Identifying Connections Between Science Learning and Mathematics Education

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Introduction

Given novel and extreme global challenges such as climate change, new energy demands, and dynamics related to an increasing global population, there is a need for students to be prepared to be innovative problem solvers and thinkers. These challenges will not have simple solutions and will require both cross-disciplinary collaboration and knowledge of mathematics and science. As such, recent research has called for the integration of academic disciplines, such as mathematics and science, in education.

Research indicates that using an interdisciplinary or integrated approach to mathematics and science education provides opportunities for learning experiences for students that are more relevant and less fragmented than when these subjects are taught separately (Aguirre-Munoz et al., 2021; Berlin & White, 2010; Penuel et al., 2018; Leszczynski et al., 2014). For instance, problems that require an understanding of both mathematics and science more closely resemble the real-life problems of scientists and engineers than manufactured lessons that do not integrate the disciplines (NCSM & NCTM, 2018). Furthermore, integrated mathematics and science education leads to student enthusiasm and engagement, increased mathematics and science achievement, and authentic experiences for students to engage in problem-based learning (Trevallion & Trevallion, 2020).

Currently, secondary education is artificially segregated by academic discipline, leading students to develop compartmentalized conceptions of the disciplines (Chiu & Linn, 2011). Teaching academic disciplines in a fragmented manner leads to an understanding that is akin to singular puzzle pieces that lack coherence—integrating the disciplines brings the larger puzzle's picture into focus (Furner & Kumar, 2007).

Although prior research has identified the benefits of integrated science and mathematics instruction, more work needs to be done to further clarify what integrated mathematics and science instruction should look like in practice and to identify barriers that may be inhibiting the widespread implementation of this kind of instruction. To better understand what integrated mathematics and science instruction looks like at the secondary level, as a part of a project funded by the Bill & Melinda Gates Foundation, our team recruited and spoke with experts in mathematics and science education, reviewed literature, and interviewed in-service secondary mathematics and science teachers (see appendix for details). We took a journalistic approach to highlight noteworthy examples that would provide context for other educators. This brief is informed by research and guided by the following questions; however, it is not a formal research study.

1. Are there examples of educators and/or programs that successfully leverage connections between mathematics and science? If so, what is known about the potential gains of that approach (e.g., improved student achievement, increased confidence and participation in mathematics and/or science courses and careers)?
2. What do we know about ways that mathematics learning and science learning support one other, specifically at the middle and high school grades?
3. What is known about barriers and gatekeeper courses in mathematics education that may also impact participation in science learning, especially for girls and historically underrepresented students?

To explore these investigative questions, the team interviewed practitioners and expert advisors. The team also generated a list of key terms that were used to guide a search for relevant literature. Advisors helped define these key terms (as detailed in the appendix) and provided recommendations for literature to review. Below, we define two key terms of special relevance to this report:

- ***Integrated mathematics and science instruction.*** With input from our expert advisors, we developed a working definition of integrated mathematics and science instruction to guide a literature search and interviews, as follows: integrated instruction (a) intentionally addresses mathematics and science standards (content and practices) for at least one grade, 6–12, within the same unit of instruction; and (b) such instruction may occur in classes or programs that are labeled “science” or “mathematics” only, STEM, or other integrated programs (e.g., engineering academies or after-school programs).
- ***Historically underrepresented and minority students.*** We were especially interested in knowing how integrated instruction impacts historically underrepresented and minority (HURM) students. We define HURM students as persons who are members of racial, ethnic, or gender groups that have been disproportionately underrepresented for a period of more than 10 years. HURM students are members of groups that have historically comprised a minority of the U.S. population (Goforth, n.d.).

The Appendix contains further information on the approach our team took to gather information about the current landscape of integrated mathematics and science instruction at the secondary level, including a full list of key project terms.

This report will first explore how mathematics and science integration has been defined in the literature. Next, we present three profiles of teachers who we interviewed who have integrated the two disciplines in different ways. We then discuss the barriers and challenges that teachers face as well as some promising practices for integrating mathematics and science that were uncovered in teacher interviews/focus groups and the literature. The report concludes with key takeaways, implications, and recommendations for future work. All names in this report are pseudonyms.

What Is Mathematics and Science "Integration"?

After starting with our working definition of integrated mathematics and science instruction, our literature search revealed additional, more nuanced definitions, which tended to coalesce around two major themes: standards-based instruction (e.g., instruction focused on practices and crosscutting concepts outlined in standards documents) and the context of such instruction.

