, and interactions within the classroom; and the prevailing understandings about what it means to succeed within that classroom space (Black et al., 2004; Carlone, 2007; Tishman et al., 1995). The culture establishes how people treat each other, how they communicate, and how they work together to learn science (Supovitz & Turner, 2000).

Classroom culture plays a role in shaping equity within the classroom because it determines whose voices, experiences, epistemologies, and cultural connections have credence within science learning. Within a single classroom, the classroom culture may operate differently for different students, depending on *who* is afforded certain roles and opportunities and *whose* voices, experiences, and knowledge are valued. Moreover, the distance between students' lived worlds and the culture of the science classroom shapes their enculturation within the classroom and within the world of science, making connections to science easier for some students and more difficult for others (Aikenhead & Jegede, 1999).

For this dissertation, I seek to understand the role of equitable classroom cultures in shaping student experiences and outcomes in middle-school science. What features of the science classroom culture have the potential to increase equity in science? What specific benefits do particular features of equitable classroom cultures have for students? How can teachers attend to classroom culture in ways that support students? What is the role of curriculum in shaping equitable cultures within middle-school science classrooms? These questions are immediately consequential because they directly mold the experiences that students have every day in school science. They also have the potential to influence science pathways more broadly by creating opportunities for students from historically marginalized communities to develop the desire and motivation to persist within science education and careers.

Unifying Conceptual Framework

My research is primarily concerned with how classroom culture can support equitable science learning experiences and outcomes for youth. Throughout this work I take a sociocultural perspective on science learning, acknowledging that learning and development are fundamentally social processes, shaped by social and cultural factors (Vygotsky, 1978).

Classroom cultures are the milieu within which learning takes place, and as such, they mediate the social dynamics and individual histories within the classroom and influence how and what students learn within those spaces (Squire et al., 2002). Teachers have a role to play in building the classroom culture through the norms they establish with their students and through their instructional practice (Milner et al., 2018; Schenkel & Calabrese Barton, 2020). The curriculum also influences the classroom culture through its presentation of science content and the ways in which it structures student learning (Joseph, 2011; Milner, 2010). Here, I build on existing theories of science learning and educational equity to think about how best to create equitable science learning opportunities for students within the classroom.

Science Learning as a Sociocultural Endeavor

Science and science education are both human social activities, conducted within the bounds of extant cultural frameworks (Lemke, 2001). Science classrooms, accordingly, are cultural spaces that reflect the histories and cultures of science as a discipline, of schooling, and of our broader society. Science classrooms can be both a force for social justice and a powerful mechanism for supporting the status quo of inequitable social hierarchies. Due to the range of potential outcomes connected to science classroom culture, this dissertation aims to identify and better understand features of classroom culture that support equitable science classrooms.

Traditional school science perpetuates societal inequities

Left unexamined, the standard structures and practices of school science tend to perpetuate the status quo because centuries-old inequities are ingrained into the fabric of these institutions and activities—they are baked into the educational system, the practice of schooling, and the disciplinary domain of science (Croizet et al., 2019; Zhao, 2016). As such, traditional science education reflects historicized inequities and constrains learning opportunities for students from nondominant groups (Calabrese Barton & Tan, 2020). Epistemologically, schooling legitimizes certain kinds of knowledge over others. Schools inherently value academic, school-based knowledge and skills over non-academic forms of knowledge and skills that are sometimes more prevalent within poor and minoritized communities (Moll et al., 1992). The result is that school science has traditionally been disconnected from students' everyday lives, especially for students from nondominant communities whose everyday lives do not intersect as much with the culture of formal schooling (Bang and Medin, 2010).

Schools also tend to maintain historical white-patriarchal assumptions about what science is, who can do science, what it means to be a scientist, how scientists think and operate (Lemke, 2011). Science itself is a cultural endeavor: a set of practices for investigating and making sense of the world, that are socio-historically defined and imbued with established values (Bang and Medin, 2010). Within science, these established—or "settled"—notions about what constitutes science are too narrow to support successful learning opportunities for a plurality of students (Bang et al., 2012). Moreover, settled notions of science lead to deficit views of nondominant students and communities to the extent that they may not approach science with the same epistemological orientation. These narrowly construed forms of participation in science alienate students with other ways of thinking and knowing, create barriers to belonging, and hinder their development of positive disciplinary identities (Bell et al., 2017).

Classroom culture reflects an amalgam of practice and materials

A sociocultural perspective leads us to recognize the importance of social interaction for learning and lays the groundwork for examining the interplay between teacher practice, classroom culture, student experiences, and the materials that shape teacher and student activity. Through their instructional practices, teachers shape the classroom culture and simultaneously communicate influential messages about what science is, how science gets done, and what knowledge and experiences are relevant and valuable for learning science. Because they are so integrally connected, it is somewhat artificial to talk about instructional practice and classroom practice as two separate things. Indeed, if teachers are soliciting students' funds of knowledge and making those resources available for collective sensemaking, then the classroom culture is one in which student funds of knowledge are respected as valued resources for learning. In a sense, they are like two sides of a coin–you cannot have one without the other (there is no such thing as a one-sided coin), and they are mutually determinative (the coin is necessarily of one and the same type on both sides). Nonetheless, for purposes of describing features of equitable science classrooms, I have separated the discussion into two pieces, one around classroom cultures (roughly focused on the nature of the shared cultural space within the classroom) and another around teacher instructional practices (roughly focused on things that teachers do to create certain types of environments). I also discuss the role of the curriculum in shaping equity within science classrooms. And I describe how classroom culture, teacher practice and curriculum always implicitly embody an epistemological stance, which also shapes equity within science classrooms.

Equitable Science Classroom Cultures Create Equitable Learning Opportunities

Classroom culture shapes the experiences and opportunities that students have within science and is thus one area (of many) where we can seek change. Classroom culture encapsulates the nature of the relationships and interactions within the classroom, including norms for speaking and working together (Supovitz & Turner, 2000), as well as the roles and participation structures that are available to and expected of students (Black et al., 2004). Classroom culture reflects how knowledge-building happens within the classroom and who participates, including the kinds of thinking and sensemaking that are valued, and what students are held accountable for knowing (Black et al., 2004; Tishman et al., 1995). The culture is also evident in what it means to be considered "smart" or "successful" within the classroom (Carlone et al., 2011). In science classrooms specifically, the culture reflects how science itself is presented to and experienced by students, with attendant implications for whether and how students have opportunities to connect with the discipline of science (Tal & Kedmi, 2006).

Classroom culture plays a role in shaping equity within the classroom because it determines whose voices, experiences, epistemologies, and cultural connections have credence within science learning. Equitable classroom cultures serve to dismantle historical barriers, expand the boundaries of sanctioned disciplinary participation, and broaden opportunities for students to connect with science. The culture shapes and communicates whose "life-worlds" are valued for science learning (Aikenhead & Jegede, 1999). Classrooms are borderlands where multiple sociocultural contexts collide (Gutierrez, 1999) and they often align more closely with the life-worlds of some students than others. While some students may be able to fluidly navigate between their own lives and the culture of school science, others may experience hazardous or even nearly impossible "border crossings" between the two cultural spaces (Aikenhead & Jegede, 1999). As such, the culture can facilitate connections with science for some students, while presenting obstacles for others.

Third spaces and hybridity in science education

One way to bridge these cultural divides is to create what Gutierrez (2008) calls "Third Space", where learners' primary cultures and discourses (i.e., those used at home and within the community) overlap with their secondary cultures and discourses (i.e., those validated at school and in other formal settings). In many traditional school environments, students come to believe that they must set their own culture aside to adopt and be successful within the sanctioned school or disciplinary culture, thus causing students to leave behind many valuable resources for learning at the classroom door. These hybrid spaces, however, allow for the coexistence of multiple cultures, rather than preferencing traditional, school cultures over students' home cultures and lived experiences. Classroom cultures that offer students a hybrid space for learning enable students to bring their knowledge, experiences, and varied ways of knowing to bear for their school learning. Scholars have suggested that these hybrid spaces help learners to bridge the gap between everyday ways of knowing and disciplinary ways of knowing (Gutierrez, 2008; Barton and Tan, 2009). Within these spaces, learners can integrate their diverse resources for learning to support new knowledge-building and sensemaking (Moje et al., 2003).

Classroom culture and science identity

The classroom culture, as manifest especially through classroom-level norms, also greatly influences students' opportunities to develop disciplinary identities. Bell et al. (2017) state that "school-level processes of racialized and gendered storylines within STEM disciplines can impact students' disciplinary identification, sense of belonging and forms of participation in schooling" (p.373). Normative classroom practices surrounding science can hugely influence students' conceptions of themselves as scientists. Carlone and colleagues (2011) found that in classrooms where students were expected first and foremost to produce the right answer to share with the teacher, peers did not collaborate as much with one another, and the "smart students" were those who most often individually produced the desired response. However, in classrooms where the normative culture promoted keen observations and scientific collaboration, peers did share their thinking with one another, and the "smart students" were those who could make good observations and facilitate collaborative problem-solving. These more inclusive norms offered students a greater variety of "subject positions" to adopt within school science, thus creating expanded opportunities for affiliation with and participation in science. Specifically, these norms offered students more ways to see themselves as "smart students" and "scientists" and thus promoted affiliation rather than dissociation with science.

Equity-focused Science Pedagogies Disrupt the Status Quo

To create classroom cultures that are more equitable for all students, educators need to actively disrupt settled notions of school and of science and instead implement practices that expand, rather than constrain, learning opportunities for all students—especially those from nondominant communities. As a field, we know a substantial amount about the kinds of teaching practices that foster equitable classroom cultures, disrupt historical inequities, and support learning for all students.

Asset-based perspectives and funds of knowledge

The gap between the academic performance of students from dominant groups as compared with students from non-dominant groups—known as the “achievement gap”—has been well-documented and oft-discussed. Traditional framing of this achievement gap presents lower-performing students as having deficits that need to be remedied to boost achievement. This deficit orientation, however, fails to account for the ways in which the “gap” is an artifact of the structure of schooling (and assessment) more than a reflection of the abilities or potential of students from nondominant groups (Darling-Hammond, 2018; Ladson-Billings, 2006). Worse, this deficit orientation leads to viewing students from nondominant groups as lacking in ways that are central to academic achievement. Moving away from deficit-oriented approaches, some scholars began to focus on school science itself, suggesting that we should reform school science so that students are producers rather than consumers of science (Carlone et al., 2011). This evolution in school science is certainly helpful, but is not, on its own, sufficient to counteract entrenched inequities.

To further counteract deficit-thinking, scholars have encouraged asset-based perspectives that recognize the strengths that students, families, and communities possess. These strengths, including students’ “funds of knowledge” (Moll et al., 1992) and communities’ “cultural wealth” (Yosso, 2005) are legitimate and valuable, and can and should be leveraged to support learning.

Funds of knowledge are “the historically accumulated and culturally developed bodies of knowledge and skills essential for household or individual functioning and well-being” (Moll et al., 1992, p.133). Educators should acknowledge, value, and build upon the diverse resources that students bring with them to the classroom and to learning. Scientifically, students all have experiences with the world around them that help to shape their existing knowledge of scientific phenomena, even if they do not perceive their knowledge and experiences as “scientific” per se.

Linguistically, students also have a wealth of resources, including home- or heritage-language resources and everyday registers to communicate their ideas about science. Teachers should encourage students to use any of these linguistic resources to engage with scientific material and communicate their ideas with others (Edelson et al., 2020; Gutierrez, 1999). Building on students’ funds of knowledge in this way, students come to understand that they (and their families and communities) have knowledge, resources, and expertise that are pertinent for learning and doing science.

Valuing multiple ways of knowing about science

Connected with drawing on student funds of knowledge, educators can also support multiple ways of knowing and experiencing science. Western science is deeply rooted in a particular epistemology that values information gleaned through a systematic process of investigation over other kinds of information and knowledge (Rudolph, 2002). Yet students encounter science regularly within their everyday lives, outside of formal scientific inquiry. Those scientific encounters and everyday ways of knowing about scientific phenomena can help students to draw connections between science and life and support science learning. Just as educators should explicitly draw on students' funds of knowledge to support science learning, they should also encourage students to bring their everyday ways of knowing about science to bear in their formal scientific endeavors (Warren et al., 2001). This approach is particularly relevant when it comes to language, for both native English speakers and emergent bilinguals (MacSwan, 2017; Martin-Beltrán, 2014). Although science has a large and precise vocabulary that helps scientists with their practice, students often use their everyday language to access and communicate scientific ideas—and teachers should encourage students to use their full repertoire of linguistic resources to engage with scientific concepts.

Science teaching as a sociopolitical practice

Science is itself a cultural endeavor that embodies particular social, historical, and political assumptions and perspectives (Lemke, 2001). Science both shapes and is shaped by the values, power, and ideologies of scientists, past and present. One important aspect of disrupting normative features of the culture of science, then, is to explicitly address them as part of instruction. Being explicit about the nature of science in this way provides students with an understanding of the historical and present-day inequities that exist within science and of the ways in which science culture still creates barriers to participation. With this understanding, educators and learners can collaboratively dismantle those barriers (Bang et al., 2012) and expand the boundaries of science and scientific contributions. Calabrese Barton and Tan (2010) define equitable science classrooms as providing spaces where students can expand their academic and scientific roles, negotiate their participation, and share epistemic authority. More broadly, educators need to take on the political struggles that will ultimately enable students to claim their “rightful presence” within schooling and within science (Calabrese Barton & Tan, 2020). This process of redefining who can legitimately and productively engage in science helps to transform the cultural structures that exist to be more inclusive for students from nondominant communities.

Curricula Shape Science Education Equity

Of course, teacher instruction does not operate in isolation within the classroom. We often think of what happens within the classroom as being part of a larger system. Cohen and Ball (2000) describe this system as an instructional triangle, consisting of teachers (and their instruction), students (and their participation roles), and content (including curricula and other resources). Each of these components, and their relationships to one another, situated within a particular context shape the learning opportunities that students experience. Far from being neutral with respect to equity, curricula have long served as a vehicle for perpetuating social inequities (Kirchgasler, 2023; Margolis et al., 2008; Yosso, 2002). For example, curricula serving students from lower socioeconomic classes and racialized communities have often offered limited content, lower standards, and less rigor than curricula geared toward students from dominant communities (Kirchgasler, 2023; Margolis et al., 2008; Songer 2002).

Myriad strategies exist for designing curricula that support greater equity. Most commonly, these strategies involve adding content to represent diversity within the field—for example, anecdotes of successful minorities or images of minority students participating in science (Banks, 1989). Other more transformative approaches tackle issues of power and privilege more directly by incorporating teaching explicitly about social justice issues (Mensah, 2022). In science, the NGSS calls for curricula that attend to equity and provides case studies to describe equitable science instruction (NASEM, 2019). However, the standards do not provide specific guidance for how to design curricula where the content, materials, and activity structures themselves directly support equitable learning opportunities for students (Tzou et al., 2021).

Underlying Epistemologies of Science

The science cultures, pedagogies, and curricula that support equity share an underlying epistemology of science: these approaches recognize that science is a means of satisfying our curiosities about the world by asking questions and gathering evidence to incrementally expand our understanding of natural phenomena. The practice of science and science knowledge are inextricably intertwined, as knowledge drives questions that lead us to engage in scientific practices in the pursuit of further knowledge (Berland, 2016; Manz, 2020). Engaging in science practices also means making mistakes, iterating, and revising our thinking as we build ever deeper understandings. As a sociocultural endeavor, science also involves collaboration, sharing and debating ideas, and vulnerability to share incomplete or unconfirmed thinking with others.

The current practice-turn in science education reflects the belief and the hope that through engaging in authentic, meaningful, and consequential science practices, students will construct a broader and more flexible understanding of science—one that necessarily allows for their own belonging (Duschl, 2008; Lehrer & Schauble, 2006). Scholars recognize the importance for students of having a grasp of how science operates and what it entails (Berland et al., 2016; Ford and Forman, 2006). The literature offers myriad strategies for structuring student engagement with science practices in ways that enable students to obtain this grasp of science epistemology, e.g., through ambitious instruction (Stroupe, 2014), affording students epistemic agency (Miller et al., 2017), and rethinking science investigations in ways that help students to understand science as locally meaningful and productive (Manz et al., 2019). However, research has shown that engagement with practices as currently instantiated in most science classrooms is insufficient for students to intuit this broader and more flexible understanding of science (Gouvea & Passmore, 2017; Sandoval & Morrison, 2003; Sandoval, 2005), leaving open questions about the potential need for greater attention to epistemology within science classrooms.

Dissertation Study Context

My dissertation research takes place within the context of a large-scale implementation research study of OpenSciEd, a full middle-school science curriculum aligned with the Next Generation Science Standards (NGSS) and freely available to the public through Open Educational Resources (OER). The field test of OpenSciEd took place from fall 2018 through spring 2021, involving a total of 341 teachers and more than 12,400 students over that span of time. As part of the field test data collection, the research team gathered teacher surveys, student surveys, and conducted interviews with a subset of participating teachers. OpenSciEd has been developed from the ground up with intentionality around disrupting the status quo to support equity in science teaching and learning, and thus provides a fruitful context for examining equitable science classroom cultures.

OpenSciEd Background and Goals

OpenSciEd has an ambitious goal: the developers hope to transform science teaching and learning across the country through student-centered, reform-oriented instructional materials that place equity at their core (Edelson et al., 2021). Specifically, they seek to transform school science such that: 1) students learn science through active investigations of complex phenomena that enable them to construct new understandings and competencies; 2) teachers establish the learning context, organize learning experiences, and facilitate productive social interactions, while removing inequitable obstacles and expanding access to science learning. These goals reflect the sociocultural underpinnings of the curriculum, and the view that learning happens through active engagement with content that builds on prior histories and experiences and is shaped by culture and relationships.

The OpenSciEd design team, consisting of teachers and researchers working in partnership, constructed multiple design features to support their goals around student sensemaking and equity. Each of these design features also helps teachers establish equitable classroom cultures where students are actively engaged in scientific knowledge-building. First, the curriculum uses a storyline framework to drive the content. Storylines begin with a phenomenon or problem that anchors the rest of the unit. Students generate questions that they deem necessary for understanding the phenomenon or designing a solution to the problem and then use science and engineering practices to seek out answers. Teachers guide and facilitate the process, steering students toward more productive lines of questioning, providing information and resources to address their questions, explaining key features of the science, and helping students to extract the core concepts. Within this model, students collaborate to build scientific knowledge, bringing their full repertoire of experience, knowledge, and resources to bear in the process.

Second, OpenSciEd professional development provides explicit guidance around engaging students in scientific sensemaking and building equitable cultures. For example, during professional development, teachers engage in “student hat” where they participate in knowledge-building together as if they were students. The purpose of this “student hat” exercise is to help teachers gain a feeling for what it feels like to be a student inside a classroom where knowledge is being constructed together, and not simply given by the teacher or text (Lowell & McNeill, 2020). By participating in and subsequently debriefing on this experience, educators gain perspective on student experiences in the classroom, the vulnerability required to participate in the uncertain endeavor of scientific sensemaking, and the care required to support student participation.

Finally, OpenSciEd also includes educative materials for teachers, or instructional guidance embedded within the teacher resources (Davis & Krajcik, 2005). For example, the curricular materials include “equity callouts” to help teachers enact equity-oriented practices and build equitable science classroom cultures. These equity callouts focus on multiple aspects of equity including soliciting and drawing out students’ funds of knowledge; connecting the content to students’ lives and communities; supporting the use of everyday language, native languages and alternate registers; and attending to historical and political injustices connected with the content.

Taken together, the foundational orientation of the OpenSciEd initiative, along with specific design features and built-in supports for teachers, provides a fertile context for our study. OpenSciEd classrooms offer an opportunity to explore features of classroom cultures that may be associated with equitable student experiences and outcomes; and to examine the teacher practices that support the cultivation of such classroom cultures.

OpenSciEd Field Study

The studies proposed for this dissertation are all part of the larger OpenSciEd Field Test. This field test ran from fall 2018 through spring 2021 in middle school science classrooms across the United States. Ten partner states volunteered to join the initiative, together comprising the State Steering Committee. Each state's representative recruited partner teachers within their state who volunteered to participate in the field test. A total of 341 teachers took part in the curriculum field test, distributed across 97 districts and ten states. The field test included over 12,400 students representing diverse racial, gender, and linguistic backgrounds and a wide range of abilities. Teachers participated for varying amounts of time, ranging from a single semester to three or more years. Each teacher implemented one or more OpenSciEd units, with topics ranging from Ecosystems to Thermal Energy to Natural Selection. Data collection for the field test involved multiple types of surveys with participating teachers and students (Table 0.1). The team also conducted interviews with a subset of 89 participating teachers; in total the team conducted 120 interviews, with some teachers participating in a single interview and others participating in up to four interviews. These teachers were selected to represent a range of implementation profiles, based on self-reported implementation data on surveys. The sections describing each of the three proposed papers, below, specify the participant sample and data for that paper in greater detail.

Table 0.1. OpenSciEd Field Test Survey Data Collection

Category	**Survey Instrument**	**Year 1 (2018-2019)**	**Year 2 (2019-2020)**	**Year 3 (2020-2021)**
Context and Moderator Variables	Teacher Background	X	X	X
	District Characteristics	X	X	
	Class Demographics	X	X	X
Professional Learning	PL Facilitator Surveys		X	X
	PL Teacher Surveys	X	X	X
Implementation	Teacher Logs	X		
	Teacher End-of-Unit Surveys	X	X	X
Student Experiences	Student Electronic Exit Tickets	X	X	X
	Student End-of-Unit Surveys		X	X

Dissertation Overview

My dissertation examines the contours of equitable science classroom cultures and their relationships with positive student experiences and outcomes in science. In Paper 1, I consider two specific features of classroom culture–namely, collective enterprise and care. Using data from student surveys, I examine how these features of the classroom culture can support interest development in science for students from historically minoritized communities. In Paper 2, I examine how the classroom cultures reflect particular epistemologies of science, as evidenced through student reports about how their science classrooms treat things like asking questions, making mistakes, and sharing ideas. Using student survey data, I examine the relationship between the science epistemology that students perceive in their classrooms, with students' sense of belonging in science class. For Paper 3, I use interview data from a subset of participating teachers to explore the role of curricular structures for advancing equitable science teaching and learning. Taken together, this suite of papers will contribute to our understanding about the nature of equitable science classroom cultures and their consequences for student experiences and outcomes in science, as well as providing insights about other components of curricular activity systems that aid in the construction of equitable science classroom cultures.