In the literature, there is a lack of consensus on what integrated instruction is and what it looks like, which makes it hard to know exactly what the impacts are (English, 2016). Some views emphasize the role of standards and concepts by defining mathematics and science integration as "instruction that coordinates science and mathematics standards, disciplinary practices and/or coordinating concepts" (Aguirre-Munoz et al., 2021, p. 63). While incorporating one discipline into the other is viewed as integration by some (Furner & Kumar, 2007), others specify that a certain amount of each discipline needs to be present to be able to define instruction as truly "integrated" (Ireland, 2015). Still, some others argue that mathematics and science integration should go beyond simply using mathematics as a tool in the context of science, but rather should give equal weight to both disciplines (Aguirre-Munoz et al., 2021). While many researchers agree with the aim of giving equal weight to both mathematics and science, many have noted that full integration—in which you lose a sense of which discipline is actually being foregrounded—does not typically happen in classrooms due to the way schools typically separate mathematics and science courses (Berlin & White, 1992; Huntley, 1999; Kurt & Pehlivan, 2013).

Still others have found that mathematics and science integration can, and often does, occur in the context of other disciplines, such as engineering or art (Boakes, 2020). Indeed, integration has been described as teaching problems or activities that cross subject lines and more closely resemble science, mathematics, and engineering problems and activities outside of school (Valtorta & Berland, 2015). This means that science or mathematics content knowledge is acquired through an emphasis on real-world situations (Trevallion & Trevallion, 2020). Instruction that emphasizes real-world situations frequently requires cross-disciplinary teacher collaboration because integration without collaboration would require a high level of both content knowledge and pedagogical content knowledge that is not usually asked of individual teachers and is not taught in secondary teacher education programs (Aguirre-Munoz et al., 2021; Furner & Kumar, 2007; Marco-Bujosa, 2021; Riordan & Klein, 2010).

Importantly, previous literature has paid more attention to how mathematics is used in science instruction and less attention has been paid to how science content can be used in mathematics instruction (Roehrig et al., 2021). Leszczynski et al. (2014) states, "Although one can hardly imagine a lesson in physical science or earth science that does not contain mathematical procedure, examples of mathematics lessons in which science content or processes (or both) act to enhance student learning of mathematics are less common" (p. 96). For this reason, this report largely focuses on how mathematics has been integrated into science content and courses.

Why Mathematics and Science "Integration"?

Using mathematics in the context of science is something that students need to be able to do and something that teachers should be supported in emphasizing in their instruction, particularly because it is explicitly called for in the current national science standards (NGSS Lead States, 2013), which have been adopted widely across the country. Further, research has found that there are positive impacts on student achievement, attitude, interest, communication skills, and problem-solving after participation in integrated mathematics and science programs (Siregar, 2019). Two of the three case studies in this report (Calvin's and Mindy's stories) illustrate positive student outcomes related to attitude and interest in math after participating in integrated lessons or experiences. Importantly, integrated mathematics and science instruction has been shown to support HURM students to participate and persist in STEM courses (Trevallion & Trevallion, 2020).

Girls and other HURM students are underrepresented in high-level STEM courses in middle and high school, STEM majors in college, and STEM careers (Morgan et al., 2016; National Girls Collaborative Project, 2022). Research reveals that girls lose interest in STEM courses between 6th and 8th grade (Burke & Mattis, 2007), and by 8th grade, Black and Latinx girls are less likely to aspire to STEM careers than White male students (Catsambis, 1994). These findings highlight middle school as a critical stage for researchers and practitioners alike to consider for retention of HURM students in STEM.

Much has been said about the reasons for attrition of HURM students in STEM subjects, beginning in elementary school and continuing all the way through secondary and postsecondary education (Berwick, 2019; Ferguson et al., 2015; Fernandez et al., 2022; Jansen et al., 2016; Miller & Bichsel, 2004). Some research has shown that integrated instruction is one way to address concerns about the retention of HURM students in STEM courses (Boakes et al., 2020).

Instruction that integrates mathematics and science in authentic ways supports students' understanding of the purpose of the activities they participate in during class time. This is especially true when those activities are project-based (National Academy of Sciences, Engineering, and Medicine, 2008). Research shows that when girls were asked if they wanted to be engineers, they were twice as likely as boys to say no. However, when girls were asked to design a safe water system, save the rainforest, or use DNA to solve crimes, they were more likely to answer that they were interested in being an engineer to solve these kinds of problems (National Academy of Sciences, Engineering, and Medicine, 2008).

Mathematics and science integration has the potential to help students see the value of mathematics. This is especially true for HURM students. For example, Simpkins et al. (2006) found that 10th grade girls' mathematics grades were more strongly associated with their feelings about the usefulness of mathematics than they were for boys. Additionally, whether girls saw mathematic as useful was found to be a predictor of their persistence in mathematics. These findings suggest that there is a need to couch mathematics in authentic contexts that help students see the purpose and utility of mathematics, especially girls and other HURM students, which may help keep their interest in STEM courses and careers.

Profiles of Teachers Integrating Mathematics and Science Instruction

To better understand the kinds of integrated mathematics and science instruction that is currently taking place at the middle and high school levels in the U.S., we searched for educators to interview who could share examples of successfully leveraging connections between mathematics and science. Notably, our search for interviewees did not return many programs or people that are doing integrated instruction that aligned with the definition presented earlier in this report. We identified eight mathematics and science teachers that were engaged in, or at least expressed desire to engage in, the integration of mathematics and science in their instruction. Three teachers were able to meet for one-on-one interviews and the remaining teachers were split into two focus groups. (See the Appendix for details about our recruitment process.)

In this section, we present three brief teacher profiles that feature practices and strategies for integration and represent a continuum of success with integration. Two of the profiled teachers described being able to integrate mathematics and science in their instruction and one teacher described not being able to do so due to numerous challenges and barriers. Although we interviewed mathematics teachers, there are no teachers that only teach mathematics included in the case studies because the math-only teachers in our sample did not describe integrating science into their mathematics instruction at all. Following these teacher profiles, we include findings from our interviews with the other teachers.

It is important to note that the kind of integrated instruction that was described in the interviews with teachers does not directly align with the definition of integrated instruction presented earlier in this report. This suggests that teachers may need support in understanding and implementing integrated instruction, a recommendation that we discuss further after the presentation of the three teacher profiles.

Teacher Profile #1: Providing a Backdoor to the Museum of Mathematics

Calvin is a high school science teacher who taught biology, chemistry, physics, computer science, and design engineering. He teaches at a small K–12 private school (student-to-teacher ratio of 3 to 1) in a suburban area of California. His school specifically serves students with mild-to-moderate learning differences. Calvin explained that most of the students he teaches have ADHD, dyslexia/dysgraphia, language proficiency disorders, Asperger's, or other types of learning differences.

Calvin described rich examples of integrated mathematics and science instruction. He began by describing his purpose for integrating mathematics and science in his instruction by painting a picture of a museum. He said that the wonderful museum of mathematics is often inaccessible because "kids get discouraged with arithmetic." In this way, students' early experiences in school shape their beliefs about themselves as learners, meaning that, as Calvin put it, "Students are kept out from being able to experience the rest of the museum." Through his integrated instruction, he hopes to "sneak" students into the mathematics museum by using science as a backdoor.

Calvin recounted a design engineering lesson in which students were tasked with designing a parking lot. Calvin designed this lesson to align with the overarching goal of engaging students in technical engineering skills that could be used in a variety of jobs. The goal of this particular lesson was to engage students in civic engineering, and Calvin aimed to have students work with scale and measurement. Students started by using Google Maps to study the layouts of nearby parking lots they knew. From there, students sketched their own parking lot and proposed three different designs. After creating their designs, the class took a field trip to a parking lot that was walking distance from their school. Here, they took measurements of different kinds of parking spots (e.g., handicap spots, motorcycle parking), the cement blocks at the front of the parking spots, and any planters or other materials in the parking lot. After taking these measurements, students picked one of their three designs and represented it on a large piece of graph paper by using their measurements and making sure to scale parking spots and items appropriately.

Calvin elaborated about how this lesson "made the math so intensely applicable to students" because they have all been in and experienced parking lots. He noted that his students of all different abilities had been in parking lots and that, as a result of this experience, they had cognitively internalized a parking lot's dynamic system and were able to manipulate factors easily. As a result of this activity, Calvin described how students were able to access mathematical discussions. Calvin thought that this was because "while the project was influenced by numbers, it was not necessarily about the numbers."

He specifically remembered that two of his students who had expressed disliking mathematics before were now engaging in algebraic discussions with their peers and with him when talking about scale and measurement. He cautioned that while these two students did not develop a passion for mathematics just from this activity alone, he recalled them sharing with him that they saw mathematics as both accessible and useful.