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Paper 1: The Role of Equitable Classroom Cultures for Supporting Interest in Science[1]

Introduction

For the past many decades, broadening participation in science and other STEM fields has been of key national importance. Although elementary school students typically express a strong interest in and curiosity about science, that interest declines sharply in the middle grades, particularly for girls and racially minoritized youth (see Potvin & Hasni, 2014, for a review). Scholars now understand that this declining interest is not due to a lack of ability, but rather to sociocultural features of schooling and of science as a discipline that continue to exclude girls and students of color (e.g., Ceci et al., 2009; Su & Rounds, 2015). Cultural aspects of schooling and of science in particular hinder students from developing the interest in science and identification as scientists that are essential to pursuing future education and careers in these fields (Calabrese-Barton & Tan, 2020; Carlone, 2017).

Interest in science is of critical importance because it supports better science learning and promotes persistence in science and other STEM fields (i.e., technology, engineering, and math). Interest is particularly central to learning for students from low-income and minority backgrounds who have historically been under-represented in the sciences (Bang & Marin, 2015). Students who are interested in a topic learn better because their interest supports greater focus and attention within the learning process (Deci & Ryan, 1994; Deci, et al., 1991; Koestner & Losier, 2002; Reeve, 2002; Schiefele, et al., 1992). Interest is also a key determinant of both science identity development and pursuing future education and careers in STEM (e.g., Kang et

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al., 2019; Kang & Keinonen, 2017; Maltese & Cooper, 2018; Nugent et al., 2015; Wang, 2013). Research has found that interest, above and beyond achievement, influences who chooses to pursue careers in STEM (Tai et al., 2006).

This paper explores the conjecture that classroom culture is one factor that influences student interest development in science. Classroom culture is essential in shaping the science learning experiences that students encounter because it determines the nature of relationships and interactions within the classroom, as well as the roles, tasks, and participation structures available to students (Black et al., 2004; Supovitz & Turner, 2000). In science classrooms, the culture reflects how science itself is presented to students, and shapes the opportunities that students have to engage in scientific sensemaking (Krist et al., 2016; Tal & Kedmi, 2006). Classroom cultures can be more or less equitable, depending on the extent to which they value and legitimize the identities, knowledge, and experiences of all students in the room, particularly those from backgrounds that have historically been marginalized within school science (Aikenhead & Jegede, 1999). Equitable classroom cultures serve to expand and improve science opportunities for students who are often marginalized in society and in school (Carlone, 2007; Penuel et al., 2023).

Our research explores the relationship between features of equitable classroom cultures and student interest in science at scale. We examine the extent to which classrooms vary in key elements of classroom culture. And we explore the relationship between that classroom-level variation and reported student interest in science across a large number of middle-grades science classrooms. This large-scale study enables us to examine how much of the variation in experiences of classroom culture and interest in science are particular to the student or the classroom, and where relationships between the two are consistent across individuals and contexts. This study aims to provide evidence from across a broad swath of classrooms, operating within varied school, district, and state contexts, about the relationship between specific features of equitable classroom cultures and student interest development in science.

The context for our study is the field test of OpenSciEd middle school curriculum units, a set of full open-access instructional materials designed to align with the Next Generation Science Standards (NGSS; NGSS Lead States, 2013) and designed from the outset to support more equitable participation in science learning. Data come from 847 students in 34 teachers' classrooms located in nine different states. With this study, we aim to contribute to the field's understanding of equitable classroom cultures that support interest development in science for all students, especially girls and youth from historically minoritized racial/ethnic communities.

Conceptual Framework

The focus of our work is to explore the classroom-level conditions that support equitable interest development in science. Here, we draw on existing theories of interest and interest development, as well as literature about equitable classroom cultures and science learning, to theorize about how and why particular science classroom features might promote science interest for all students, particularly those from historically marginalized racial/ethnic and gender populations.

The Nature of Interest and Its Role in Science Persistence

Scholarship on interest tells us that interest in a particular object is not an innate characteristic. Instead, culture, context, and relationships all play a role in shaping interest, both as a state of enjoyment or curiosity and as a more enduring state of being (Azevedo, 2011; Barron, 2006; Hidi & Renninger, 2006). Interest consists of multiple components that interact dynamically with one another and with the environment to shape the strength of one's interest in a given topic at a given time, or over an extended period of time. Here we explore the unique characteristics of interest to lay the foundation for understanding how science classroom cultures connect with student interest in science.

Characteristics and components of interest

The person-object theory of interest defines interest as the relation between a person and the object of interest and argues that interest consists of three central characteristics: cognitive, emotional, and values-related (Krapp, 2007). The *cognitive* aspect of interest refers to a person's readiness to acquire new knowledge in relation to the topic of interest. People who are interested in a particular subject are not content with their existing knowledge or abilities; rather, they have a desire to expand and apply their knowledge and skills. The *emotional* aspect of interest refers to positive emotions such as enjoyment that are connected with an area or activity of interest. These emotional aspects of interest drive motivation (Wigfield & Eccles, 2000); that is, when people feel positive emotions associated with a subject or activity, they develop intrinsic motivation to continue. Finally, the *values-related* characteristics of interest refer to the fact that objects of interest will hold personal significance for the individual, and the goals of the interest area will be compatible with the goals and values of the individual. We propose that by "plugging into" each of these components of interest, science classroom cultures can support student interest in science.

The development of individual interest

The four-phase model of interest development describes how interest develops from context-dependent situational interest to more enduring individual interest (Hidi & Renninger, 2006). Capturing situational interest is an important first step in building sustained interest; while supporting the transition to sustained individual interest is important because this form of interest has especially strong benefits for learning and persistence within a particular field (e.g., Koestner

& Losier, 2002). External factors, notably the learning environment and instructional tasks, influence both the triggering of situational interest and the development of more sustained individual interest. Learning environments that provide “meaningful and personally involving activities” – such as project- and problem-based learning and cooperative group-work – can help build situational interest (Hidi et al., 1998, p.114; Mitchell, 1993; Renninger et al., 2004; Riegle-Crumb et al., 2019; Schraw & Dennison,1994; Sloboda & Davidson, 1995). In turn, learning environments and tasks that provide both challenge and opportunity lend support for emerging individual interest (Nolan, 2006; Pressick-Kilborn & Walker, 2002; Renninger, 2000; Renninger & Shumar, 2002).

Interest in science and science classrooms

The cognitive, emotional, and values-related aspects of interest have been examined in several studies focused on science. Students are more likely to develop interest in science when they perceive that science connects with their values. Scholars have found that promoting the perceived utility value of science by encouraging students to make connections between science and their lives and futures boosts interest for students (Basu & Barton, 2007; Hulleman & Harackiewicz, 2009). Cognitively and emotionally, scholars have found that curiosity and enjoyment related to particular practices of scientific inquiry contribute to the development of interest in science (Ainley & Ainley, 2011; Luce & Hsi, 2015). For example, students may experience a thrill when, having made a prediction about the outcome of an experiment, they then conduct the experiment and find their prediction substantiated. These emotions connected with the doing of science (as opposed to feelings about science as a topic) can help to drive interest in science.

Many scholars have also documented the importance of perceived recognition for interest development in science (Carlone, 2007; Kalendar et al., 2019). Perceived recognition refers to the feeling that influential others see you as competent and capable in science. This component of interest development is particularly important in science classrooms, where students are accustomed to receiving judgements from teachers (and peers) about their abilities as science students–judgments that play an outsized role in shaping students' beliefs about their own place within the field of science. These unique characteristics of interest development in science point to aspects of the classroom culture that matter for establishing the fertile ground that can support students to develop interest in science.

The Importance of Interest for Persistence in Science

Interest plays a key role in students' persistence in science and other STEM fields. Interest in science is often sparked early (middle-school or before) and through school-based factors and experiences (Maltese & Tai, 2010). Females in particular point to the role of teachers and other mentors in sparking their early interest in STEM fields (Maltese & Cooper, 2010; Maltese et al., 2014). This inchoate interest in science has the potential to impact students' course-taking and career choices, even above and beyond their math and science achievement (Tai et al., 2006). Ainley and Ainley (2011) found that interest in science was highly correlated with students' future participation in science-related activities and careers. Maltese and Cooper (2017) similarly found that interest was the most common factor for persisting in STEM over time. Researchers have found that there is no singular pathway leading toward successful STEM majors, in terms of the timing or manner of triggered interest (Maltese & Cooper, 2017; Maltese et al., 2014). Nonetheless, the consistent role of interest in STEM persistence, combined with the known influence of school on triggering (or sometimes dampening) science interest, points to the critical importance of attending to the classroom-based factors that can effectively support student interest in science, particularly for students from historically marginalized populations.

Equitable Science Classroom Cultures and Interest

Classroom culture refers to an amalgamation of factors within the classroom that together create the environment that students experience and that shapes their opportunities for learning and growth (Cavanaugh & Waugh, 2004). Classroom culture encapsulates the nature of the relationships and interactions within the classroom, including norms for speaking and working together (Kang & Nation, 2022; Kang & Furtak, 2021; Krist, 2020; Supovitz & Turner, 2000), as well as the roles and participation structures that are available to and expected of students (Anderson et al., 2018; Goldman et al., 2019). Classroom culture reflects how knowledge-building happens within the classroom and who participates, including the kinds of thinking and sensemaking that are valued, and what students are held accountable for knowing (Black et al., 2004; Calabrese Barton et al., 2020; Stroupe, 2014). The culture is also evident in what it means to be considered “smart” or “successful” within the classroom (Carlone et al., 2011).

In science classrooms specifically, the culture reflects how science itself is presented to and experienced by students, with attendant implications for whether and how students have opportunities to connect with the discipline of science (Tal & Kedmi, 2006). The culture establishes how people treat each other within that space, how they talk to and with one another, what role they have in building knowledge, how they handle uncertainty and mistakes, etc. Classrooms can vary substantially in each of these areas–for example, in some classrooms, teachers may be in charge of presenting established knowledge to students, whereas in other classrooms students may be expected to take part in collective knowledge-building efforts.

We conjecture that equitable classroom cultures can broaden interest development in science by expanding *who* has opportunities to connect with the cognitive, emotional, and values-related aspects of interest development in science. Such classrooms offer environments where all students, but particularly those from historically marginalized racial/ethnic and gender backgrounds, have the opportunity to experience epistemic emotions connected to scientific practice–emotions that drive both curiosity and interest. Such classrooms also can expand students' understanding of what science is, how it happens, who can participate, and toward what ends–thus expanding the potential for students to see their own values reflected in the scientific enterprise.

The role of equitable classroom cultures in science

Recognizing the sociocultural nature of science and science learning points to the importance of understanding how students affiliate with and/or become alienated from science, via their experiences within their science classroom communities (Carlone, 2007; Lave & Wenger, 1991). The classroom culture and the nature of the relationships and interactions within classrooms shape student experiences and opportunities for interest development (Renninger & Hidi, 2002; Sansone & Smith, 2000). As we elaborate below, equitable classroom cultures can serve to attenuate effects of systemic inequities, expand the boundaries of sanctioned disciplinary participation, and broaden opportunities for students to connect with science. These openings are essential for students to find the emotional, cognitive, and value-related connections to science that can drive interest in the discipline.

Classrooms are borderlands where multiple sociocultural contexts collide (Gutiérrez et al., 1999) and they often align more closely with the lives of some students than others, implicitly communicating the value of some knowledge, experiences, and ways of knowing over others (Bang et al. 2012; Bell et al., 2017). Through didactic teacher-centered instruction and a focus on individual accomplishment over joint knowledge-building, many science classroom cultures also implicitly communicate that science is a “finished body of knowledge” and that the good science students are the ones who always have the right answer to the teacher’s questions (Schwab, 1982). These narrowly construed ideas about what science is and how to do science alienate many students, particularly those from racially and ethnically minoritized communities (Bang et al., 2012; Bell et al., 2017). By expanding ideas about what science is and who can meaningfully participate, equitable classroom cultures can lay the foundation for a broader range of students to connect with science (Bang et al., 2017).

Concomitantly, a single classroom environment can function very differently for different students or groups of students. Although a group of students may occupy the same classroom space with the same teacher and peers, they do not necessarily experience the classroom culture in the same way (Carlone, 2007; Schweig & Martinez, 2021). Indeed, a single classroom can contain multiple cultures in one, reflecting differential expectations for subgroups of students, different sets of rules, expectations, and pedagogical strategies (Babad, 1993; Brophy & Good, 1974; as cited in Schweig & Martinez, 2021). Here, we discuss two features of classroom cultures–collective enterprise and care–and describe how they can manifest within contemporary science classrooms and what it means for them to be cultivated equitably.

Connecting Collective Enterprise with Interest in Science

Collective enterprise means that students and the teacher work together to build and advance students’ understanding of scientific concepts (Scardamalia & Bereiter, 1991). This endeavor entails collaboratively sharing and exploring ideas, respectfully critiquing one another’s ideas, and engaging in collective sense-making to reach conclusions and build understanding (Reiser et al., 2017). Practices where students engage together in making sense of phenomena further underscore that students have a role to play in science, and moreover that science is a collective, collaborative endeavor.

Fostering equitable collective enterprise means establishing norms and expectations of inclusion wherein students have (and perceive themselves to have) equitable opportunities to contribute to group discussion and sense-making. In these spaces, teachers support purposeful sensemaking where, through students' exercise of their own agency with others, they advance the class' understanding of phenomena they are studying (Alzen et al., 2022). To create such environments, teachers and students must recognize the diverse ways that students can contribute to the group and invite and accept contributions reflecting varied ways of knowing and forms of experience (Clarke et al., 2016; Patterson, 2019).

We conjecture that in classrooms where students engage in collective enterprise, students build the emotional, cognitive, and values-related foundations for developing interest in science. Classroom cultures and norms that encourage student initiative and problem posing, serve to build intellectual and emotional ownership over the work, and can promote science interest (Azevedo, 2018). Moreover, engaging in collective enterprise enables students to see science as a communal effort geared toward solving scientific problems, and connects to the values-driven component of interest. Connecting to communal values has been found to be particularly relevant for girls: Research has shown that girls place high value on communal goals but that they often perceive science as being antithetical to such goals (Bielefeldt, 2017; Ceci & Williams, 2011; Diekman et al., 2010; Diekman et al., 2011; Kang et al., 2019). As such, communicating to students that science is a collaborative and communal endeavor may be important for supporting interest development in science.

Connecting Caring Environments with Interest in Science

Caring environments are those in which teachers and students attend to one another's needs and welfare (Noddings, 2012). In science, caring environments demonstrate fidelity to persons, that is, the commitment of students to the growth and well-being of others, grounded in caring relationships (Krist & Suarez, 2018). As students engage with scientific practices, *epistemic caring* is particularly important; this type of caring entails positioning students as knowledgeable and their ideas as valuable, treating one another's ideas with respect, working to understand one another, and collectively building a shared understanding of the phenomenon at hand (Krist & Suarez). Teachers can also demonstrate caring in science by letting students know that they empathize with the struggle to understand new ideas (Jaber et al., 2022). Such environments foster the trust that students need to feel comfortable being vulnerable–an essential feature of grappling with the uncertainty that is inherent to scientific inquiry and sensemaking (Krist, 2020).

Within caring environments concerned explicitly with equity, teachers and students notice harms and inequities within interactions, particularly how others may be silenced or made to feel invisible in classrooms (Patterson, 2019) and work to build a culture that affirms racially minoritized students and elevates their voices (Carlone et al., 2011). Such environments also promote *critical caring*, which conjoins culturally relevant curricula and identity-affirming pedagogies with high-quality relationships and high expectations for student success (Antrop-González & De Jesús, 2006).

We propose that caring environments also have the potential to nurture student interest in science. Classroom cultures oriented toward caring and collective well-being lay a foundation of trust and safety that enable students to take on the risks and vulnerability required to engage in scientific practices and sensemaking together (Carlone et al., 2021) which in turn provide a foundation for interest. Classrooms built around relationships and around science activities that further students' social priorities, greatly support the development of sustained interest in science (Basu & Barton, 2007). Strong and caring relationships support feelings of enjoyment associated with the subject, which supports the emotional dimension of interest. Finally, showing care by communicating to students that they are knowledgeable, and their ideas are valuable, likely provides students with the recognition that in turn supports interest development.

The Current Study

The current study aims to identify specific aspects of equitable classroom cultures that support student interest in science at scale. The study is part of a larger implementation field test of the OpenSciEd middle school curriculum. The field test and associated research took place from 2018 through 2021 in science classrooms across the country. This section provides details about the OpenSciEd curriculum, and about the participant sample, data collection, and research methods for this study.

The Intervention: About OpenSciEd

The teachers in the study were implementing field test versions of six- to eight-week science units aligned to the Next Generation Science Standards (NGSS; NGSS Lead States, 2013). Each unit follows a storyline that begins with an anchoring phenomenon and develops around student questions and investigations about that phenomenon (Reiser et al., 2021). These storyline units are a form of project-based learning in the sense that students figure out key ideas through engaging in science and engineering practices to explain phenomena and design solutions to problems (NASEM, 2019; Penuel et al., 2022). As detailed below, an integrated set of teaching routines, educative supports embedded in materials (Davis & Krajcik, 2005), and professional learning help teachers to foster an equitable culture that supports collective enterprise and caring.

Support for collective enterprise

A central feature of collective enterprise is that students work together to figure out science by sharing and exploring ideas together. In storyline units, the curricular materials and a core set of routines support students in collaborating to figure out a phenomenon or solve a problem; students do not figure things out in isolation. For instance, within the Anchoring Phenomenon Routine students collaboratively explore a puzzling phenomenon or problem, develop initial models to explain what is happening, and identify related experiences and phenomena that could help them explain the phenomenon or problem. As part of this routine, students generate and prioritize questions that the class agrees are important to pursue over the course of the unit, and they identify potential investigations that could help them answer their questions. The process of building scientific knowledge also happens collaboratively: throughout each unit, students engage in tasks that require them to synthesize information gathered across small groups (e.g., using the Jigsaw technique); to compare and evaluate explanatory models of peers; and to come to consensus on models of phenomena that best reflect evidence students have encountered and developed as part of the unit.

The OpenSciEd professional learning provides additional resources and opportunities to prepare teachers to cultivate classroom cultures where students work together to figure out key science ideas. For example, teachers receive discussion planning tools, which direct them to establish goals for discussion, plan for how they will encourage students to work with one another’s ideas and decide on how to synthesize agreements and disagreements among students.

An important feature of professional learning is engaging educators as if they were students participating in knowledge-building together in “student hat” (Lowell & McNeill, 2020), a strategy intended to help teachers gain a feeling for what it feels like to be a student inside a classroom where knowledge is being constructed together, and not simply given by the teacher or text.

Support for caring

Support for caring is embodied in a set of common agreements for OpenSciEd classrooms that are introduced and modeled in professional learning and supported within curriculum activities (Table 1.1). These agreements are intended to support equitable participation by fostering a community in which people are committed to one another’s learning and well-being. The agreements acknowledge that the cultures that typically emerge in science classrooms often align with dominant cultures; to disrupt that pattern, teachers and students must intentionally co-construct classroom norms that help all students feel respected and valued. The agreements fall into four broad categories, each of which integrates a dimension of care: respectful, equitable, committed to our community, and moving our science thinking forward. For example, under the category of respectful, specific norms encourage mutual support and debate where ideas are critiqued but not persons. Under the category of equitable, norms encourage active seeking out of voices and appreciation of diversity. Together, these agreements are intended to cultivate spaces where students experience the care required to support the vulnerability and uncertainty required to engage in figuring out science.

Table 1.1. OpenSciEd Classroom Agreements Reflecting Support for Care

Norms	**Agreements**	**Talk Moves to Support Norms**
Respectful *Our classroom is a safe space to share.*	● We provide each other with support and encouragement. ● We share our time to talk. We do this by giving others time to think and share. ● We critique the *ideas* we are working with, but not the *people* we are working with.	● "Daniel, that's a great idea. How do you think we could investigate it?" ● Give time to think using wait time, turn and talk, or during individual writing time, such as Stop and Jot. ● "Why do you disagree with Juan's idea?" rather than "Why do you disagree with Juan?"
Equitable *Everyone's participation and ideas are valuable.*	● We monitor our own time spent talking. ● We encourage others' voices who we have not heard from yet. ● We recognize and value that people think, share, and represent their ideas in different ways.	● "I'd like to hear from someone who hasn't yet gotten a chance to talk." ● "How did we do today in our discussion making space to hear from everyone?" ● "The way Shayna described ____ really helped me think about it in a different way."
Committed to our community *We learn together.*	● We come prepared to work toward a common goal. ● We share our own thinking to help us all learn. ● We listen carefully and ask questions to help us understand everyone's ideas. ● We speak clearly and loud enough so everyone can hear.	● "Who can paraphrase what Selma just said?" ● "What did your partner say?" ● "What questions do you have for Shereen about her idea?" ● "I think I heard what you said, but can you say it again to make sure everyone heard?"
Moving our science thinking forward *We work together to figure things out.*	● We use and build on other's ideas. ● We use evidence to support our ideas, ask for evidence from others, and suggest ways to get additional evidence. ● We are open to changing our minds. ● We challenge ourselves to think in new ways.	● "Why do you think that? What's your evidence?" ● "Do you agree or disagree with what Juan said? Why?" ● "Who can add onto Jerome's' idea?" ● "Did you see something represented in someone else's work that changes how you are thinking about ____?"

Table reproduced from OpenSciEd Middle School Curriculum, Teacher Handbook Version 4.0

Research Methods

This study focused on examining the relationships between features of equitable classroom cultures and students' interest development in science. Specifically, we sought to answer the following research questions:

- To what extent do classrooms vary in the degree to which they reflect cultures of collective enterprise and caring?
    - How do student reports of classroom culture vary by race/ethnicity or by gender subgroups?
- To what extent do classrooms vary in the extent to which students express science interest?
    - How do student reports of interest vary by race/ethnicity or by gender subgroups?
- How do collective enterprise and caring relate to students' reported interest in science?
    - Is the relationship between classroom culture and interest moderated by student race/ethnicity or by gender?

To address these questions, we first investigated the degree of variability both between and within classrooms with respect to reports of classroom culture (i.e., collective enterprise, care) and interest. To be equitable, we would expect that students with a variety of different identities (e.g., race/ethnicity, gender) from different backgrounds would report experiencing similar, high levels of collective enterprise and care (as well as interest) within the same classroom. In turn, we seek to understand the relationship between those features of the classroom culture and student interest in science.

Participant Sample

Ten states participated in the OpenSciEd field test: California, Iowa, Louisiana, Massachusetts, Michigan, New Jersey, New Mexico, Oklahoma, Rhode Island, and Washington state. The project leads within each state recruited teachers for the study and made decisions around compensation structures, which consequently differed by state. The data for this study come from survey responses gathered in Spring 2021 from 847 middle-grades science students in 34 teachers' classrooms across nine different states (Washington did not participate that semester). On average, each teacher had 24.9 students (*SD*=19.2) respond to the student end-of-unit survey. During the Spring 2021 semester, each classroom worked with one OpenSciEd unit: 6th graders studied Cells; 7th graders studied Earth's Resources; and 8th graders studied Natural Selection. Just over half of the participants self-identified as white (54%); the next largest group was students who identified as Latinx or Hispanic (17%), followed by students from multiple racial/ethnic groups (15%). African Americans (7%), Asian Americans (4%), and American Indians / Native Alaskans (3%) each made up less than 10% of the participants (Table 1.2). We had fewer than five students identifying as Native Hawaiian / Pacific Islander in our sample (n=3), and so we removed these observations from the data. Separately, just over half of the sample identified as female (52%), while 46% identified as male, and about 1% identified as non-binary.

Table 1.2. Demographics of the Sample

	n	%
Race/Ethnicity		
African American or Black	57	6.88%
American Indian / Native Alaskan	22	2.65%
Asian or Asian American	30	3.62%
Latinx or Hispanic	143	17.25%
Multiple	127	15.32%
White	450	54.28%
Gender		
Male	376	46.48%
Female	424	52.41%
Nonbinary	9	1.11%

Data Source & Measures

The data source for this study was a student survey, which was a composite measure created by the research team based on the literature, including existing validated scales for middle-schoolers. Students completed the survey at the end of their OpenSciEd unit in the Spring of 2021. The survey included questions about students' background and home language, their experience of the classroom culture within their science class, and their interest and identification with science.

The research team created scales for collective enterprise, care, and interest (among others that do not form part of the analysis for this study). The collective enterprise scale drew on ideas from Alzen et al. (2022) that define collective enterprise as a commitment to "collaborative idea production" among all members of a community and that emphasize the importance of engaging with and acting on student ideas to advance scientific understanding. The care scale drew on ideas from Krist & Suarez (2018) arguing that care in science learning environments entails a) respecting students in part by respecting their ideas and b) a commitment to everyone's well-being and growth. The interest scale drew on the Expectancy Value Cost Scale of Interest (EVC; Kosovich et al., 2015) and the Students' Perceived Utility Value Scale (Harackiewicz et al., 2012). Both of these scales had high levels of internal consistency; and the EVC scale was found to be related to relevant external outcomes, such as future interest in science. The resulting interest scale for our study also aligns with Krapp's person-object theory of interest, in that it addresses emotional, cognitive, and values-related components of interest.

We conducted a post-hoc exploratory factor analysis of the student end-of-unit survey items relevant to our study to provide information about how items cluster along the three target constructs: collective enterprise, care, and interest. Initial factor analysis of the 19 items theorized to comprise these constructs resulted in three distinct factors based on the eigenvalues, of which three factors had values above the threshold of 1 (see Appendix).

We then focused on the 13 items we theorized to make up collective enterprise and care and the six items that are part of our interest scale. For the collective enterprise and care items, the eigenvalues showed two distinct factors. We used promax oblique rotation (as opposed to orthogonal rotation) because we had theoretical reasons to believe that the two factors (constructs) would be correlated. Subsequent analysis confirmed this relationship, showing a correlation coefficient of 0.64 between the two factors. Eleven of the thirteen items loaded onto one or the other of our two factors with a loading of at least 0.3 or above; one item loaded onto both factors; and one item did not load onto either factor. The item that loaded onto both factors read, *We work together with our teacher to make decisions in our class.* This item has a strong conceptual alignment with the collective enterprise construct, and so we included it in that scale. The item that did not load onto either factor was a reverse-scored item that read, *The teacher makes all the decisions about what we do in class.* The reverse nature of the item may have caused confusion; and students may have had different interpretations of what it means for the teacher to make "all the decisions" about the class. Consequently, we decided not to include this item as part of either scale. A separate factor analysis of the six interest items showed these items to be unidimensional, with one eigenvalue above the threshold value of 1, and with all items strongly loading onto one single factor. The final scales were structured as follows:

Collective Enterprise. The scale measuring collective enterprise contained six items. Questions included statements such as: *"We work together to come up with explanations for the phenomena we are studying"*, *"We are expected to connect our ideas to the ideas of other students"*, *"We incorporate everyone's ideas into our explanations of phenomena",* and *"My* *questions/interests/wonderings influence what we do in class."* The item response options were: (1) strongly disagree, (2) moderately disagree, (3) slightly disagree, (4) slightly agree, (5) moderately agree, and (6) strongly agree. The Cronbach's alpha for our scale was 0.84, suggesting strong reliability of the scale.

Care. The scale measuring care contained five items. These items included statements such as, *"The teacher shows respect for everyone's ideas"*, *"The teacher gives help to those students who need it"* and *"All students are treated fairly."* Again, students responded on a six-point agree/disagree Likert scale. The Cronbach's alpha for this scale was 0.91, also suggesting strong reliability of the scale.

Interest. The scale measuring interest contained six items, aligned with Krapp's person-object theory of interest (Table 1.3). Two of the items reflect emotional characteristics of interest, such as a sense of enjoyment. One item addressed the cognitive component of interest, asking about the extent to which students are interested in the content of the class. Three items addressed the values-related component of interest, thinking about whether science is helpful and worthwhile. The item prompt asked students how much each statement "describes you", and the answer choices were: (1) Not at all like me; (2) a little bit like me; (3) somewhat like me; (4) quite a bit like me; (5) exactly like me. The Cronbach's alpha for this scale was 0.90, suggesting strong reliability across items.

Table 1.3. OpenSciEd Interest Measure & Alignment to Person-object Theory of Interest

Interest Scale Item	**Component of Interest**
I enjoy science activities.	Emotional characteristic
I look forward to my science class.	Emotional characteristic
I am interested in the things I learn in science class.	Cognitive characteristic
I think making an effort in science class is worthwhile.	Values-related
I think science will help me even when I am not in school.	Values-related
I think it is important to do well on science assignments.	Values-related

Analytic Approach

In the first phase of analysis, we examined aspects of classroom culture–specifically collective enterprise and care–as the outcome variables, using hierarchical linear models with students nested within classrooms. With these models, we examined both the degree of classroom-level variation in aspects of classroom culture and the extent to which participating OpenSciEd classrooms were equitable with respect to student experiences of the classroom culture. Specifically, to understand classroom variability in aspects of classroom culture, we fit unconditional models with care and collective enterprise as the dependent variables. We examined the classroom- and student-level variance components for these models, and the intra-class correlations, to understand the proportion of variation that exists at the classroom and student levels in the data. We also tested the null hypothesis that the classroom-level variation in collective enterprise and care was equal to zero, using an (exact) restricted likelihood ratio test to test the significance of the random effects.

To interrogate the degree of equity within these classrooms, we fit additional models that included indicator variables for student gender and race/ethnicity as fixed effects. We used Black students as our reference group, to decenter the white experience as the standard for comparison. We used emmeans (Lenth, 2022) to test the significance of the differences for all the applicable pairwise contrasts. Equitable classrooms would be ones in which characteristics of student identity, such as gender or race/ethnicity, are not associated with students' experience of care and collective enterprise in classroom cultures.

In the second phase of analysis, we modeled reported student interest as the dependent variable, again using hierarchical linear models and nesting students within classrooms. We examined the proportion of classroom- and student-level variation using an unconditional model of interest, with students nested within classrooms. We tested the null hypothesis that classroom-level variation in science interest was equal to zero, again using an (exact) restricted likelihood ratio test to test the significance of the random effects. To interrogate the degree to which students of different race/ethnicities and students of different genders report similar or different levels of interest, we added students' self-identified race/ethnicity and gender as fixed effects within the model, again nesting students within classrooms. We used emmeans to test all the relevant pairwise comparisons between student gender and race/ethnicity subgroups. We also investigated differences by grade-level/unit in terms of student interest in science. Here, we used 6th graders (studying the cells unit) as the reference group; the other groups were 7th graders (studying Earth's resources) and 8th graders (studying natural selection).

Finally, we created two separate models to investigate relationships between classroom culture and interest: in one model, we used student-reported collective enterprise as our focal covariate and in another we used student-reported care as the focal covariate. We included interactions between care with gender and race/ethnicity respectively, and between collective enterprise with gender and race/ethnicity respectively, in order to understand whether the relationship between culture and interest varies by student background characteristics. We retained grade-level/unit as a covariate for interest. Our final Level 1 and Level 2 models for science interest with care as the covariate of interest were:

Composite Model with Care * Gender Interaction:

$$\text{INTEREST}_{ij} = \beta_0 + \beta_1(\text{CARE})_{ij} + \beta_2(\text{RACE})_{ij} + \beta_3(\text{GENDER})_{ij} + \beta_4(\text{UNIT})_j + \beta_5(\text{CARE}_{ij} * \text{GENDER}_{ij}) + u_{0j} + r_{ij}$$

Composite Model with Care * Race Interaction:

$$\text{INTEREST}_{ij} = \beta_0 + \beta_1(\text{CARE})_{ij} + \beta_2(\text{RACE})_{ij} + \beta_3(\text{GENDER})_{ij} + \beta_4(\text{UNIT})_j + \beta_5(\text{CARE}_{ij} * \text{RACE}_{ij}) + u_{0j} + r_{ij}$$

Wherein:

i = Level-1 unit (i.e., the ith individual student)
j = Level-2 unit (i.e. the jth classroom)
r_{ij} = Level 1 residual (unexplained student-to-student variability)
u_{0j} = Level 2 random effect (unexplained group-to-group variability)

With the following assumptions:

$r_{ij} \sim N(0, \sigma^2)$
$u_{0j} \sim N(0, \tau_{00})$

The models for science interest with collective enterprise as the covariate of interest were the same, replacing care with enterprise. Based on these models, we examined the relationship between classroom culture (enterprise, care) and student interest in science.

Findings

Classroom culture varies substantially across classrooms, but mostly not by student gender or race/ethnicity

We found that classrooms varied in the degree to which they reflected cultures characterized by collective enterprise and care (Figure 1.1). Specifically, classroom-level variation accounts for about 12% of the total observed variation in care, and about 7% of the total observed variation in collective enterprise; and this classroom-level variation was significant (*p*<0.001 for both care and enterprise) at the *p*<0.05 level (Tables 1.4 and 1.5). We note that this degree of classroom level variation is only slightly lower than typical rates of classroom variation in student achievement outcomes (Hedges & Hedberg, 2007), which nonetheless undergird myriad classroom-level interventions for improving student achievement. At the same time, as with achievement, the degree of variation in experiences of culture is much greater at the individual student level than at the classroom level (as evidenced by the larger values of the variance components at the student level than at the classroom level, in the models for both care and collective enterprise). The data underscore that for students, the classroom culture was not uniform within the classroom, but experienced differently by different individual students.

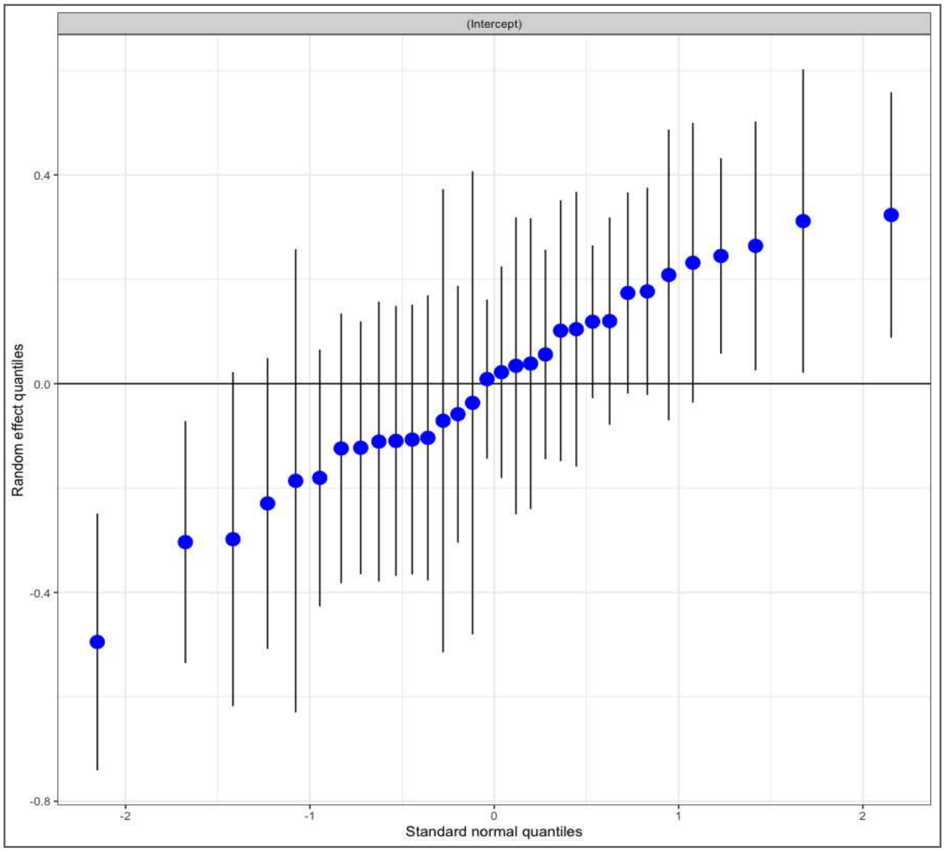

Figure 1.1. Classroom-level variation in care (ICC=0.12)

Although we observed student-to-student variation in experiences of the classroom culture (both within and across classrooms), we did not observe *systematic* variation in experiences based on student gender identity or race/ethnicity. That is, student background characteristics were not associated with experiences of the classroom culture (Tables 1.4 and 1.5). Hence, we do not have evidence to suggest that the OpenSciEd classrooms in our sample were inequitable with respect to student experiences of collective enterprise and care. Specifically, we found no statistically significant or practically meaningful differences between males and females in the degree to which they perceived that the class engaged in collective enterprise (β_{MALE}=-0.09; p=0.10) nor in their experience of caring within the classroom (β_{MALE}=0.02; p=0.75). Some differences did emerge for non-binary students, who reported lower levels of collective enterprise than females (β_{NB}=-0.54; p=0.04); and lower levels of care than both females (β_{NB}=-0.73; p=0.01) and males (β_{NB}=-0.74). In each case, non-binary students (n=9) were about half to three-quarters of a point lower on the Likert scale responses of classroom culture than females; however the small sample size creates a great deal of uncertainty in the estimates and makes it necessary to interpret these results with caution.

Table 1.4. Classroom-level Variation, and Gender and Race/Ethnicity Differences, in Reports of Care

	Care 1			**Care 2**			**Care 3**		
	Estimates	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	5.17	5.04 – 5.30	**<0.001**	5.23	5.11 – 5.36	**<0.001**	5.28	5.01 – 5.55	**<0.001**
Fixed Effects									
Gender (ref=female)									
Male				0.02	-0.10 – 0.13	0.753			
Non-binary				-0.73	-1.27 – -0.18	**0.009**			
Race (ref=Black)									
Native American							-0.04	-0.51 – 0.44	0.883
Asian American							-0.06	-0.47 – 0.34	0.755
Latinx							-0.11	-0.40 – 0.19	0.486
Multiple							-0.22	-0.51 – 0.08	0.145
White							-0.09	-0.35 – 0.17	0.486
Random Effects									
Classroom (var)	0.10			0.06			0.10		
ICC	0.12			0.08			0.11		
N (classrooms)	33			30			33		
N (students)	836			801			821		
R^2 (Marginal / Conditional)	0.000 / 0.118			0.008 / 0.089			0.003 / 0.118		

Table 1.5. Classroom-level Variation, and Gender and Race/Ethnicity Differences, in Reports of Collective Enterprise

	Enterprise 1			**Enterprise 2**			**Enterprise 3**		
	Estimates	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	4.85	4.75 – 4.95	**<0.001**	4.95	4.85 – 5.05	**<0.001**	4.93	4.68 – 5.18	**<0.001**
Fixed Effects									
Gender (ref=female)									
Male				-0.09	-0.21 – 0.02	0.100			
Non-binary				-0.54	-1.07 – -0.02	**0.044**			
Race (ref=Black)									
Native American							-0.10	-0.55 – 0.36	0.678
Asian American							-0.30	-0.69 – 0.08	0.125
Latinx							-0.13	-0.41 – 0.15	0.365
Multiple							-0.19	-0.47 – 0.09	0.192
White							-0.01	-0.26 – 0.24	0.947
Random Effects									
Classroom (var)	0.05			0.03			0.05		
ICC	0.07			0.05			0.06		
N (classrooms)	34			31			34		
N (students)	844			809			829		
R^2 (Marginal / Conditional)	0.000 / 0.065			0.007 / 0.060			0.009 / 0.069		

With respect to race/ethnicity, we found no statistically significant differences between subgroups of race/ethnicity in their reports of collective enterprise or care within the classroom, at the $p<0.05$ level. Inspecting the magnitude of the coefficients, we also do not see any differences of practical significance. (Even for the largest differences between groups, the point estimates nonetheless hover around 5, or “moderately agree”; and for many groups, the confidence intervals are fairly wide due to the small sample size within those categories.)

Student interest varies substantially across classrooms, but not by student gender or race/ethnicity

Our analysis revealed that classrooms varied in the average extent to which students expressed interest in science. Specifically, about 17% of the observed variation in reported student interest was attributable to differences at the classroom level, when not controlling for demographics (Table 1.6). This classroom-level variation was found to be statistically significant at the $p<0.05$ level, using an (exact) restricted likelihood ratio test of random effects ($p<0.001$). This finding is important because interest is popularly seen as a purely individual metric–something that individuals have or develop, largely independent of their environment, and certainly independent of any single teacher or class. This analysis, however, demonstrates that whole classrooms can be higher or lower than the overall average in terms of students expressing interest in science.

Importantly, we did not find evidence to suggest that reported student interest in science was associated with student identity (either gender or race/ethnicity) in these models. That is, on average, we did not find significant differences based on student gender or race/ethnicity with respect to reported levels of interest in science. In terms of magnitude, the value of the difference in reported interest ranges from -0.35 to 0.05 units on the interest scale, which is a difference of less-than halfway from one response to the next (e.g., strongly agree to agree).

With respect to grade-level or unit (which were the same in our analysis), we found that 8th graders (or students working with the natural selection unit) reported lower levels of interest than 6th graders (studying cells) and 7th graders (studying Earth's resources). The relationship was statistically significant at the $p<0.05$ level ($\beta_{GR8}= -0.44$, $p<0.01$). The magnitude of this difference in interest levels between 6th graders (cells unit) and 8th graders (natural selection unit) translates to a decrease of roughly half-way from one level on the Likert scale to the next lower-level on the Likert scale, i.e., from "Quite a bit like me" down to "Somewhat like me".

Table 1.6. Classroom-level Variation in Science Interest and Associations with Student Identity, Grade/Unit

	Interest 1			**Interest 2**		
	Estimates	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	3.79	3.64 – 3.95	**<0.001**	4.04	3.72 – 4.37	**<0.001**
Fixed Effects						
Gender (ref=Female)						
Male				-0.03	-0.16 – 0.09	0.571
Non-binary				-0.35	-0.91 – 0.21	0.225
Race/ethnicity (ref=Black)						
Native American				-0.04	-0.55 – 0.46	0.860
Asian American				-0.19	-0.59 – 0.21	0.360
Latinx				-0.12	-0.42 – 0.19	0.450
Multiple				0.05	-0.26 – 0.35	0.758
White				0.01	-0.26 – 0.28	0.937
Grade/unit (ref=6th grade/cells)						
7th grade (earth's resources)				-0.12	-0.41 – 0.18	0.432
8th grade (natural selection)				-0.44	-0.75 – -0.12	**0.007**
Random Effects						
Classroom (var)	0.15			0.10		
ICC	0.17			0.12		
N (classrooms)	32			30		
N (students)	813			771		
R^2 (Marginal / Conditional)	0.000 / 0.172			0.039 / 0.159		

Collective enterprise and care are strongly associated with student interest in science

Our hierarchical linear models showed that both aspects of classroom culture were significantly associated with students' reported interest in science: collective enterprise ($\beta_{\text{ENT}} = 0.49$, $p < 0.001$) and care ($\beta_{\text{CARE}} = 0.57$, $p < 0.001$). In other words, a one-unit increase in reports that the classroom reflected collective enterprise or care was associated with at or more than a half-unit increase on the interest scale, that is, students identifying more strongly with statements about interest in science (Tables 1.7 and 1.8). We note that the average effect of care on interest was slightly stronger than that of collective enterprise. An examination of the marginal R^2 values shows that adding either collective enterprise (marg R^2 =0.23) or care (marg R^2 =0.33) to the model enables us to explain a substantially higher portion of the variation in interest than we can without those variables (marg R^2 =0.04).

We further explored relationships between classroom culture, equity, and interest by building models to examine interaction effects between culture (collective enterprise, care) and student identity (gender, race/ethnicity). These models allowed us to understand whether classroom culture matters more for some groups of students than others, with respect to developing interest in science. Regarding gender, we found that males reported lower levels of interest than females when care is equal to zero, for the average classroom and holding race/ethnicity and grade-level constant. We also found that care influenced interest more strongly for males than females: a one-unit increase in classroom care was associated with a 0.51-unit increase in interest for females and a 0.63-unit increase in interest for males, for the average classroom and with all else constant. Regarding race/ethnicity, we found that students who self-identified as "multiple" reported lower levels of interest than Black students (our reference group) when collective enterprise or care, respectively, is equal to zero, for the average classroom and holding gender and grade-level constant. The relationship between both care and collective enterprise with interest was stronger for students with multiple races/ethnicities than for Black students—that is, a one-unit increase in collective enterprise or care, respectively, was associated with a greater increase in interest for students with multiple races/ethnicities than for Black students.

Table 1.7. Influence of Care on Interest, Main Effects and Interactions with Gender, Race/Ethnicity

	Care w/Interest 1			**Care w/Interest 2**			**Care w/Interest 3**		
	Estimates	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.98	0.57 – 1.40	**<0.001**	1.30	0.79 – 1.81	**<0.001**	2.08	0.70 – 3.46	**0.003**
Fixed Effects									
CARE	0.57	0.51 – 0.63	**<0.001**	0.51	0.42 – 0.59	**<0.001**	0.37	0.11 – 0.62	**0.004**
Grade/unit (ref=6th/cells)									
7th grade (earth's resources)	-0.15	-0.35 – 0.05	0.152	-0.15	-0.34 – 0.05	0.149	-0.15	-0.36 – 0.05	0.148
8th grade (natural selection)	-0.40	-0.62 – -0.18	**<0.001**	-0.39	-0.61 – -0.17	**<0.001**	-0.40	-0.62 – -0.18	**<0.001**
Gender (ref=female)									
Male	-0.05	-0.15 – 0.05	0.317	-0.69	-1.33 – -0.05	**0.033**	-0.05	-0.15 – 0.05	0.312
Non-binary	0.07	-0.41 – 0.54	0.777	-0.81	-2.71 – 1.10	0.406	0.08	-0.40 – 0.56	0.742
Race/ethnicity (ref=Black)									
Native American	0.08	-0.34 – 0.50	0.710	0.10	-0.31 – 0.52	0.634	-1.76	-4.43 – 0.92	0.198
Asian American	-0.14	-0.48 – 0.19	0.407	-0.14	-0.47 – 0.20	0.430	-0.16	-2.41 – 2.09	0.887
Latinx	-0.03	-0.28 – 0.22	0.840	-0.02	-0.27 – 0.23	0.868	-1.15	-2.71 – 0.40	0.145
Multiple	0.16	-0.09 – 0.41	0.211	0.17	-0.09 – 0.42	0.195	-1.52	-3.05 – 0.02	0.053
White	0.09	-0.14 – 0.31	0.452	0.09	-0.13 – 0.31	0.422	-0.90	-2.36 – 0.55	0.222
Interactions									
CARE x Male				0.12	0.00 – 0.24	**0.046**			
CARE x Non-binary				0.18	-0.22 – 0.59	0.373			
CARE x Native American							0.35	-0.17 – 0.87	0.183
CARE x Asian American							-0.00	-0.42 – 0.42	0.996
CARE x Latinx							0.21	-0.08 – 0.49	0.152
CARE x Multiple							0.31	0.03 – 0.60	**0.029**
CARE x White							0.18	-0.08 – 0.45	0.178
Random Effects									
Classroom (var)	0.04			0.04			0.04		
ICC	0.07			0.07			0.07		
N (classrooms)	30			30			30		
N (students)	771			771			771		
R^2 (Marginal / Conditional)	0.328 / 0.375			0.332 / 0.377			0.331 / 0.381		

Table 1.8. Influence of Collective Enterprise on Interest, Main Effects and Interactions with Gender, Race/Ethnicity

	Enterprise w/Interest 1			**Enterprise w/Interest 2**			**Enterprise w/Interest 3**		
	Estimates	*CI*	*p*	*Estimates*	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	1.52	1.07 – 1.97	**<0.001**	1.74	1.15 – 2.33	**<0.001**	2.54	1.19 – 3.88	**<0.001**
Fixed Effects									
ENTERPRISE	0.49	0.42 – 0.55	**<0.001**	0.44	0.34 – 0.54	**<0.001**	0.28	0.02 – 0.54	**0.035**
Grade/unit (ref=6th/cells)									
7th (earth's resources)	-0.09	-0.33 – 0.16	0.495	-0.09	-0.34 – 0.16	0.487	-0.08	-0.33 – 0.18	0.560
8th (natural selection)	-0.41	-0.68 – -0.14	**0.003**	-0.41	-0.68 – -0.14	**0.003**	-0.40	-0.67 – -0.12	**0.005**
Gender (ref=female)									
Male	0.01	-0.10 – 0.12	0.839	-0.36	-1.03 – 0.31	0.297	0.01	-0.10 – 0.12	0.834
Non-binary	-0.09	-0.60 – 0.41	0.720	-1.74	-5.33 – 1.85	0.342	-0.11	-0.62 – 0.39	0.657
Race/ethnicity (ref=Black)									
Native American	0.06	-0.38 – 0.51	0.787	0.06	-0.38 – 0.51	0.782	-1.17	-4.06 – 1.71	0.425
Asian American	0.03	-0.33 – 0.39	0.855	0.04	-0.32 – 0.40	0.825	-0.17	-2.41 – 2.07	0.878
Latinx	0.01	-0.26 – 0.28	0.928	0.01	-0.26 – 0.28	0.931	-0.51	-2.07 – 1.04	0.517
Multiple	0.17	-0.10 – 0.44	0.225	0.17	-0.10 – 0.44	0.217	-1.80	-3.31 – -0.29	**0.019**
White	0.09	-0.15 – 0.32	0.477	0.09	-0.15 – 0.33	0.470	-0.87	-2.27 – 0.54	0.226
Interactions									
ENT × Male				0.07	-0.06 – 0.21	0.276			
ENT × Non-binary				0.37	-0.44 – 1.17	0.370			
ENT × Native American							0.25	-0.33 – 0.83	0.402
ENT × Asian American							0.03	-0.43 – 0.49	0.901
ENT × Latinx							0.10	-0.21 – 0.41	0.525
ENT × Multiple							0.40	0.10 – 0.70	**0.009**
ENT × White							0.19	-0.09 – 0.47	0.178
Random Effects									
Classroom (var)	0.07			0.07			0.07		
ICC	0.11			0.11			0.12		
N (classrooms)	30			30			30		
N (students)	771			771			771		
R^2 (Marginal /Conditional)	0.228 / 0.311			0.230 / 0.313			0.236 / 0.324		

Discussion

Our study provides evidence from across a wide range of classrooms that equitable science classroom cultures support student interest in science for all students, equally including those from populations that have been historically excluded from science (e.g., girls and students of color). Past research, primarily from qualitative case studies and ethnographies with small numbers of participants, demonstrated the importance of classroom culture for a variety of desired student outcomes in science, including equity (e.g., Aikenhead & Jegede, 1999; Bang et al., 2012; Bell et al., 2017; Carlone, 2011). Other research has demonstrated the benefits of collective enterprise for engaging students in scientific knowledge building and strengthening their understanding of science (Clark et al., 2016; Patterson, 2019); and the benefits of care for positioning students to grapple with science with the knowledge that they and their ideas are respected and valued (Krist & Suarex, 2018; Krist, 2020). We conjectured that by connecting with the cognitive, emotional, and values-related aspects of interest, collective enterprise and care might also support student interest in science. Our research substantiated this conjecture, revealing a strong and consistent relationship between classrooms reflecting cultures of collective enterprise and care, with student interest in science—a relationship that held true across a wide variety of classrooms and students.

In terms of pedagogy, the relationships between collective enterprise and care with interest in science underscore the importance of relationships within science teaching and learning and the importance of relational approaches to building productive science classroom cultures. Both collective enterprise and care are relational constructs that pertain to the ways that students interact with one another and with scientific sensemaking. In this sense, our research provides additional evidence to bolster calls from many researchers and practitioners about the need to place relationships at the center of efforts to create more equitable science learning opportunities for students (Aikenhead & Jegede, 1999; Bang et al., 2017; Krist & Suarez, 2018). The observed relationship between collective enterprise and interest in science also provides support for practice-based approaches to science education, where students are invited to actively engage in the scientific endeavor, participating in the collaborative sensemaking and knowledge-building processes along with their fellow students. In order for this collective enterprise to be equitable, all students in the classroom–particularly those from communities that have historically been excluded from science–should feel that their ideas are valued as part of the scientific conversation. This valuing of ideas is in turn reflective of caring science classroom cultures.

Beyond relationships between culture and interest, our study also establishes that science classrooms have a culture unto themselves–their own unique identity and ethos–separate from each individual's experience of the classroom. The observed degree of classroom-level variation in culture was only slightly lower than typical classroom-level variation in student achievement, typically about 12-15% (Hedges & Hedberg, 2007). Just as research and policymaking justifiably focus on classroom-level interventions to improve student achievement, our findings also provide a warrant for investing research and development efforts around strategies for building equitable science classroom cultures. The classroom is an important lever for improving students' science learning experiences and increasing their opportunities to develop a sustained interest in science.

Contrary to popular wisdom about the purely individual nature of interest, our analysis also demonstrated that there is also a significant classroom-level component to science interest alongside the (admittedly larger) individual-level component of interest. While interest theory recognizes the role of the social and institutional setting in shaping interests (Krapp & Penzel, 2011), most of the literature on interest nonetheless focuses on interest development for individuals, rather than the potential of a particular setting to shape interest for a group of individuals. By demonstrating significant between-classroom variability in interest–that is, that whole classrooms can be higher or lower on the interest scale than others–our study suggests that there is a communal component of interest, connected with shared experiences within a particular environment. In practical terms, this finding underscores the importance and value of designing classroom-level interventions to boost science interest.

We know that teachers play an important role in shaping the culture of the science classroom (e.g., Supovitz & Turner, 2000) but need additional research to identify specific instructional practices that might promote equitable science classroom cultures in general, and collective enterprise and care specifically. Calabrese Barton and colleagues (2019) found that when teachers recognize and make visible students' scientific resources, the class can leverage those resources for collective knowledge-building. In their study of science classrooms, Carlone and colleagues (2011) similarly found that instituting a normative practice of sharing scientific ideas promoted an understanding of scientific investigation as a collaborative, generative endeavor and of scientific knowledge as shared and jointly constructed. When teachers recognize students' emotions connected with systemic injustices and with science, they legitimize students' feelings of wanting to belong, to learn, and to engage with their communities in meaningful ways (Calabrese Barton et al., 2019). This recognition of students' emotions humanizes students and centers care as an essential component of the classroom culture.

While teachers have a crucial role to play in establishing the classroom culture, our research provides early evidence that curricula themselves may also contribute to the culture of science classrooms. Within our sample of OpenSciEd classrooms, we found that student background characteristics (namely, race/ethnicity and gender) were not associated with student experiences of the classroom culture, in terms of collective enterprise and care. We recognize that the degree of equity observed within these classrooms is not necessarily the norm for middle-school science classrooms across the country and so we caution against drawing any conclusions about science classroom cultures writ large based on this particular finding about equity in OpenSciEd classrooms. On the other hand, the equity observed within these classrooms points to the potential power of curricula (including professional development and educative instructional materials) to support more equitable science education (Mensah, 2022; Tzou et al., 2021). Additional research is required to understand what about the curricula supported teachers to foster equitable collective enterprise and caring within their science classrooms.

Conclusions

Our study demonstrated that classrooms varied substantially with respect to their classroom culture; and that in classrooms where students experienced greater collective enterprise and more caring relationships, they also developed greater interest in science. Interest in science is an outcome of critical importance because of its well-documented relationship with persistence, future course-taking, and career trajectories in science. For their part, classrooms encapsulate different cultures for science learning–cultures that are both perceptible and consequential for students. The importance of collective enterprise and care in particular underscores myriad calls, emerging from implementation research on OpenSciEd (Cherbow & McNeill, 2022; Penuel et al., 2023) and from the field more broadly (e.g., Carlone et al., 2011), for attending closely to classroom culture and the relational aspects of science learning.

Much work remains to figure out how best to cultivate science classroom cultures reflective of collective enterprise and care that support science interest development equitably for all students. There is no question that the cultures of our larger society and of science shape the cultures of science classrooms. As such, systems-level perspectives are required to disrupt deeply entrenched inequities that infiltrate science classroom cultures. We also believe that teachers can play a role in shaping the dynamics within their classroom. And we remain hopeful that our growing understanding of equitable science classrooms will help more students, particularly those from historically marginalized communities, to find their home in the world of science.

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Paper 2: The Potential of an “Epistemic Boost” to Support Student Belonging in Science[2]

Introduction

Science education reforms have long sought to help more students to connect with and succeed in science. The latest era of reform, guided by the *Framework for K-12 Science Education* (NRC, 2012), embodies a science-as-practice approach to science education. This approach builds on lessons from prior eras showing the importance of having students engage with science practices as a means for building shared knowledge to advance communal goals (Duschl, 2008; Ford, 2008; Manz, 2014). Through engagement in science practices, students have opportunities to build science knowledge and skills and also to develop an identity and sense of belonging in science (NRC, 2012; Schwarz et al., 2017). With respect to the latter, engaging in practices is purported to help students grasp an authentic understanding of science, one that expands the boundaries of sanctioned disciplinary participation and creates more space for students to see themselves within the world of science (Berland et al., 2016; Manz, 2020).

However, research has shown that engagement in science practices on its own is not sufficient for helping students to grasp this broad and flexible understanding of science (Gouvea & Passmore, 2017; Sandoval & Morrison, 2003; Sandoval, 2005). Classroom instantiations of NGSS-aligned curricula often focus on individual practices, which can undermine the goals behind the desired integrated approach to science practices and concepts (Berland et al., 2020). At the same time, cultures of schooling and of school science impart an understanding of what it

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means to “do” science, particularly in the context of being a good science student, that starkly oppose the expansive epistemology implicit within science-as-practice approach (Jimenez-Alexandr et al., 2000). Within these traditional cultures of school science, teachers hold the expertise about a fixed body of scientific knowledge which they are tasked with imparting to students. This understanding of science as settled knowledge leads students to perceive a disconnect between themselves and science; to believe that they do not belong in science if they do not have all the right answers (Carlone, 2007; Carlone et al., 2011).

In this paper, we examine the extent to which classrooms that cultivate an expansive epistemology of science also support students’ sense of belonging in science. By an “expansive epistemology of science” we refer to an understanding of science as an endeavor driven by our curiosities about the world. An expansive epistemology of science recognizes that science involves uncertainty and mistakes as scientists (and students) work to revise and augment prior understandings. An expansive epistemology also recognizes that achieving the communal knowledge-building goals of science requires collaboration, space for multiple ways of knowing, the sharing and critiquing of ideas, and persistence in gathering evidence to incrementally advance our understanding. Belonging is a critically important outcome because it is associated with both learning and persistence in science (e.g., Hazari et al., 2020; Lee et al., 2020)

Ultimately, we argue that fully realizing the vision of the “practice turn” requires that we also embrace an “epistemic boost” to advance equity and belonging in science education. Past research has shown that the combination of practice-oriented approaches to science instruction with specific attention to science epistemology supports student interest and identification with science (Sandoval, 2005; Sandoval & Morrison, 2003). An expansive epistemology has the potential to support belonging, too, as it creates space in students' understanding of science for a broader range of valid identities, ways of knowing, and forms of participation within science.

Conceptual Framework

The purpose of this paper is to explore the relationship between an expansive epistemology of science and the extent to which students feel a sense of belonging in science. To build this argument, we first establish the importance of belonging as an essential condition for student learning and attainment in science. Then, we briefly review the "practice turn" in science education, including its promise and limitations with respect to transforming science teaching and learning in ways that expand opportunities for students. We pay particular attention to how the practice turn does or does not support students to develop an expansive epistemology of science. Finally, we explore how attending to epistemology might fill some of the gaps in our current thinking about science education and support students' sense of belonging in science.

Importance of Belonging in School Science

A feeling of belonging is considered a basic human need in any setting (Baumeister & Leary, 1995; Cacioppo & Patrick, 2008). In academic settings, a sense of belonging refers to the feeling of being seen, heard, accepted, valued, included, and respected (Goodenow, 1993). A sense of belonging also means feeling that one is encouraged and supported by others, and that one is an important part of the community and its endeavors. In science classrooms, a sense of belonging means that students feel that they are valued and respected members of the classroom community, whose participation and voice are appreciated as meaningful contributions to the collaborative sensemaking and knowledge-building efforts taking place within the classroom (Carlone, 2011; Patterson, 2019).

For students, a sense of belonging directly supports learning because learning is a social endeavor that requires participation and engagement with others within the learning community (Lave & Wenger, 1991; Lee et al., 2020). Belonging and school performance can mutually reinforce one another when students who feel a strong sense of belonging participate and engage (Penuel et al., 2023) and hence perform well (Edwards et al., 2022; Roeser et al., 1996), which can in turn build stronger belonging within the community (Cohen et al., 2009). Conversely, threats to belonging can undermine both motivation (Ibañez et al., 2004) and also school performance (Steele et al., 2002; Walton & Cohen, 2007).

A sense of belonging in school science is particularly important because it gives students the confidence to show up as themselves, share their thinking (including “first draft thinking”), and engage in collective scientific sensemaking with their teacher and peers (Adams-Wiggins, 2020; Patterson, 2019). This participation in the cultural community of the science classroom is essential for student learning (Lave & Wenger, 1991; Gutierrez & Rogoff, 2003). Moreover, a sense of belonging in science also supports student interest in science and the development of science identities (Carlone, 2004; Hazari et al., 2020).

Despite its importance, an abundance of research has shown that students, particularly those from historically minoritized communities, do not feel a sense of belonging in school science (Chen et al., 2021; Steele, 1997). Schools tend to maintain historical white-patriarchal assumptions about what science is, who can do science, what it means to be a scientist, how scientists think and operate (Lemke, 2011). Within science, these established—or “settled”—notions about what constitutes science are too narrow to support learning and belonging for a plurality of students (Bang et al., 2012). Moreover, settled notions of science lead to deficit views of historically minoritized students and communities to the extent that they may not approach science with the same epistemological orientation. These narrow ideas about legitimate forms of scientific knowledge and practice alienate students with other ways of thinking and knowing, create barriers to belonging, and hinder the development of positive disciplinary identities (Bell et al., 2017).

The Promise of the "Practice Turn" for Science Education

The "practice turn" in science education reflects an underlying shift from an acquisition view of learning to a participation view of learning and is intended to support both deeper learning and essential affective outcomes like disciplinary identification and belonging (Forman, 2018). The acquisition view of learning aligns with Freire's description of "banking" methods of education that view learners as empty vessels to be filled with knowledge. In contrast, the participation view of learning recognizes learners as participants in a community of practice who acquire new knowledge, skills, and identities through the process of engaging with that community (Lave and Wenger, 1991). The participation view of learning leads us to prioritize engagement in the cultural practices of science as a central mechanism for learning (Bell et al., 2017). Engagement in practices also supports "practice-linked identification" wherein students develop an identity as doers of science—and hence, as scientists—through active engagement in the practices of science (Nasir and Cooks, 2009; Van Horne & Bell, 2017). Some scholars have also argued that through reflective engagement in scientific practices students develop both an understanding of the epistemology underlying the scientific endeavor and understandings of explanatory scientific concepts (Duschl, 2008; Lehrer & Schauble, 2006).

Recent scholarship has theorized about how to engage students in scientific practices in ways that might realize the science-as-practice vision (e.g., Berland et al., 2016; Berland et al., 2020; Gouvea & Passmore, 2017; Manz, 2015). First and foremost, there is a recognition that engagement in scientific practices must be meaningful to students. This meaning comes from the epistemic culture of the classroom, which includes shared goals and community norms that lend meaning to the scientific work that students are doing (Manz, 2015). In other words, students should not be creating models or engaging in argumentation merely because the teacher instructed them to do so, but rather because engaging in those practices is critical for answering the scientific questions that they have set out to answer (Berland et al., 2016). Scholars have offered suggestions for making particular scientific practices more meaningful for students, including designing models as a tool for inquiry (rather than as representations of existing knowledge; Gouvea & Passmore, 2017) and engaging in argumentation as an activity that both questions and stabilizes community knowledge (rather than in more procedural ways; Berland et al., 2016; Manz, 2015).

Challenges to Achieving the Science-As-Practice Vision for Science Education

In spite of these deep understandings about how best to engage students in science practices, the approach has often fallen short of fully realizing the science-as-practice vision of science education (Chinn & Malhotra, 2002; Windschitl et al., 2008). Two key factors play a role: First, curricula and classroom implementation often focus on individual practices rather than the broader pedagogical vision of science-as-practice intended to help students understand the interconnected work of scientific sensemaking via multiple practices working together toward building scientific knowledge (Berland, Russ & West 2020). Indeed, the ways in which students are expected to participate in scientific inquiry is still often “essentialized to the point of becoming rote” (Krist, 2020, p.421).

The second factor is that teachers and students within a classroom community interpret disciplinary practices by adapting them to fit within existing cultures, goals, and expectations within the school context (Berland, 2011; Berland & Reiser, 2011; Calabrese Barton & Tan, 2009; Hogan & Corey, 2001). This phenomenon is problematic because traditional cultures of schooling and of school science are pervasive and often counter to the vision of science-as-practice. Students have often absorbed messages from their educational and school science careers that lead them to see learning as passively receiving authoritative knowledge from the teacher, who is positioned as an expert (Rosenberg et al., 2006). To the extent that classroom cultures emphasize traditional school expectations over scientific knowledge construction goals, students are likely to experience less productive adaptations of scientific practices (Berland & Hammer, 2012a; McNeill & Pimentel, 2010; Schneider, Krajcik, & Blumenfeld, 2005).

One particularly tenacious notion that students have about school science is around what it takes to be “smart” at science and, therefore, to be a “good” science student. Carlone (2012) found that students had very different ideas, developed based on features of their classroom environment and messages from their teachers, about what it means to be “smart” in science. In some classrooms, students understood being smart to mean providing teachers with the right answers. In other classrooms, students had a broader understanding of smartness that included things like asking good questions, making good observations, and being a good collaborator. These understandings about what it takes to be smart in turn shaped how students saw themselves and their own place within the scientific enterprise.

Importance of Attending to Epistemology in Science Teaching and Learning

Achieving the science-as-practice vision of science education may require an intentional “epistemic boost” aimed at communicating an expansive epistemology of science while also working to disrupt traditional cultures around school science. As scholars and educators, we need to find ways to help students to understand the “hows and whys” of science and to build an epistemic understanding of how people acquire, interpret, justify, and use scientific knowledge (Green, Sandoval, and Braaten, 2016; Krist 2020). Attention to epistemology within the science-as-practice approach may support these epistemic goals (Berland et al., 2020; Quale, 2002; Russ, 2018).

Helping students to internalize this expansive epistemology is important not only because it offers a more authentic view of science epistemology than traditional school science, but also because it expands opportunities for disciplinary participation and identification. Scholars have argued for varied ways to support students in engaging with the epistemic goals and practices of science (Krist, 2020; Manz et al., 2019; Russ, 2018; Stroup, 2014). At the heart of these approaches is the understanding that teachers send messages about knowledge and learning that have substantial, tangible implications for how students understand science and, in turn, for their science learning and identification (Russ, 2018). In her work, Krist (2020) argues for featuring epistemic learning goals prominently within science education and proposes strategies for supporting students’ meaningful participation in scientific practices in contextually valid ways. Manz and colleagues (2019) focus on how to design science investigations that enable students to grasp an expansive epistemology by highlighting “the social and locally embedded nature of practice and the inherent interdependence of concept and activity.” Russ (2018) suggests that teachers can use “epistemic messages” to convey to students what ideas deserve space in the classroom and what thinking has value. Stroupe (2014) argues that “ambitious instruction” can help students to understand an expansive epistemology by establishing norms around what knowledge is valuable, what counts as scientific knowledge, how knowledge is constructed, and who has epistemic agency to construct that knowledge.

Our conjecture is that classroom cultures that impart an expansive epistemology of science will also support students in developing a stronger sense of belonging within the classroom and within the discipline of science. Features of science classrooms that reflect an expansive epistemology of science—such as recognizing science as a cultural practice, seeing mistakes as part of the knowledge building process, valuing collaboration and the sharing of ideas—have been shown to support student interest and identification with science (Basu & Barton, 2007; Calabrese Barton et al., 2013; Carlone, 2011). We also know that student disciplinary identity and belonging are strongly associated with one another (Bell et al., 2017; Hughes et al., 2021) and so it is reasonable to expect that factors that support one might also support the other.

This study aims to examine the connection between students' epistemologies of science and students' sense of belonging in science class, across a wide variety of students and classrooms. We also examine whether student identity (race/ethnicity, gender) plays a role in shaping the relationship between epistemology and sense of belonging. We know that students from historically marginalized backgrounds often feel less belonging in school science than students from dominant backgrounds (Archer et al., 2012; Poirier et al., 2009). To the extent that an expansive epistemology might counteract persistent messaging about science and belonging, students from minoritized backgrounds may especially benefit.

The Current Study

This study used data from the OpenSciEd field test to examine the extent to which classrooms reflected an expansive epistemology and the relationship between students' epistemologies of science and their sense of belonging. The study is an example of implementation research that seeks to explore dimensions of variation between science classrooms that are consequential for students (Confrey et al., 2001; Fixsen et al., 2005).

OpenSciEd Approaches to Science Practice and Epistemology

The OpenSciEd curriculum actively engages students in science and engineering practices and is intentional about creating classrooms where students take an active role in "figuring out" science. Beyond practices, OpenSciEd also reflects an expansive epistemology, although the extent to which that perspective carries through within the classroom may vary depending on local context and implementation.

The program uses a storyline model designed to support "coherence from the student perspective" (Reiser et al., 2017). Each storyline unit begins with an anchor phenomenon and presents students with the opportunity to ask questions that will drive the class' inquiry. Students engage in the process of knowledge building "because it addresses goals of figuring out and solving problems their classroom community has adopted" (Penuel et al., 2021). Within the OpenSciEd curriculum, as in science in the broader world, knowledge building is collaborative, incremental, and iterative. For students, the inquiry should also be connected to their everyday experiences and their knowledge of the real world. To achieve these goals, the curricular materials are structured to enable students to draw on their intuitive ideas to explain phenomena.

The OpenSciEd curriculum also includes classroom routines designed to engender a sense of shared responsibility and ownership for knowledge building. These routines could be understood as working to impart an expansive epistemology to students (Krist, 2020). For example, routines help establish norms for classroom behavior and social interaction, solicit student questions to guide the ongoing work of the class, and create processes for students to track the evolving models that the class is building to explain the anchor phenomenon.

Research Questions

This study focused on examining relationships between classroom epistemologies of science and students' sense of belonging within those science classrooms. The research sought to answer the following research questions:

1. To what extent do classrooms vary in the extent to which they engender an expansive epistemology of science?
    a. How do student reports of classroom science epistemology vary by race/ethnicity and/or gender subgroups?
2. To what extent do classrooms vary in the extent to which students report feeling a sense of belonging in science?
    a. How do student reports of belonging vary by race/ethnicity and/or gender subgroups?
3. How does the classroom epistemology of science relate to students' reported belonging in science?
    a. Is the relationship between classroom science epistemology and belonging moderated by student race/ethnicity and/or gender?
4. How do students describe what it takes to be "smart" in their science classrooms? What kinds of descriptions are most prevalent? How can we understand student ideas about "smartness" in relation to classroom epistemologies of science?

We note that our study does not take up questions around how teachers communicate or otherwise impart an expansive epistemology of science to students. We can look to the OpenSciEd curriculum, including its curricular structures, instructional routines, guidelines for classroom norms, and professional learning to consider features that might, theoretically, support students in developing an expansive understanding of the epistemology of science. But our data do not reflect on teacher practice specifically, nor do they allow us to identify patterns and relationships between teacher practice and student reports about classroom epistemologies of science. Rather, we seek to explore the relationship between student reports about the epistemology of science reflected within their science classrooms and the extent to which they feel a sense of belonging in science.

Participant Sample

The data for this study come from 847 middle-school science students, distributed across 31 teachers' classrooms and nine different states (Table 2.1). Students responded to a survey in Spring 2021 about their experiences in their OpenSciEd classroom. On average, each teacher had 24.9 students (*SD*=19.2) respond to the student end-of-unit survey. Just over half of the participants self-identified as white (54%); the next largest group was students who identified as Latinx or Hispanic (17%), followed by students from multiple racial/ethnic groups (15%). African Americans (7%), Asian Americans (4%), and American Indians / Native Alaskans (3%) each made up less than 10% of the participants. We had fewer than five students identifying as Native Hawaiian / Pacific Islander in our sample (n=3), and so we removed these observations from the data. Separately, just over half of the sample identified as female (52%), while 46% identified as male, and about 1% identified as non-binary.

Table 2.1. Demographics of the Sample

	n	%
Race/Ethnicity		
African American or Black	57	6.88%
American Indian / Native Alaskan	22	2.65%
Asian or Asian American	30	3.62%
Latinx or Hispanic	143	17.25%
Multiple	127	15.32%
White	450	54.28%
Gender		
Male	376	46.48%
Female	424	52.41%
Nonbinary	9	1.11%

Data Sources & Measures

The OpenSciEd student end-of-unit survey covered many topics and constructs related to students' experiences of their science class. Here we describe the specific items and scales that we used for the current analysis.

Expansive Science Epistemology. The survey included an item that read, *"Below are a list of statements that influence things that people do in science classrooms. Pick the statements that are true about your science class."* The survey presented a list of sixteen statements about science class, and students selected all that apply to their own experience. For analysis, I treated each of the sixteen statements as their own items, with a binary "yes/no" response from students. We conducted a post-hoc exploratory factor analysis to determine which of the sixteen items loaded onto a single factor. The psychometric analysis revealed that eleven of the sixteen items loaded onto a single factor, while the remaining five items loaded separately (Table 2.2). These results aligned with our own literature-informed assessment of the content validity of the items. Two of the eliminated items were "reverse" items that may have complicated their reliability. The other three eliminated items were ambiguous as to whether they connote behaving as scientists in a constructivist or a prescribed manner and thus, not surprisingly, did not align with the other items in the scale. The final epistemology scale comprises eleven items and has a Cronbach's alpha of 0.77, demonstrating strong reliability. The survey data included responses from 808 students for this scale.

Table 2.2. Construction of the Expansive Epistemology Scale

Items Retained in Scale
● We like science. ● In science we ask questions that we can investigate. ● In science, we are expected to make careful observations. ● In science, we have to record our observations. ● In science, we are expected to answer questions we are curious about. ● We are expected to solve science problems together. ● It is ok to make mistakes in science. ● If we don’t get it right the first time, it is important for us to keep trying. ● My classmates in science are expected to share ideas with each other. ● It is ok to disagree with my classmates’ science ideas. ● In this class there are lots of possible solutions for science problems.
Items Removed from Scale
● In science we are expected to use scientific vocabulary (words). [Reverse] ● We are expected to keep our science ideas secret. [Reverse] ● We have to design our own experiments to answer questions. ● We have to talk like scientists. ● We have to think like scientists.

We consider this scale to reflect science epistemology because of the emphasis on *characteristics* of science and scientific knowledge. For example, the scale includes items that get at the nature of scientific knowledge–namely, that knowledge connects to our curiosities, builds from observations, and has many possible solutions. And the scale includes items about how we build scientific knowledge–namely, collaboratively, with mistakes and perseverance, and through sharing and debating ideas. One item in our scale—the one that reads, *In science we ask questions that we can investigate*—does also align with two of the science practices articulated in the *Framework*, namely “asking questions” and “planning and carrying out investigations” (NRC, 2012). We chose to retain this item in the scale for two reasons: first because the psychometric analysis suggested unidimensionality with the other science epistemology items; and second because the item also reflects an important epistemological understanding of science as being driven by questions for which we can conduct investigations and gather evidence (as opposed to questions of faith or ideology).

Belonging. The belonging scale consisted of three items. The items were: 1) I feel that I belong; 2) I am an active member who participates; and 3) I feel that I can relate to others. These three items reflect elements of belonging from the literature, e.g., that belonging entails feeling connected to others. Students responded to each item on a 5-point Likert scale from strongly disagree to strongly agree. The Cronbach's alpha of 0.82 suggests that the scale has strong reliability. The survey data included responses from 809 students for this scale.

Conceptions of "smartness". To provide additional context for our analysis of classroom epistemology and belonging, we also analyzed data from an open-response item with a prompt that read, *To be smart in this science class, you have to….* Students wrote in responses to finish the statement. The survey data included written responses from 814 students for this item. The responses ranged in length from one word to a maximum of about fifty words.

The "smartness" item was inspired by the work of Heidi Carlone (2011) showing that different classroom cultures can (often inadvertently) communicate very different messages to students about what it takes to be "smart" or "successful" within that environment. Even within the context of reform-based science classrooms, some classroom cultures impart to students the idea that being smart means having accurate answers to the teachers' questions; while other classroom cultures impart to students a more expansive notion of what it means to be smart at science that includes things like asking good questions, making good observations, and collaborating well in the inquiry and knowledge-building processes. These more expansive notions about what it means to be smart align with an expansive epistemology of science, and thus provide another avenue for understanding the messages about science that students received within different classrooms.

Analytic Approach

We used both qualitative and quantitative methods to analyze the data in service of the research questions.

Analysis of Relationships between Classroom Culture and Belonging

We used hierarchical linear modeling to examine questions pertaining to the degree of classroom-level variation in science epistemology and in belonging, and to examine relationships between these two constructs. We used unconditional models to estimate the proportion of variance in science epistemology and sense of belonging, respectively, attributable to classroom- and individual-level factors. We tested the null hypothesis that classroom-level variation in science interest was equal to zero, using an (exact) restricted likelihood ratio test to test the significance of the random effects.

We then fit additional models that included indicator variables for student gender and race/ethnicity as fixed effects, in order to interrogate the degree of equity within these classrooms, along these dimensions. We used emmeans (Lenth, 2022) to test all of the relevant pairwise comparisons between student gender and race/ethnicity subgroups. Observing a relationship between student background characteristics and reports of expansive epistemologies of science or sense of belonging, would provide some evidence that students within a classroom experienced the science class differently.

Finally, we examined relationships between classroom culture variables related to scientific epistemology and student-reported sense of belonging in science class. We used hierarchical linear regression models, nesting students within classrooms, to account for the correlation of student observations within the same classroom. We added interaction terms to the model, to understand the extent to which the relationship between classroom science epistemology and student belonging depends on student background characteristics. Our final composite model for belonging was:

Composite Model with Interactions:

$$\text{BELONG}_{ij} = \beta_0 + \beta_1(\text{EPISTEM})_{ij} + \beta_2(\text{RACE})_{ij} + \beta_3(\text{GENDER})_{ij} + \beta_4(\text{EPISTEM}_{ij} * \text{GENDER}_{ij}) + \beta_5(\text{EPISTEM}_{ij} * \text{RACE}_{ij}) + u_{0j} + r_{ij}$$

Wherein:

i = Level-1 unit (i.e., the i^{th} individual student)

j = Level-2 unit (i.e. the j^{th} classroom)

r_{ij} = Level 1 residual (unexplained student-to-student variability)

u_{0j} = Level 2 random effect (unexplained group-to-group variability)

With the following assumptions:

$r_{ij} \sim N(0, \sigma^2)$

$u_{0j} \sim N(0, \tau_{00})$

Qualitative Analysis of Classroom Culture Open-Response Data

To analyze the open-response survey data from the item about what it means to be smart in your science classroom, two researchers each read through half of the data and created an initial inductive coding scheme, based on themes constructed from the data (Strauss & Corbin, 1998; Williams & Moser, 2019). The two researchers then compared codes, discussed codes that were overlapping but distinct and codes that appeared in one list but not the other, and arrived at a single streamlined coding scheme. From there, we worked iteratively, going back-and-forth between the data and constructs aligning with extant literature, to revise and finalize the coding scheme (Strauss & Corbin, 1998). After finalizing the coding scheme, we went back through the open-response data to code each response according to the scheme. We coded each response with as many codes as applicable; we did not limit ourselves to a single code per response. In the end, half of the responses received just a single code; while the other half was coded for multiple constructs (with the majority of those, 39%, receiving two codes).

Descriptive Analysis of Coded "Smart" Data

Based on this final coding of the open-response data, we converted the coded data into quantitative data to use in analysis. To do so, each code became a dichotomous (0/1) variable, and each respondent received a 0 or a 1 for each construct, depending on whether their open-response had been coded for that construct or not. We then conducted descriptive analysis of the data, including the percentage of respondents who mentioned each construct.

Findings

Science epistemology varied across classrooms, with some differences by student background

We found that the culture around the epistemology of science varied between classrooms. Specifically, the unconditional model shows that approximately 7% of the variation in science epistemology is attributable to classroom-level factors (Table 2.3). This classroom level variation was statistically significant at the $p<0.05$ level ($p<0.001$), as evaluated by an (exact) restricted likelihood ratio test to test the significance of the random effects. While individual student experiences still account for the vast majority of the variation in reports of science epistemology, the classroom-level variation nonetheless warrants attention.

Table 2.3. Classroom Variation & Demographic Differences in Reports of Expansive Epistemology

	Epistemology 1			**Epistemology 2**		
	Estimates	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	0.83	0.80 – 0.85	**<0.001**	0.86	0.83 – 0.89	**<0.001**
Fixed Effects						
Gender (ref=female)						
Male				-0.03	-0.06 – -0.00	**0.034**
Non-binary				-0.12	-0.26 – 0.01	0.079
Race/ethnicity (ref=white)						
Black				-0.05	-0.11 – 0.01	0.078
Native American				-0.01	-0.10 – 0.09	0.913
Asian American				-0.03	-0.10 – 0.05	0.468
Latinx				-0.03	-0.07 – 0.01	0.126
Multiple				-0.01	-0.05 – 0.03	0.654
Random Effects						
Classroom (var.)	0.00			0.00		
ICC	0.07			0.05		
N (classrooms)	30			29		
N (students)	805			765		
$\mathbf{R^2}$ (Marg/Cond)	0.000 / 0.067			0.015 / 0.065		

In order to interrogate the degree of equity around epistemologies of science in these classrooms, we added indicator variables for student gender and race/ethnicity (Table 2.3). We found that males reported lower levels of expansive epistemology of science than females, but the magnitude of the point estimate is tiny and not practically meaningful ($\beta_{MALE} = -0.03$, $p=0.03$). Non-binary students reported even lower levels of expansive epistemology, but the difference is still not practically meaningful and because of the small sample it also does not reach statistical significance ($\beta_{NB} = -0.12$, $p=0.08$). With respect to race/ethnicity, we did not find any statistically significant or practically meaningful differences in reports of classroom epistemology based on student subgroups. In each case, the mean differences between groups would translate to students perceiving less than one additional aspect of an expansive epistemology of science within their classroom culture around science.

Belonging varied across classrooms and between student sub-groups

Our models suggest that there was a notable classroom-level component associated with sense of belonging in science, with roughly 6% of the variation in belonging attributable to classroom-level factors (Table 2.4). Again, the (exact) restricted likelihood ratio test suggested that this classroom-level variation in belonging was statistically significant at the $p<0.05$ level ($p<0.001$).

Adding indicator variables for student background characteristics revealed differences in reports of belonging in science between some sub-groups of students. Specifically, males reported marginally higher levels of belonging in science than females ($\beta_{MALE} = 0.14$, $p = 0.05$). White students reported higher belonging than students from all other racial/ethnic subgroups (although only the differences between white students with Asian American students and Latinx students, respectively, were statistically significant at the $p<0.05$ level).

Table 2.4. Classroom Variation & Demographic Differences in Reports of Student Belonging

	Belonging, Unconditional			**Belonging with Subgroups**		
	Estimates	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	4.71	4.59 – 4.83	**<0.001**	4.81	4.67 – 4.95	**<0.001**
Fixed Effects						
Gender (ref=female)						
Male				0.14	0.00 – 0.28	**0.047**
Non-binary				-0.44	-1.13 – 0.25	0.209
Race/ethnicity (ref=white)						
Black				-0.20	-0.50 – 0.10	0.186
Native American				-0.46	-0.95 – 0.03	0.068
Asian American				-0.43	-0.80 – -0.07	**0.021**
Latinx				-0.26	-0.46 – -0.05	**0.013**
Multiple				-0.14	-0.35 – 0.07	0.194
Random Effects						
Classrooms (var.)	0.06			0.04		
ICC	0.06			0.04		
N (classrooms)	31			29		
N (students)	806			764		
R^2 (Marg/Cond)	0.000 / 0.060			0.027 / 0.064		

An expansive epistemology of science was strongly associated with students' sense of belonging in science

Across all models, regardless of the covariates or demographic controls that we included, science epistemology was strongly and consistently associated with students' sense of belonging in science (Table 2.5). In the model without any additional covariates, we see that a one-unit increase in expansive epistemology was associated with a 1.5 unit increase on the belonging scale ($\beta_{EPISTEM} = 1.50$, $p<0.001$). This association is meaningful in the real world: On average, in classrooms that reflect just one additional facet of an expansive epistemology of science, student experiences of belonging are more than an entire Likert-scale response category higher (e.g., "strongly agree" instead of "agree" that they feel they belong in science class).

Examining the interactions between science epistemology and student background, we find that neither student gender nor student race/ethnicity significantly moderated the relationship between epistemology and belonging. We note, however, that the magnitude of the interaction coefficients for non-binary students and for Asian American students are practically meaningful: in our sample, we observed an expansive epistemology to be more strongly related to belonging for non-binary students (as compared with females) and for Asian American students (as compared with white students). These student groups (non-binary students and Asian-American students) reported the lowest levels of belonging in science when expansive epistemology was equal to zero; but they had the steepest slopes, meaning that as classroom epistemologies of science become more expansive, these students' sense of belonging increased more than other groups and ultimately surpassed that of some other demographic subgroups (Figure 2.1). Of course, the small sample sizes in these categories mean that the uncertainty in the estimates is substantial and the estimates must be interpreted with care.

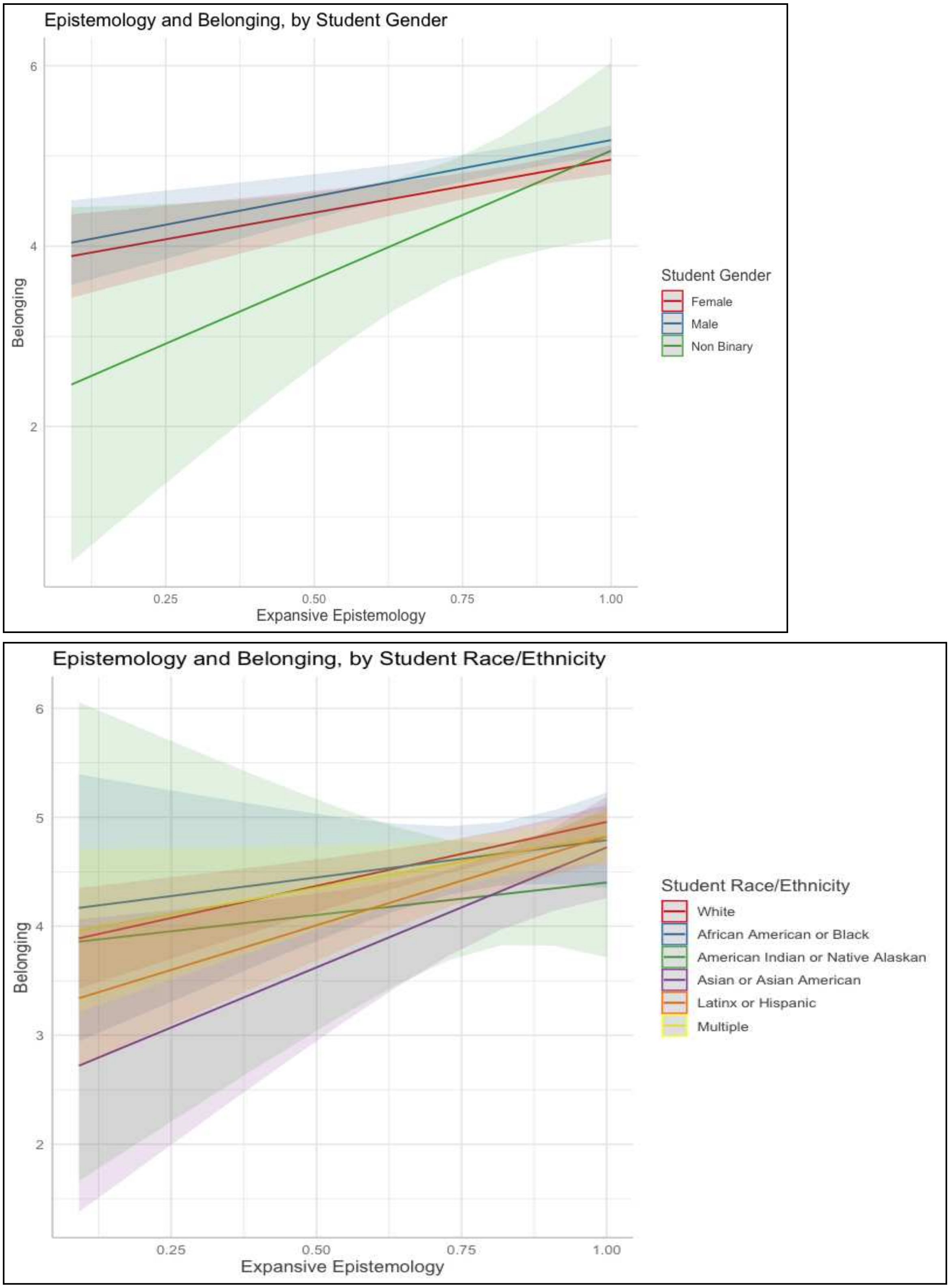

Figure 2.1. Predicted Values of Belonging by Expansive Epistemology and Student Subgroup

Table 2.5. Relationship between Expansive Epistemology and Belonging in Science, Main Effects and Interactions

	Belonging w/Epistemology			**Belong w/Epistem and Subgroups**		
	Estimates	*CI*	*p*	*Estimates*	*CI*	*p*
(Intercept)	3.48	3.18 – 3.78	**<0.001**	3.78	3.27 – 4.30	**<0.001**
Fixed Effects						
EPISTEM	1.50	1.16 – 1.83	**<0.001**	1.18	0.59 – 1.76	**<0.001**
Gender (ref=female)						
Male				0.14	-0.46 – 0.74	0.642
Non-binary				-1.58	-3.84 – 0.69	0.173
Race/ethnicity (ref=white)						
Black				0.32	-1.05 – 1.70	0.643
Native American				0.02	-2.45 – 2.50	0.986
Asian American				-1.26	-2.75 – 0.23	0.097
Latinx				-0.59	-1.34 – 0.16	0.122
Multiple				0.09	-0.78 – 0.96	0.836
Interactions						
EPISTEM × Male				0.08	-0.62 – 0.77	0.832
EPISTEM × Non-Binary				1.68	-1.21 – 4.56	0.255
EPISTEM × Black				-0.49	-2.18 – 1.19	0.565
EPISTEM × NativeAm				-0.58	-3.52 – 2.36	0.699
EPISTEM × AsianAm				1.03	-0.73 – 2.79	0.252
EPISTEM × Latinx				0.46	-0.42 – 1.34	0.304
EPISTEM × Multiple				-0.22	-1.22 – 0.78	0.668
Random Effects						
Classrooms (var.)	0.05			0.03		
ICC	0.05			0.03		
N (classrooms)	30			29		
N (students)	801			761		
R^2 (Marg/Cond)	0.087 / 0.131			0.103 / 0.133		

Students equated being “smart” with being a conscientious student

Overall, the most common student responses about what it takes to be smart in science class reflected traditional and widespread norms about what it means to be a “good” or conscientious student (62% of responses; Table 2.6). For example, students talked about the need to "pay attention", “try hard", and "participate." On their own, these responses do not provide much insight about the nature of the classroom environment, since these behavioral expectations could fit within either very traditional teacher-centered environments or more progressive student-centered environments. However, the dominance of these “good student” responses over other more epistemologically-oriented responses could be understood to reflect the prevalence and persistence of ideas about what it means to “do school” in the right ways. Seen in this light, these responses could reflect similar underlying attitudes as many of the responses that more clearly reflected traditional cultures of schooling and of school science (15%). These responses included ideas such as “listen to the teacher”, “do what you are told”, “be perfect”, and “get every right answer.”

Table 2.6. Frequency of Student "Smartness" Responses

Code	Illustrative Examples	Category	Frequency
Pay attention	Pay attention, focus, listen, listen carefully	Conscientious Student	62%
Make an effort	Work hard, do your best, try your best, try hard, never give up		
Participate	Participate, be an active member, engage in conversations		
Cognition	Cognitive verbs not captured elsewhere, use previous knowledge, be creative, have passion, make hypothesis, have an active brain, have ideas	Science cognition	32%
Share ideas	Share ideas, put your ideas out there, engage in conversations, discuss, talk about what you are thinking	Science epistemology	17%
Collaborate	Work together, be a team player, use teamwork, work with others to solve problems		
Make mistakes	It's ok to be wrong, it's ok to make mistakes, do not be afraid to be wrong, mistakes are necessary, fail and learn		
Teacher-centered	Listen to the teacher, follow instructions, do what you are told to do, be on task, finish your work	Traditional cultures of schooling	15%
Be right	Be smart, be perfect, know everything you write down, act smart, get every right answer		

In contrast, another category of student responses (32%) reflected cognitive aspects of engaging with science. This category included things like asking questions and making observations, and verbs like think and learn. Some examples of student responses that fell into this category were: "figure things out", "think outside the box", "move your science thinking forward", and "use past knowledge." A final category of student responses (17%) reflected important ways in which students interacted with one another and with science in order to build knowledge. These responses included things like sharing ideas, collaborating, and making mistakes. Some examples of the student responses that fell into this category were: "if you fail at first, keep trying", "share your ideas and work with others", and "talk about what you are thinking." Together, these categories of responses could be seen as connecting with an expansive epistemology of science, in that they reflect ideas about what science entails (asking questions, making observations, etc.) and how science is carried out (collaboratively, iteratively, etc.).

Discussion

Our study provides evidence from across a wide range of classrooms that in science classrooms that reflected more expansive epistemologies, students also felt a stronger sense of belonging in science. The fact that these epistemologies are related to belonging in science is important because belonging is correlated with participation and contribution in science, both of which support greater learning; and with future course-taking and career decisions which are required prerequisites for broadening participation and representation in STEM fields (Roeser et al., 1996; Cacioppo & Patrick, 2008; Patterson, 2019; Edwards et al., 2022; Penuel et al., 2023). This finding indicates that students' understanding of the epistemology of science is related to their own evolving sense of themselves and their position within the field of science.

With respect to epistemologies of science, our analysis revealed that classrooms varied in the degree to which they manifest a more expansive epistemology of science. This finding fits with a conceptualization of epistemology as a characteristic of group interactions (Krist, 2020). While classrooms varied from one to another in their overall epistemological stance, students' epistemological experiences of the classroom did not vary based on student demographic characteristics. Males, females, and non-binary students all reported similar epistemological experiences of their science classrooms. Students from different racial/ethnic backgrounds also reported roughly similar experiences around science epistemology, with point estimates only varying by a maximum of 0.06 points on the epistemology scale. This degree of difference is not large enough to be practically meaningful for students.

At the same time, student responses about what it takes to be “smart” in their science class reflected a confluence of different ideas about science (oftentimes within a single response). This mixture of perspectives reflects the reality that student ideas about science and science class are shaped through multiple, sometimes competing, cultures and norms. The prevalence of responses reflecting traditional ideas about what it means to be a “good student” reflect the persistence of larger cultural norms and stances about what is important when it comes to doing science at school and being smart at science. These cultural norms may be interfering with efforts to convey a more expansive epistemology to students and could be one of the factors contributing to the observed classroom-to-classroom variation in science epistemology.

The central finding from our work is that in classrooms where students perceived a more expansive epistemology of science, they also reported a much stronger sense of belonging in science. This relationship between science epistemology and sense of belonging in science underscores the importance of culture in sustaining or dismantling historical barriers to the world of professional science. The way that people—specifically students from historically marginalized communities—understand science directly relates to their understanding of their own position within or outside of that community. The more that students see science as a fixed body of facts that one either knows or does not know, absorbs or does not absorb, the more they internalize the reasoning that mistakes must mean that they do not belong. In contrast, the more that students understand science as an iterative, collaborative endeavor, involving mistakes and corrections and new knowledge building, the more they understand that a place for them exists within that world.

Importantly, we found that the relationship between an expansive epistemology of science and sense of belonging in science held true for students from across all demographic backgrounds. Our analysis did reveal that some students (notably males and white students) reported greater sense of belonging in science than students from other backgrounds. Nonetheless, the relationship between classrooms reflecting an expansive epistemology and student sense of belonging held true across all student subgroups.

Our sample suggests that not only does the relationship between an expansive epistemology and sense of belonging hold true for all groups of students but that, in some cases, the relationship may be the strongest for students from historically minoritized communities. Within our sample, the relationship between expansive epistemology and belonging was strongest for those with the lowest baseline levels of belonging in science, namely non-binary students and students who identify as Latinx or Asian American. While none of the interactions between epistemology and demographics reached statistical significance, the point estimates are of practical relevance. This observation is important because it suggests that emphasizing a broad and flexible understanding of science epistemology could prove even more valuable for students who are struggling most with feeling a sense of belonging in science. Not surprisingly, we find that addressing the epistemology of science—specifically presenting a new vision that both disrupts historical patterns of exclusion and imparts a broader and more flexible understanding of science epistemology—may be most impactful for students from communities that have historically been excluded from the field.

An important next question is to understand *how* to cultivate classroom cultures that express this expansive epistemology to students and help them to adopt this broader understanding for how science works, what knowledge is valuable, and who can meaningfully participate. The literature is clear that engaging in scientific inquiry is itself insufficient for students to grasp these ideas about science epistemology (Abd-El-Khalick & Lederman, 2000;

Schwartz et al., 2003). Some scholars have argued that understanding the nature of science is itself a cognitive learning outcome that is best addressed explicitly through classroom teaching and learning (Bianchini & Colburn, 2000; Akerson et al., 2000, Smith et al., 2000). Our research suggests classroom norms may play a role for cultivating and imparting a realistic understanding of science epistemology. Norms that focus, for example, on the importance of collaboration, observation, and creativity, and on the inevitability and potential knowledge-building value of mistakes, align explicitly with an expansive epistemology of science. As such, these norms may serve to reinforce a broad and flexible understanding of the epistemology of science for students.

Conclusions

This paper aims to contribute to the literature and to broadening participation in STEM by building our understanding about the relationship between classroom science epistemologies and students' sense of belonging in science. We know that a sense of belonging in science is essential for learning, interest development, and persistence in STEM (Roeser et al., 1996; Cacioppo & Patrick, 2008; Patterson, 2019; Edwards et al., 2022). Our research demonstrates that an expansive epistemology of science can support belonging in science, perhaps especially for students from communities that have been historically excluded from the field. Our research further suggests that classroom norms that promote creativity, curiosity, collaboration, and iteration and refinement of ideas may help students to develop a broader and more flexible understanding of science. With that in mind, an "epistemic boost" that attends to students' epistemologies of science and cultivates an expansive epistemology of science may advance the goals of the science-as-practice vision for science education. Our hope is that by building classrooms that effectively communicate an expansive epistemology of science to students, we can build the foundation for students to recognize their own belonging in science

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Paper 3: Curricular Structures and Equity in Science Education

Introduction

Expanding equity in science education in order to broaden participation in STEM fields has been a long standing and increasingly urgent goal within U.S. education. By and large, discussions about equitable education have focused on education policy (e.g., Bishop & Noguera, 2019; Cairney & Kippin, 2021; Movrogordato, 2012), educational structures (e.g., Ansalone, 2001; Lee, Ready, & Welner, 2002; Murphy, 1993; Ready, Lee & Welner, 2004; Van de Werfhorst & Mijs, 2010) and pedagogy and instruction (e.g., Atwater, Russell, & Butler, 2014; Bang et al., 2013; Ladson-Billings, 1995a; Ladson-Billings, 1995b; Ladson-Billings 2023; Windschitl & Calabrese Barton, 2016). To the extent that curriculum has been seen as a mechanism for increasing equity in science education, discussion has mostly centered around increasing representational diversity within curricula—that is, including more vignettes of minority scientists and more images depicting minority students doing science (Banks, 2003; Mensah et al., 2018).

Curricular purposes and structures directly shape what happens in the classroom and are consequently at the center of any educational reform movement focused on transforming learning (e.g., Davis et a., 2017; Edelson et al., 2021; Penuel & Gallagher, 2009; Penuel et al., 2015; Schneider et al., 2022). I propose that the very same curricular purposes and structures that impact content learning can and do also shape equity. Certainly, teacher practice dictates curricular enactment and plays an enormous role in shaping both learning and equity. And yet, the curriculum forms the foundation for what teachers do in the classroom and the intentions built into the curriculum permeate teacher practice and influence students both directly and indirectly (Flake, 2017; Yates, 2009).

When it comes to learning, curriculum is viewed as a core mechanism for shaping not only what is learned but also how students learn, including how they engage with content and build knowledge and skills (Cohen et al., 2003). Since the introduction of the *Framework for K12 Science education* and the Next Generation Science Standards, curriculum developers have worked to develop curricula that reflect the *Framework's* intentions and align with the standards. These NGSS-aligned curricula are fundamentally different from science curricula of yore. While previous science curricula focused on helping students to *learn about* science, NGSS-aligned curricula guide students to *figure out* science. This approach intersects with the "practice turn" in science education and involves giving students opportunities to engage authentically in scientific practices in order to incrementally build scientific knowledge (Ford & Forman, 2006; Forman, 2018; Furtak & Penuel, 2019).

In contrast, the push for equity in science education often focuses not on curricula but on teachers: overlaying the reform curricula with equitable pedagogical practices that provide all students with access to those advanced concepts and skills *and* that promote identity and belonging. In this paper, I draw on interviews with teachers who implemented a reform science curriculum to argue that curricular purposes and structures can also directly target equity – and moreover that the very same structures that support learning science as practice are the same structures that also support equity.

Conceptual Framework

The idea that curricula shape social outcomes (not just learning outcomes) is not new, but has often been addressed through overlaying representation or equity-oriented pedagogy on top of core curricular structures (Anyon, 1980; Banks, 1989; Brown & Livstrom, 2020; Mensah, 2022). Here, I share a conceptualization of the role of curricula in shaping equity in science education. First, I describe how I conceptualize equity in science education and how I define curricula. Next, I discuss how curricular purposes and structures have historically been used to promulgate and maintain societal hierarchies, thus unlocking the possibility that transforming curricular purposes and structures could also transform educational equity. Finally, I draw connections between the structures of NGSS-aligned curricula and instructional approaches known to support equity in science education, laying the foundation for the possibility that the very curricular structures designed for a new type of science learning could *also* support equity in science education.

Defining Equity in Science Education

In the context of this work, I understand equity in science education to mean intentionally designing and employing materials, instructional practices, and classroom norms to support student identification, belonging *and* learning in science, with particular attention to disrupting patterns of historical inequity that have created barriers to participation for students from historically marginalized populations (Bang et al., 2012; Calabrese Barton & Tan, 2020). Equitable science education begins with the interests and curiosities of students and leverages those curiosities to drive inquiry about relevant real-world phenomena in order to better understand our natural world (Penuel et al., 2022). Within equitable learning environments, teachers notice, value, and leverage students' funds of knowledge, experiences, linguistic resources, and cultural ways of knowing to support scientific knowledge building within the classroom (Bang & Medin, 2010; Calabrese Barton et al., 2020; Moll et al., 2006).

Defining Curricula As Part of An Integrated Activity System

By science curricula, I refer to the concrete materials associated with a particular instructional program, including both teacher and student materials and resources, designed activities, specified instructional routines and classroom norms, and educative materials incorporated into teacher resources for the program. Of course, curricula do not operate in isolation. Within the crucible of the classroom, we can think about curricular activity systems—the combination of curricular materials, professional development, and teachers—as playing a role in shaping science teaching and learning (Roschelle et al., 2010). For the current discussion, however, I focus specifically on the role that the curriculum itself plays in shaping both teaching and learning *and* equity within science classrooms.

Curricula Shape Science Education (In)equity in the Classroom

The fact that curricula shape learning opportunities with respect to the content, skills, and depth of learning is well documented and widely accepted (DeBoer, 1991; Edelson et al., 2021; Rudolph, 2002). The idea that curricula also play a role in shaping educational equity or inequity is also not new, but I argue it has been understood in limited ways within current conversations about educational equity.

Freire famously exposed the role of curriculum in perpetuating existing social hierarchies and maintaining an inequitable status quo (Freire, 1970). Historically, curricula have reflected a “banking” method of education wherein the goal is to transfer knowledge to students who are essentially seen as empty vessels waiting to be filled up with facts (Yosso, 2002). These curricula also reflected deficit perspectives on minority students and thus limited the amounts and types of knowledge available for transferring to students. Curricula serving students from lower socioeconomic classes and racialized communities (e.g., Black and brown students) have typically reflected less academic content, lower standards, and less rigor than curricula being used for whiter and wealthier students (Kirchgasler, 2023; Margolis et al., 2008; Songer 2002). The focus on facts and procedures in these curricula limited opportunities for critical thinking and problem solving and aligned with the view that certain students need preparation for rote and repetative low-wage jobs (Anyon, 1980). More recently, scholars have argued that these types of learning environments limit opportunities for students to develop a sense of identity and belonging within scholarly fields (Bang et al., 2012; Bell et al., 2017; Calabrese Barton & Tan, 2020; Carlone et al., 2011).

The most common strategies for creating more equitable or justice-oriented curricula focus on including extra content designed to intentionally address discrimination and injustice (Banks, 1989). This approach involves adding stories of “ethnic heroes” or even a full unit focused on a particular ethnic group or community and their contributions to a field. These strategies are relatively easy to implement because they do not require transforming the base curriculum. By not altering the core curriculum, however, these approaches do not help students to grapple with broad concepts related to the interconnected histories of dominant and marginalized groups, nor systemic issues of power and oppression (Rodriguez, 2021). Further, these approaches tend to reify the mythology of the American Dream, wherein anyone who works hard enough can achieve greatness (Banks, 1989).

Less common but more productive forms of multicultural curricula transform traditional core curricula to enable students to view concepts from varied perspectives and to build an understanding that knowledge is socially constructed (Mensah, 2022). The most transformative versions also enable students to make decisions and act on social issues that are important to them and their communities, based on content and connections they are making as part of their learning (Mensah, 2022). However, these types of transformative multicultural science curricula are rare, leading scholars to recommend that pre-service teachers receive training to create them individually (Brown & Livstrom, 2020).

Separate from efforts to design multicultural science curricula, Yosso (2002) argued for the creation of a "Critical Race Curriculum." Such a curriculum would reflect the core tenets of Critical Race Theory (CRT) by acknowledging the prominent and intersecting roles of systemic social subordination (e.g., racism, sexism, etc.); challenging dominant social and cultural assumptions; working toward goals of social justice and critical consciousness; developing counter narratives that draw on students' lived experiences; and bringing together interdisciplinary content and analysis to teach about social injustice (Yosso, 2002). While a curriculum that achieved these goals would no doubt reflect a thorough restructuring of traditional curricula, it remains unclear whether and how the presentation and instruction of subject-matter content itself would differ from traditional curricula. Furthermore, within the context of the current "conflict campaign" among conservative state and local entities, such curricula would almost certainly become political targets, potentially rendering them moot (Pollock et al., 2022).

The scholarship to date on critical and multicultural curricula has not offered much guidance on changes to the actual subject-matter content. A key question becomes: How might science curriculum developers create science curricula that expand equity in science education, not only through greater representation, discussion of social justice, and so forth—but also through the design and approach to science content learning itself?

Reform-Oriented Science Curriculum Design Leaves Equity to Teachers

Advancing the vision of the *Framework* and NGSS goals has required a major transformation of traditional science curricula. These curricular changes have been framed in terms of new approaches to science learning (e.g., Penuel and Reiser, 2018; Vigeant, 2021). For example, the NGSS specifies that curricula should employ scientific phenomena and engineering design challenges to motivate scientific inquiry and learning (NASEM, 2019). NGSS-aligned curricula should also integrate content and processes so that science practices become a mechanism for building science knowledge (rather than learning about science content and the scientific methods as separate strands). And finally, these curricula should enable students to build their knowledge incrementally, beginning with their own experience of the world and gradually revising and augmenting that knowledge toward a more robust and generalizable understanding of scientific phenomena (NRC, 2012).

To support the *Framework's* vision and NGSS goals, both of which center equity, new curricula must also design for equitable participation in science. However, design guidance for equity has been largely unspecified within NGSS documents themselves (Tzou et al., 2021). The NGSS released a series of case studies intended to provide some additional information to further address equity within the NGSS. The case studies are valuable, but they primarily offer vignettes of effective practice, rather than guidance for curriculum development (NGSS Lead States, 2013). As such, curriculum designers and researchers have been left to articulate equity-oriented design principles and strategies for themselves (Alozie et al., 2018; Penuel & Reiser, 2018).

Some recent efforts have attempted to address the need for more explicit attention to equity within NGSS-aligned curricula. The Culturally Responsive-Sustaining STEAM Curriculum Scorecard from NYU, for example, provides a framework for evaluating the extent to which a particular curriculum is culturally responsive and sustaining (Peoples et al., 2021). The scorecard takes an expansive view of equity that goes well beyond simply adding minority representation into a textbook. Along with representation, the scorecard includes sections on social justice, teacher materials, and (student) materials and resources. The social justice section, for example, focuses on whether and how curricula explicitly address issues of power and privilege associated with a particular discipline. However, the Scorecard does not look at the ways in which a curriculum scaffolds student interactions with the core content itself—and how those curricular structures and student-content interactions might also shape equity. Indeed, the section on teacher materials reveals the perception that much of the work of shaping students' interaction with content in equitable ways lies with the teacher. Here, the Scorecard focuses on whether teacher materials *guide teachers* to use students' everyday experiences and ways of knowing as an entrypoint for learning and to encourage a range of valid student responses. This approach sidelines the possibility that curricular structures themselves might have a role to play in designing activities that allow for multiple entry-points and validate varied kinds of knowledge.

By and large, NGSS-aligned curricula lean on teachers to advance their goals around equity, emphasizing the need for teachers to implement equity-oriented pedagogies and establish equitable classroom cultures. Teachers are instructed to establish classroom participation norms, for example, that emphasize active listening, respect for others, critiquing ideas and not people (Berland & Reiser, 2011; Bricker & Bell, 2008; Calabrese Barton & Tan, 2009; Duschl & Osborne, 2002; Osborne, Erduran, & Simon, 2004). Teachers can build on these norms by employing instructional practices grounded in asset-based perspectives of students: encouraging students to leverage all of their communication resources, build on their existing knowledge and experiences, and engage both traditional and academic ways of knowing to support their science learning (Calabrese Barton & Tan, 2020; Gutierrez et al, 1999; Moll et al., 1992).

Leaving the task of advancing equity to teachers—through the classroom cultures they build, the norms they establish, and the instructional practices they employ—is at best a missed opportunity for advancing equity in science education and at worst detrimental to the cause. The surreptitious influence that curricular structures can and do have on equity makes it imperative to design those structures intentionally to support goals around equitable science participation and learning. Curricular structures that support and advance equity can then serve as a foundation that both anchors and propels the culture and norms that teachers and students put in place within the classroom.

The Current Study

The current study took place within the context of a large-scale field test of an NGSS-aligned middle-grades science curriculum called OpenSciEd. The field test and associated research took place from fall 2018 through spring 2021 in science classrooms across the country. Participating teachers implemented field test versions of six- to eight-week science units, each of which followed a storyline that began with an anchoring phenomenon and developed around student questions and investigations about that phenomenon (Reiser et al., 2021). As detailed below, the OpenSciEd curriculum supports an NGSS-aligned, science-as-practice approach to science teaching and learning.

Research Methods

The intent of this study was to understand the factors that enabled and supported teachers to create equitable science learning opportunities within their middle-grades OpenSciEd classrooms. The following research question guided our inquiry: *What aspects of teaching with OpenSciEd do middle school science teachers point to as supporting equity within their classrooms?*

Knowing that OpenSciEd includes both professional development and educative materials that focus very explicitly on equitable instruction, I anticipated that teachers would point to those very straightforward elements of the program as having supported equity. An initial review of the data, however, revealed that while teachers did mention professional development and educative materials, they talked even more about how various curricular structures supported equity in their classrooms. In an effort to better understand this phenomenon, I decided to focus my analysis on understanding how teachers experienced curricular features as enabling equity within science education.

Participant Sample and Data Sources

Ten partner states joined the OpenSciEd initiative: California, Iowa, Louisiana, Massachusetts, Michigan, New Jersey, New Mexico, Oklahoma, Rhode Island, and Washington state. Each state recruited teachers from within their state who volunteered to participate in the field test. Ultimately a total of 341 teachers participated in the field test, located across 97 districts, throughout all ten partner states. Teachers participated for varying amounts of time, ranging from a single semester to three or more years. Each teacher implemented one or more OpenSciEd units, which together address all of the NGSS for the middle grades.

For this study, I decided to focus on interviews from two strategic groups of teachers: 1) teachers who grew in their use of equity-oriented instructional practices; and 2) teachers who participated in interviews in Spring 2021. I focused on the first group of teachers with the idea that these teachers might be particularly “tuned in” to classroom equity and factors that support or enable equity within OpenSciEd classrooms. I selected the second set of teachers because the interview protocol used that semester included a question that asked explicitly about equity, thus providing data directly oriented toward our research question.

I used survey data from teacher end-of-unit surveys to identify teachers who grew in their use of equity-oriented practices. Surveys were administered to participating Field Test teachers between fall 2019 and spring 2022. The survey included four items addressing equity-oriented teaching practices. These items asked teachers how frequently they implemented each of the following practices: 1) teach science as a cultural endeavor that shapes and is shaped by the values, power and ideologies of scientists; 2) encourage students to use their primary or home language and other resources for communicating in science class; 3) identify cultural knowledge in families and communities that could be used to help select the focus of science instruction; and 4) help students navigate between their everyday ways of knowing and scientific ways of knowing. The response scale had the following frequency options: never; rarely (a few times a year); sometimes (1-2 times a month); often (1-2 times a week); daily or almost daily.

To identify teachers who increased their use of equity-oriented instructional practices, I first collapsed the individual teaching practices data into a scale and calculated a mean scale score for each teacher at each timepoint that they took the survey. Next, for each teacher, I calculated a “growth” score by subtracting their initial equity-oriented practices scale score from their last score. For some teachers, the initial score came from fall 2019, for others it came from fall 2020 (with a small number of teachers who had scores at both timepoints); for everyone the final scale score came from spring 2021. Teachers with a positive growth score therefore increased their overall use of equity oriented instructional practices from baseline to follow-up. In our sample, sixteen unique teachers grew in their use of equity-oriented instructional practices. Of those sixteen teachers, twelve participated in one or more interviews.

The final interview sample consisted of 38 interviews from 27 teachers (Table 3.1). These teachers came from 9 different states: California, Louisiana, Massachussettes, Michigan, New Jersey, New Mexico, Oklahoma, Rhode Island, and Washington. Collectively, the interviews are associated with ten different OpenSciEd units (e.g., ecosystems, chemical reactions, etc.), thus covering a broad range of topic areas.

Table 3.1. Interview Data, Number of Teachers and Interviews

Interview Sample	**No. Interviews per Teacher**	**No. Teachers**	**Total Interviews**
Sample A: Teachers Who Increased Equity Practices	1 each	5 teachers	5 interviews
	2 each	4 teachers	8 interviews
	3 each	2 teachers	6 interviews
	4 each	1 teacher	4 interviews
	Subtotal	**12 teachers**	**23 interviews**
Sample B: Additional Spring 2021 Interviews	1 each	15 teachers	15 interviews
TOTAL Interview Sample		**27 teachers**	**38 interviews**

The primary data source for this study was the interviews with these selected teachers. Interviews focused on teacher experiences using OpenSciEd in their classrooms. Interviewers asked teachers what went well during the unit; what was difficult; and what changes, if any, the teacher made to the unit. They also asked teachers about their trajectory with OpenSciEd: how their experience had evolved, what had gotten easier, and what remained challenging. Four questions explicitly addressed the OpenSciEd materials and how they influenced instruction and equity:

- Do you find that you are teaching differently now that you have used OpenSciEd materials?
- How have the materials helped you to teach science differently?
- How does teaching science with storylines work for the range of the students that you teach? Who is well-served by this approach and who may be less well-served?
- How do you see equity being addressed in the materials and in professional learning? Are there ways that equity is not adequately addressed?

These four questions were the most directly relevant to our study and did in fact yield a majority of the data for our analysis. Nonetheless, content pertaining to our research questions and analytic focus arose throughout the expanse of the interviews, and so I included the entire interview transcripts in our analysis and did not limit the analysis to content arising only in response to those four questions.

Analytic Approach

The analysis for this study consisted of an in-depth qualitative analysis of interview data from the sampled teachers. First, I read through the interviews and coded the data using low-inference codes that reflected the broad topics of interest for this analysis. These topical codes included things like teacher role, professional development, teacher resources/educative materials, instructional routines, classroom norms, and OpenSciEd curricular features. The primary purpose of this step was to identify the broad topical themes that existed within the interviews and that were relevant to my research question, and to identify the specific interview segments that addressed those topics. It was at this stage that I identified the prevalence of teacher commentary around curricular structures supporting equity in their classrooms, and decided to focus the rest of the analysis specifically on curricular structures.

Next, I engaged in a process of analysis and theory-development, taking place through an interactive back-and-forth between interview data, prior literature on instructional change and equity-oriented instruction, and discussions with other OpenSciEd researchers (Miles & Huberman, 1994; Straus & Corbin, 1998). I began by reviewing the relevant interview data and creating a set of more analytic, inductive codes based on themes and patterns observed in the data (Strauss & Corbin, 1998). During this phase of analysis, I focused on understanding teacher reports about *how* curricular structures supported equitable science learning opportunities for students. The codes that I constructed for this analysis included ideas related to equitable science instruction, such as: students leading inquiry; students asking questions; shared entry points; valuing diverse perspectives & ways of knowing; valuing mistakes and rough-draft thinking; multiple ways to show what you know; etc. Finally, I reviewed themes and patterns across curricular structures to construct findings about how structures support equitable participation more broadly, i.e., not limited to a structure-by-structure analysis.

The OpenSciEd Curriculum

OpenSciEd was developed by a consortium of state science leaders, curriculum developers, science teachers, and science education researchers. The consortium had an ambitious goal: to transform science teaching and learning across the country through student-centered, reform-oriented instructional materials that place equity at their core (Edelson et al., 2021). Specifically, they sought to transform school science such that: 1) students learn science through active investigations of complex phenomena that enable them to construct new understandings and competencies; 2) teachers establish the learning context, organize learning experiences, and facilitate productive social interactions, while removing inequitable obstacles and expanding access to science learning. These goals reflect the sociocultural underpinnings of the curriculum (and of NGSS), and the view that learning happens through active engagement with content that builds on prior histories and experiences and is shaped by culture and relationships.

The OpenSciEd curriculum is a fully elaborated curricular activity system comprising the student-facing curriculum and materials, teacher resources, and a program of professional learning (Roschelle et al., 2010). An integrated set of curricular structures, instructional routines, and classroom norms shape the experiences that students have in the classroom. For teachers, OpenSciEd includes professional learning opportunities and educative supports embedded within teacher materials, both of which explicitly address equity within science teaching and learning.

OpenSciEd Curricular Structures

The OpenSciEd team built a curriculum with many features designed intentionally to support their goals around student sensemaking. First, the curriculum uses a storyline framework to drive the content (Reiser et al., 2021; Windschitl et al., 2018). Storylines begin with a phenomenon or problem (written into the curriculum) that anchors the rest of the unit. Students generate questions that they deem necessary for making sense of the phenomenon or designing a solution to the problem and then use science and engineering practices to seek out answers. These storyline units are a form of problem- or project-based learning in the sense that students figure out key ideas through engaging in science and engineering practices to explain phenomena and design solutions to problems (NASEM, 2019). Teachers guide and facilitate the process, steering students toward more productive lines of questioning, providing information and resources to address their questions, explaining key features of the science, and helping students to extract the core concepts. Within this model, students collaborate to build scientific knowledge, bringing their full repertoire of experience, knowledge, and resources to bear in the process.

Each OpenSciEd unit uses the storyline approach and begins with an anchoring phenomenon; from there the curriculum integrates various curricular structures that serve different functions for moving students through the storyline unit. These structures include the Driving Question Board (DQB), the progress tracker (a formative self-assessment tool used for keeping track of discoveries and supporting sensemaking), the model tracker (a portion of the student notebook designated for recording and updating models), and the consensus model (a shared classroom representation of the evolving scientific model). Teachers and students use the DQB to capture student questions as they explore the anchoring phenomenon. Students then discuss the questions on the DQB and decide which questions to pursue in order to investigate the phenomenon. Throughout any unit, the class returns to the DQB to see what questions they have answered and which questions remain unanswered and might require further investigation.

OpenSciEd Instructional Routines

OpenSciEd uses five concrete teaching routines to support student sensemaking within storyline units. Each of the routines serves a distinctive purpose in supporting students to make progress toward the 3D learning goals of the unit. The *Anchoring Phenomenon Routine* guides students toward questions that motivate the need to develop science understandings targeted in the unit. The *Navigation Routine* and *Problematizing Routine* both help students to organize the ideas they are developing and identify gaps in knowledge that can be addressed by pursuing new questions that arise from their investigation. The *Investigation Routine* helps students develop a grasp of scientific and engineering practices, by engaging students in seeing just how using the practices together can help them build knowledge. Finally, the *Putting Pieces Together Routine* helps students apply and generalize knowledge they have built through studying the anchoring phenomenon and investigative phenomena along the way.

OpenSciEd Classroom Norms

The OpenSciEd curriculum includes a set of classroom norms intended to lay the foundation for a productive and equitable classroom culture. Teachers are encouraged to share and discuss these norms explicitly with their students, and to return to the norms regularly throughout the year. The norms are designed to foster a community where people are committed to one another's learning and well-being. They acknowledge that the cultures that typically emerge in science classrooms often align with dominant cultures; to disrupt that pattern, teachers and students must intentionally co-construct classroom norms that help all students feel respected and valued. The norms fall into four broad categories: respectful, equitable, committed to our community, and moving our science thinking forward. For example, under the category of respectful, specific norms encourage mutual support and debate where ideas are critiqued but not persons. Under the category of equitable, norms encourage active seeking out of voices and appreciation of diversity. Together, these norms are intended to cultivate spaces where students experience the care required to support the vulnerability and uncertainty required to engage in figuring out science.

OpenSciEd Professional Development & Educative Materials

The OpenSciEd professional learning provides additional resources and opportunities to prepare teachers to cultivate classrooms where students work together to figure out key science ideas. The professional development also provides teachers with explicit guidance around fostering equitable learning communities. For example, teachers receive guidance for facilitating equitable discussions, incorporating universal design for learning into their instruction, and supporting equitable sensemaking by identifying and leveraging student resources, among other equity-focused professional learning opportunities.

OpenSciEd also includes educative materials for teachers, or instructional guidance embedded within the teacher resources (Davis & Krajcik, 2005). One specific goal of these educative materials is to help teachers advance equity within their classrooms. The curricular materials include “equity callouts” to help teachers enact equity-oriented practices and build equitable science classroom cultures. One call-out aimed at supporting multilingual learners reads, *“Asking questions in everyday language allows students to share their thinking or experiences, even if they do not have the appropriate scientific vocabulary yet. This is helpful for emergent multilingual students because, by not requiring scientific words at the onset, you do not limit their participation in classroom discourse.”* Other equity callouts focus on soliciting and drawing out students’ funds of knowledge; connecting the content to students’ lives and communities; and attending to historical and political injustices connected with the content.

Findings

In discussing their experiences with OpenSciEd, teachers highlighted the ways in which the curriculum itself supported equity within their science classrooms. They described how particular curricular structures provided shared entry-points for students, positioned students as drivers of the class’ science learning, expanded sanctioned forms of disciplinary participation, offered varied ways for students to show what they know, and enabled students who had been absent to connect back into the classroom enterprise. The OpenSciEd instructional routines and classroom norms reinforced key messages around asking questions, taking risks, making connections to the real world, and listening to others as valid and essential components of doing science.

Curriculum structures supporting NGSS science learning goals also support equity

As described above, the OpenSciEd curricular structures were intentionally designed to support the NGSS vision of science education. Structures such as the storyline approach, the driving question board, the scientist circle and others are intended to enable student-centered learning that is driven by student questions and ideas. These curricular structures are also intended to support students in figuring out science through engaging with scientific practices to understand real-world phenomena. Our interviews revealed that these very same structures designed to support science learning also directly supported equity within science classrooms.

Curricular structures provide a shared point of entry and opportunities for all students to contribute

Teachers reported that certain OpenSciEd structures created “shared points of entry” for students. The storylines—and especially the anchoring phenomenon—provided students with a common touchpoint that they could relate to their own lives and experiences. The practice of sharing noticings and wonderings afforded a universally accessible way into the science material. One teacher noted specifically that emphasizing phenomenon over vocabulary makes it possible for more students to engage with the lesson and easier for students to catch onto core concepts. Another teacher explained how the storyline approach offered a shared experience for students:

> “I think the power of the storyline approach is that it's really giving the kids a shared experience. We're all having a shared experience in the beginning and we're all experiencing this phenomenon that none of us really can figure out. Everybody can share something they notice, everybody can share something they wonder. I think really establishing that culture and the norms that every voice is valued, then every single student has to share a question, so we do that. I think that really works to reach all students. I think the storyline approach really helps the students to be able to see how one thing is building on the other. We're trying to figure out our questions.”

This quote also expresses the idea, shared by many teachers, that the Driving Question Board (DQB) enabled students who were starting at very different places to all make valuable contributions that helped the class move forward with their scientific understanding. One teacher explained how the DQB enabled students to meaningfully contribute to class learning through the asking and answering of questions. She explained:

> "[The students] enjoyed the driving question board because each of them had an opportunity to participate in their learning [...] They enjoyed seeing how everything [worked together] to answer all of their questions and every single one of their questions were answered and they enjoyed feeling validated that they were part of the unit and driving the instruction."

This teacher also connected the structure of the curriculum to the norms, making explicit the ways in which they are mutually reinforcing. Another teacher elaborated on the value of the DQB specifically:

> "When [students] do have…different questions, if someone is really very simplistic about their question and they're learning how to ask questions and others have already gone to the meat of the unit that first time. That's a really high-level question and how does that different entry point get valued in my classroom? I think because they're both going in the same place, they are both appreciated and respected as having ideas that are worth addressing and worth understanding better."

Through these observations, teachers highlighted the ways in which the storyline, anchoring phenomenon, and DQB provided students with a shared point of entry to the science content and opportunities for a plurality of students to participate in the knowledge building endeavor within the classroom.

Curricular structures position students as drivers of class learning

Many teachers talked about the student-centered and inquiry-driven nature of the OpenSciEd curriculum as something that supported motivation and learning for a wide variety of students. The DQB provides an infrastructure that formalizes the student-centered approach to learning in OpenSciEd classrooms and positions students as the drivers of classroom learning. Using the DQB, students pose questions about the phenomenon that they are studying and, with guidance from the teachers, collectively decide where to take their inquiry to answer the questions that they have posed.

Teachers also noted the role of the model trackers in positioning students as experts and building their confidence around what they have learned through the inquiry process. The model trackers provide a way for students to articulate their ever-deepening understanding of the phenomenon and to track their incremental gains in knowledge and understanding as they go—thus providing visual documentation of the expertise that they have gained. One teacher described her experience with a student with particularly low confidence around science:

> “I've got one [student] in particular who tends to be really insecure around her own skills. The day that she made a model… She probably made the most thorough poster to show what was going on for her animal…showing all the details and referencing the data, and she just was an expert and she knew it. [...] When you're…really understanding exactly why that's happening and being able to explain that data, that gave her a power that you could see her sit a little taller after that.”

Teachers pointed to the ways in which the OpenSciEd structures not only support student learning (e.g., by giving them an active role in science inquiry) but also position students as experts and help them to build confidence in their scientific selves.

Curricular structures expand the range of sanctioned disciplinary participation

Teachers pointed to a number of ways in which the curricular structures of OpenSciEd expanded opportunities for students to engage as productive members of the classroom’s scientific community. One of the aspects of the curriculum that teachers noted most was the role that students have in asking questions about science. Here too, the DQB formalizes this essential student role by providing a place for recording student questions about the anchoring phenomenon. In this way, the DQB also serves to communicate that having all the right answers is not the only way to be good at science; asking questions that move the inquiry process forward is also crucial and valued.

Other curricular structures reinforce the importance of asking questions, while also demonstrating that science involves uncertainty and that it is not necessary (or realistic) to have everything fully figured out from the beginning. Teachers pointed to the model tracker in particular as a place where students get comfortable with making mistakes and revising their thinking to work progressively toward a more thorough understanding of science. By tracking how the class' thinking has evolved, the model tracker celebrates this progression of scientific understanding, rather than valuing only fixed and final forms of scientific knowledge. One teacher reflected the comments of many when they said:

> "The initial models can sometimes be a huge struggle. They'll sit there and write nothing, and it's almost that fear of being wrong. I really try hard to support them in knowing that, "Hey, guys, there's no wrong answer. Whatever you're thinking is right." But it's a hard hurdle to tackle. My eighth graders have an easier time, and I think it's just because they've had more experience with the routine that they're more eager to put down an answer even if it's wrong."

Teachers also talked about the Scientist Circle as a structure that underscores messages around expanded ways to productively engage with science. One teacher explained that the discussions involve "sharing what we know and what we don't know" and thus help students to get more comfortable being vulnerable, sharing uncertainty, and recognizing that scientific understanding builds from places of not knowing. Together these structures help students to "move away from needing perfection to feeling more free to test things out".

Related, two teachers noted specifically that the OpenSciEd curricular structures provide varied ways for students to show what they know. One teacher pointed to the model tracker in particular as being a structure that enabled students to represent their understanding in many different ways—including in ways that may not have initially occurred to the teacher but that are nonetheless accurate. One of those teachers commented specifically on the fact that the curriculum provides opportunities for students to use their full repertoire of resources to communicate and demonstrate their knowledge. This teacher said,

> “I think [the curriculum] does a great job at giving students the tools they need to learn and demonstrate their understanding. The fact that modeling is such a big thing and that's support for ELL students right there. You may not be able to write your explanation or your understanding, but if you can draw and explain your thinking through that way or you can model it using a physical model. I think that provides a tremendous amount of equity for students because you are allowing students to access information and demonstrate understanding at so many different levels and essentially I feel like almost every lesson. That's one of the things I really love. You're giving the students so many opportunities to learn by reading or listening to a podcast or drawing a model or using a physical object to demonstrate, like in astronomy, showing the difference in the angles of light, using the Styrofoam ball, things like that. I think that it's just ingrained and intertwined into all the units beautifully.”

As we can see, OpenSciEd teachers pointed to specific curricular structures that not only helped their students to learn—but that also helped their students to understand science in ways that created more space for their own (valued, legitimized) participation.

Curricular structures make it possible for students to slot back in after absences

Two teachers noted that the storyline model along with the navigation routine enabled students who were absent to readily connect back into science class. These structures provided maps of where the class had been and where they were going, thus making it easier for students to jump back into learning after an absence. One teacher explained,

> “I said, “What do you think we should do next?” You know? That was my question. [...] And then this girl that hadn't even been there, that had just heard the navigation, she raises her hand, and she goes, "Oh, well what if we did blah-blah-blah?". And I'm like, "Oh, Sally Sue, great idea. Let's go with what you just said.” And so she hadn't been there for a few days, she picked up through the navigation what had been going on. And she's not an A-student, B-student, or C-student, okay? Just because she's absent so much. But

> she contributed, and she got all the credit. [...] But once again, it goes back to [...] the navigation [routine] so that a kid that hadn't even been there could get caught up very quickly."

Another teacher noted that even for "chronically absent" students, the storylines helped because they provided a mechanism (the Navigation Routine) for bringing the student up to speed. Other students could explain how the class progressed step-by-step to their current understanding of the phenomenon. More generally, a number of teachers noted that the storyline approach combined with the repeated structure of the units helped students to follow along, particularly lower-achieving and Special Education students. One teacher explained:

> Oh my gosh, when I started [teaching] I can remember thinking…I'm going to do this activity and then I'm going to do this activity. It's just funny because it's like no wonder nothing was coherent. We weren't building it or designing it to be coherent. Now I'm so protective of these [OpenSciEd] experiences because…I see how this experience gets to that one, that gets to this punchline at the end [...] We're gathering evidence to try and come up with the claim. Those processes became so habitual that it helped me structure my classroom. Then it was like, you guys do you notice how every time we make a prediction and then what comes next? We go look at evidence and figure out about our prediction. It became a habit in a good way that the kids knew what to expect was like, oh, if we made a prediction yesterday then today we're going to start trying to figure out was our prediction accurate? They already know that's what's coming. For me the story line equals coherence.

These teachers valued the ways that the OpenSciEd curricular structures made it possible for students to reconnect and re-engage as participants within the classroom scientific community.

Explicit Curricular Norms Make Curricular Purposes Visible

Of course, curricular structures do not exist in isolation: they are implemented within a particular classroom cultural context, which is established largely through classroom norms. Teachers spoke at length about the ways in which the OpenSciEd classroom norms provided the foundation for equity within their classrooms and enabled the curricular structures to fulfill their purposes. One teacher explained how she sees the classroom norms as a driving force for equity:

> “I love the discussion norms and having equity right there underneath respect is huge, and it's something that we explicitly talk about. I think [the classroom equity] is because of those norms. Actually, my remote class in my first semester, when we were doing genetics, the equity was amazing. I had such a classroom community that it was amazing to see that exist in a remote environment, the community that was created, and the most struggling students unmuting to say something that I don't see in other classes, I don't see sometimes even in my face-to-face classes. But somehow, we came up with such a way to bring everyone's voices to be heard. It was a really beautiful place. [...] I really think it was a small group of students being vulnerable and courageous enough to open up. It opened up the floodgates for, "I was scared too. If you were scared and you said it, then I'm okay to be scared and say it too." So that vulnerability that got knocked down really opened up for a more equitable place to learn.”

Teachers also spoke about the importance of revisiting the formal OpenSciEd classroom norms—which include norms around discussion, listening, giving everyone a chance to participate, and critiquing ideas and not people—in order to reinforce the idea of a classroom culture grounded in respect.

Importantly, teachers talked about OpenSciEd classroom norms in ways that revealed the mutually reinforcing relationship between curricular structures and those classroom norms. For example, through the storyline approach, the DQB, and the model tracker, students were directly engaged in asking questions, gathering data, and reasoning from evidence. Through the doing of those science practices, students have the opportunity to build ownership and expertise (not merely rote knowledge) on particular topics. The classroom agreements around moving science thinking forward and using evidence to support ideas, as well as agreements around respecting heterogeneous ways of knowing, all reinforce what students are actually doing in class via these various curricular structures. One teacher pointed to the importance of these aspects of the classroom culture for students, particularly students with IEPs:

> We're going to let some of this fear go and we're going to talk to each other like people who do science. It was just different, everything about it felt different. I think another aspect was the expertness…So I think they had some real ownership…and even kids that maybe were a little lower performing or you're like whoo, I don't know, are they going to be able to explain something to another group, they did. I have kids on IEPs who have disabilities, they became course experts and they still were able to take knowledge from their expert group and teach it to the other [groups].

Another teacher talked about how the OpenSciEd curricular structures and classroom norms helped students to overcome feelings about not belonging in science. Within this context, the DQB concretely demonstrates the value of asking questions, while the model trackers highlight the value of rough-draft thinking and the iterative nature of scientific knowledge-building. The classroom norms around providing support and encouragement, valuing each other's voices, using evidence to support ideas, and being open to changing our minds all reinforce these same messages. This teacher eloquently articulated the interconnected nature of the curricular structures and classroom norms toward supporting students and expanding equity:

> "Well, I think the biggest piece for me is that I think a lot of my students come to me feeling that they're no good at science [...] They feel like they have [the] wrong answers and they feel like they just don't know how science works and therefore, they're a bad science student. Every now and then, I'll see a kid opening their eyes like, oh my God, if I say something that's wrong, it's not [just] wrong anymore. It's an idea and we'll test it. We'll gather data to correct it, and that's just how the classroom runs, and every idea is valued. [All ideas] are valued equally and that they are on equal footing. I think that's profound and I don't think that's standard in most science classes. Being able to have that question and add it to the driving question board. Especially the questions that are weird are sometimes the best ones. Those are the ones that are going to unveil like a week's worth of lessons that like, oh my gosh, we should really figure that out. I think the uncertainty, it's certainly a risk for kids to get into this place where you don't really know this is right. We're going to try to back it up with evidence, but I don't know and we're making models with a lot of uncertainty. I think that's scary. [...] There are routines like the scientist circle and it's the way that you put questions up on the driving question board that enforce equity, but I think it's a mindset too of every voice really is valued and being genuine about it. But I think that is also the teacher. The other thing that I've

> thought about and talked about with my colleagues a lot is, the role of teacher is no longer the knowledge holder. We are just coaches, we're coaches to help kids go through the process. The kids really hold the knowledge."

Through their interviews, OpenSciEd teachers highlighted the ways in which OpenSciEd curricular structures, bolstered by the instructional routines and classroom norms that they implemented, created equitable science learning opportunities for students.

Discussion

The interviews with teachers touched upon multiple different conceptualizations of equity, ranging from thinking of equity in terms of access to and success with dominant science to considering students' identities within the context of science learning (Gutierrez, 2011). Making visible the role of curricular structures for supporting different notions of equity is important for furthering conversations about how to support equity in science education.

With respect to access, the role of storylines, the navigation routine, and other structures in facilitating integration for students who have been absent helps us to see equity-as-access as a multifaceted issue. Chronic absenteeism disproportionately affects certain student populations, including students experiencing poverty, students of color, migrant students, emergent bilingual students, and students with disabilities (Sosu et al., 2021; Singer et al., 2021), and as such is an issue of equity. Although the challenges of chronic absenteeism are fundamentally structural and ecological in nature (Kearney & Graczyk, 2022; Singer et al., 2021), supporting students who experience absenteeism to reintegrate into learning can nonetheless help to advance equity within the classroom.

Thinking about equity-as-identity means moving beyond supporting student access to, and achievement within, dominant forms of science. Rather, it means disrupting the dominant cultures of science in ways that create space for new perspectives, different cultural ways of knowing, and potentially new dynamics of power (Gutierrez, 2011). Teachers pointed to storylines and anchor phenomena as allowing for shared entry points to science—an affordance that at first blush appears to address equity-as-access. However, to the extent that the storyline and anchor phenomenon provide a "boundary object" that allows for a coming together of students' home cultures or epistemologies and those of formal science (Buxton et al., 2005), we can begin to see these structures as supporting a form of border crossing for students as well. Together with other structures like the DQB and the model tracker, they invite students to bring their own resources forward as part of the scientific endeavor. This combination of curricular structures invites a more flexible and inclusive vision of science, one that includes uncertainty, vulnerability, asking questions, making mistakes, revising our thinking, and incrementally moving our understanding forward. In combination, then, these curricular structures seemingly have the potential to facilitate border crossings for young science learners, particularly those for whom traditional science classroom cultures present the greatest cultural adjustments (Aikenhead, 1996).

Related, teachers pointed to the role of the DQB and the model trackers for positioning students as leaders in the knowledge building endeavors of the classroom community. This positioning is an essential component of epistemic agency, where students have responsibility for building scientific knowledge and engaging in scientific practices to support that knowledge-building (Alzen et al., 2020). Epistemic agency is an important component of equity in part because it affords students the ability to “author and enact identities” as scientists (Barton & Tan, 2010). Of course, inviting students to have epistemic agency is not the same as actualizing that epistemic agency (Alzen et al. 2020) and so the teacher has an essential role to play in manifesting the affordances established by the structures. Nonetheless, OpenSciEd structures formalize aspects of epistemic agency by providing a mechanism for students to document their scientific questions, make their thinking public, and track which questions have been addressed by the class.

Our study contributes to the literature on equity in science education by pointing to the role of curricular structures for advancing equity in science teaching and learning. The fact that curricula shape equity is not new; ever since Freire exposed the “banking” approach reflected in traditional curricula, scholars and educators have documented the ways in which curricula constrain or expand opportunities for learning for different populations of learners (Anyon, 1980; Banks, 1989; Mensah, 2022). At the same time, we are at a moment in time where there have been enormous efforts focused on designing new, transformative science curricula to align with the Next Generation Science Standards and thus advance the vision proposed by the *Framework for K12 Science Education*. Part of this grand vision explicitly includes attention to equitable participation in science learning. And yet, recent curricular reform has focused mostly on the shift from learning about science to figuring out science, while attending to equity has been largely relegated to discussions of the teacher role, particularly around developing equitable classroom cultures and norms.

The interviews with OpenSciEd teachers were illuminating because they pointed to the influence of concrete curricular structures designed specifically to transform science *learning* as being supportive also for advancing science *equity*. These structures, including the storyline model and anchoring phenomenon, the Driving Question Board, the model tracker, and the consensus model, each serve as formal vehicles that enable students to connect science to their everyday lives, drive science inquiry and learning, pose questions, offer inchoate ideas and refine those ideas incrementally based on evidence. As it turns out, these same structures also align with and bolster strategies for advancing equity within science teaching and learning—for example, by expanding the boundaries of sanctioned disciplinary participation and broadening ideas about what it means to be good at science and who can meaningfully contribute to the class' shared scientific endeavor.

This overlap between the learning functions and the equity functions of the OpenSciEd curricular structures is not coincidental. Many of the characteristics of these structures that make them valuable for three-dimensional science learning are the same characteristics that make them valuable for advancing equity. For example, engaging students in "figuring out science" means placing students at the center of the science learning process and giving them opportunities to engage with science as a scientist might—through considering real-world phenomena that motivate that need to learn, asking questions, conducting inquiry, making observations, creating initial explanations and revising and refining those understandings with the accumulation of evidence. These same structures also represent expanded forms of engagement well beyond the traditional banking models of education. These expanded participation models support equity by creating space for varied life-worlds, varied ways of knowing, and varied skill sets into the world of science.

Although the alignment may not be surprising, it is nonetheless important to recognize, articulate, and incorporate into curriculum design. Curricula, professional development, and teachers together comprise the "curricular activity systems" that shape student learning opportunities (Roschelle et al., 2010). These separate but deeply intertwined components of the system should ideally be driving toward the same goals, with each component reinforcing the efforts of the others. To transform teacher practice while ignoring the role of curricular structures in advancing equity is to undermine the ability of teachers to transform their instruction toward equitable goals. The other side of the same coin is that to create equitable curricular structures while ignoring the teacher role in shaping classroom cultures will similarly thwart efforts at equitable transformation. Each component must work together to reinforce the transformative work of the whole system.

The role of curricular structures for supporting equity in science teaching and learning also has important implications for curriculum developers and teachers. Multiple competing priorities for science education often create challenges for curriculum developers, who find themselves needing to adhere to multiple uncoordinated design checklists. For example, supporting three-dimensional science learning, reflecting universal design for learning, supporting multilingual learners, and bolstering identity and belonging for students from historically marginalized communities could each have their own separate check-lists for curricular design. Our work shows that in many cases those check-lists are overlapping and can be condensed to be both more manageable and more productive for advancing goals around both learning and equity.

Conclusions

Transforming science education to advance equity is an essential yet complex and multifaceted endeavor. Our research highlights the central role that curricular structures can play as part of our collective efforts to transform science teaching and learning in ways that advance equity. Participating OpenSciEd teachers made clear that the learning structures embedded and formalized within OpenSciEd are among the factors that supported equity within their classrooms. As such, we are reminded that curricula have the potential to go well beyond “equity add-ons” in the form of call-outs about historical figures from minority backgrounds or “representative” photographs and images within the text. Instead, I argue that the curricular structures themselves—including those typically conceptualized as part of a strategy for content learning—directly shape opportunities for equity within the classroom.

The potential for curricular structures to shape equity feels promising and optimistic in many ways. For one, teachers do not need to carry the burden of advancing equity alone, even within the confines of their classrooms. Some scholars have argued that because curriculum materials containing meaningful ethnic and cultural connections are in short supply, teachers themselves must become adept designers of multicultural instruction (e.g. Brown & Livstrom, 2020). But this approach places an enormous burden on teachers, while also leaving equity to the whim of individual instructional leaders. Instead, curricular structures can be designed to advance equity—and to serve as a launchpad for the pedagogical practices, classroom cultures, and interactional norms that teachers enact.

Moreover, curriculum developers can think comprehensively about how the structures they design might simultaneously advance both deep conceptual engagement and knowledge building in science and also opportunities for equitable participation within science classrooms. Finally, our research underscores the well-established but poorly-acknowledged fact that learning and equity are not a zero-sum scenario: it is possible to design curricula that simultaneously advance both three-dimensional science learning for all students and also advance equitable learning opportunities for historically marginalized students. We can, and should, design science curricula that integrate curricular structures that simultaneously advance both learning and equity.

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Summary Conclusions

Broadening participation in science is of utmost importance both for society and for individuals, particularly those who have experienced barriers to traditional school and science communities. For society, broadening participation is necessary if we are to advance scientific thinking and solutions with input from all our communities, talents, and ways of thinking. For individuals, science provides a wealth of opportunities for intellectually fulfilling, culturally valued, and economically secure career pathways. The evidence is clear that the challenge of broadening participation is not connected with ability, but rather stems from deeply ingrained socio-cultural features of schooling and of science that continue to exclude many students (Bang et al. 2012). As such, reconceptualizing science education in ways that expand opportunities for students to connect with and meaningfully participate in science is essential (Bang & Medin, 2010; Calabrese Barton & Tan, 2020; Calabrese Barton et al., 2020; Carlone, 2011).

The papers for this dissertation collectively address this challenge: they point to features of equitable science classroom cultures that support students, particularly those from historically marginalized communities, to develop a sustained interest and sense of belonging in science; and provide insights about curricular structures that symbiotically reinforce equitable cultures and practices. Student interest and belonging are critical outcomes in the effort to expand participation in science. These affective outcomes are associated not only with improved learning, but also with meaningful participation in classroom science communities, course-taking patterns, and career decisions (Adams-Wiggins, 2020; Deci & Ryan, 1994; Kang et al., 2019;

Patterson, 2019). Importantly, a focus on these outcomes also directly addresses the root barriers that students from historically marginalized communities often experience when it comes to science because they address the ways in which students understand what science is, who can do science, and how science connects to their own lives and communities.

The first two papers underscore the importance of classroom cultures for shaping student experiences and opportunities in science in ways that advance equity. More specifically, this research suggests that relationships and conceptions of science are both critically important features of the classroom culture for supporting equity. In classrooms where students experienced more care, they also reported stronger interest in science. Care speaks to the nature of the relationships within the classroom, both between the teacher and student and among students. In caring relationships, students feel respected, heard, valued, and supported. The importance of these relational and emotional aspects of science interest are supported by abundant literature about the emotional component of interest development (Krapp, 2007; Wigfield & Eccles, 2000). Cultivating classroom cultures where all students experience care in equitable ways is thus clearly essential for advancing goals around expanding interest in science for students from historically marginalized populations.

This research further demonstrated that in classrooms where students experienced greater collective enterprise, they also expressed more interest in science. Collective enterprise can be seen as reflecting both relational and epistemic aspects of science teaching and learning. Relationally, collective enterprise involves working together, as a classroom scientific community, to advance collective science goals. Epistemically, collective enterprise involves some degree of agency afforded to the class, individually and as a collective, wherein students play a role in guiding inquiry and sensemaking endeavors toward building scientific knowledge. Collective enterprise also aligns with identified features of interest-development, particularly the cognitive and values-related components. When students engage in collective enterprise, they have the opportunity to experience curiosity and excitement associated with the doing of science, which is known to support interest (Ainley & Ainley, 2011; Krapp, 2007; Luce & His, 2015). Working together to advance shared goals taps into values around collaboration and working toward a common good, which has also been shown to support interest in science (Basu & Barton, 2007).

Science classroom cultures also reflect and communicate underlying conceptions of science epistemology—that is, conceptions about what science is, how it works, what it entails, and who can meaningfully participate. An expansive epistemology of science views science as an endeavor, driven by our curiosities about the world, that involves collaboration, uncertainty, mistakes, and incremental advances in knowledge. This dissertation demonstrates that classrooms vary in the extent to which students perceived an expansive epistemology of science, and moreover that students in classrooms that reflected a more expansive epistemology also experienced a stronger sense of belonging in science. The findings align with a substantial body of literature that makes the case for thinking deeply about how we design opportunities for students to participate in science. Specifically, students need to participate in science practices in ways that go beyond *doing school* (i.e., rote execution of procedures) and instead support *doing science* (i.e., authentic engagement in science practices motivated by the desire to answer meaningful questions about the world that are relevant and consequential for students' lives and communities). Going a step further, our research complicates the notion that the science-as-practice approach to science education, as currently instantiated in classrooms, is sufficient to cultivate classroom cultures where students grasp an expansive epistemology of science. Rather, greater attention to epistemology, and specifically to cultivating classroom cultures that impart or communicate an expansive epistemology of science to students, may be necessary to fully realize the science-as-practice vision of science education.

Across both studies, we found that classroom culture varied significantly between classrooms (whether we were looking at collective enterprise, care, or expansive epistemologies of science), and that this variation was consequential for student outcomes like interest and belonging in science. While the student-level variation was still greater than the classroom-level variation (as is true for achievement too), the observed classroom-level variation shows that whole classrooms were higher or lower than others on important measures of classroom culture. This classroom-level variation points to the potential for classroom culture to serve as a lever for increasing equity in science education. Just as research and policymaking justifiably focus on classroom-level interventions to improve student achievement, our findings also provide a warrant for investing research and development efforts around strategies for building equitable science classroom cultures.

Finally, the third study in this dissertation points to the potential value of curricular structures for supporting equity in science education. A key take-away from this work is that curricular structures designed to support content learning can (and should) also support equitable participation in the science classroom. Structures such as the Driving Question Board provide a mechanism that formalizes the practice of having students pose questions to drive inquiry; this practice promotes equity by providing a shared and broadly accessible entry-point for participation in science learning and by valuing question-asking as well as answer-giving as legitimate and necessary forms of participation in science. These findings suggest a new role for curriculum in supporting equity: Beyond adding greater representation or even directly addressing issues of social justice within science (both of which have their place in science curricula as well), the very structures that drive science content learning should also be intentionally designed to support equity. In this way, curricula can support teachers in their efforts to enhance equitable science learning opportunities for students.

The papers in this dissertation contribute knowledge about equitable science education that is valuable for educational policy, district and school-level decision-making, curriculum design and development, and for teaching. The studies demonstrate the critical importance of building equitable science classroom cultures to support equitable science learning opportunities for students. These relationships are not surprising, given the strong theoretical foundation for the connections between understanding and experiencing science in more expansive ways and perceiving a place for oneself within the world of science. At the same time, the research orients us toward the potential of classroom culture—and particularly the relationships, student roles, and epistemologies of science reflected within science classroom cultures—as well as curricular structures to support equity in science education. We would be well advised to attend to these aspects of science teaching and learning as we work to advance equitable science learning opportunities for students.

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