While this lesson occurred in the context of a design engineering course—not in a science or mathematics class—it highlights how integrated instruction can be used in a multitude of education contexts and for multiple purposes. Calvin's use of both mathematics and science in the context of engineering shows the power of using disciplines like engineering or art for authentically connecting the two disciplines (Boakes et al., 2019). He used integrated instruction to help his students gain entry into the world of mathematics by presenting it in a way that is relevant and accessible to them. Calvin used a context that his students had physically experienced and could readily discuss. By doing this, Calvin is helping his students realize that mathematics is used well beyond just the domain of mathematics (or a mathematics classroom) and is a tool that is used for engineering and in the real world. Once students realize this and find that mathematics is not as "scary" as they may have initially thought—and is indeed both useful and applicable—they will hopefully be more likely to continue learning about and using mathematics in school and beyond.

Teacher Profile #2:
Supporting Students to See Mathematics as a Tool

Mindy is a retired teacher who taught for over 11 years and is now working for a government agency. She taught at a small K–12 parochial school in Virginia, where she was the only teacher at the middle school level. As such, she was often tasked with teaching many mathematics and science classes each year. Her certifications were in Middle School Mathematics and Science and High School Earth Science.

When Mindy taught 8th grade science, she explained, "Two-thirds of my class was taking Earth Science for high school credit and also taking Algebra, while another one-third was taking 8th grade Earth Science and 8th grade math." She described this latter group as being "not behind necessarily, they just weren't ahead." At the same time as she was teaching this 8th grade science class, she was also teaching the 8th grade mathematics class. This meant that she was teaching the same small group of students in both mathematics and science.

Mindy recounted that there was one particular student in her class who made a joke about the question at the beginning of each chapter of their textbook that asked, "Are you ready for the chapter?" This student joked that what it really meant was, "Are you smart enough for the chapter?" and then proclaimed that no, they were not smart enough. This proclamation was met with cheers of agreement from her peers, claiming that they, too, thought they were too "dumb" for the chapter. Despite Mindy's reassurance, this became a running class joke.

What happened next was not something that Mindy consciously planned for. She had assigned students in her science class a project from the GLOBE Program related to weather and measurement. This was an extended project in which they collected their own data across years in 6th, 7th, and 8th grade. While she was leading this project from the GLOBE Program, Mindy also started using parts of the science project as the context for the content she taught in mathematics class. For example, if students needed to learn how to make graphs for the science project, she taught them how to make graphs in mathematics class as well. Further, in mathematics class, she began to let some students work on the science project during any downtime they had. This meant that this particular group of students received more time outside of science class working on this project than other students.

Over time, the students who had spent more time on the science project became experts on particular parts of that project. For example, one student became an expert on running wind trajectory models, another on using a spreadsheet, and another on interpreting wind direction. The student who started the joke about the textbook became an expert on using a piece of specialized equipment to make measurements about wind trajectory. Mindy explained, "Eventually, everyone in their science class compared their measurements to hers." Those students who were taking Algebra and high school Earth Science began to see the other students, who before may not have been as "ahead," as experts to learn from.

Mindy explained that while her students did not necessarily like mathematics any more than they did before the activity, "they were not afraid to use it as a tool, especially for science." She said, "When we got to chapter 5 of the book, the one young lady who had initially started the joke said, 'Yes, I am ready for the chapter!'" Mindy emphasized that the most important outcome of her integrating mathematics and science instruction in this way was that this student no longer thought she was not smart. In fact, she recalled running into this student years later and found out that she chose a career in a science-related field after high school.

In Mindy's classroom, she provided opportunities for students to engage in integrated activities beyond their regular classroom time. This led students who did not have as much experience or confidence with mathematics to spend extra time using it in a context they found enjoyable and interesting—the science project. Through this process, these students gained expertise that was recognized and utilized by their peers. Mindy shared that these students gained confidence and comfort with both mathematics and science so much that the student who exhibited some of the lowest confidence in her abilities went on to feel capable of pursuing science after high school. Similar to what Calvin described, Mindy felt that integrating mathematics and science did not lead her students to immediately enjoy mathematics or science more than they did before. However, it does seem that in both of these examples, the students felt more confident in their ability to use mathematics when there was a specific purpose for doing so—either in an engineering design or for a science project

Taken together, Calvin's and Mindy's case studies in particular highlight the potential student outcome gains that extend from integrated mathematics and science learning experiences. In particular, both of these stories highlight a student outcome that has been found in prior literature as well: There are positive impacts on student attitude and interest after participation in integrated learning experiences (Siregar, 2019).

Teacher Profile #3:
Striving for Integration Despite Barriers

Susie is a high school biology teacher at a public school in Southern California. The school is located in a district that is approximately 66% Hispanic/Latino, 23% White, 3% Asian or Asian/Pacific Islander, 1% Black, 0.7% Native Hawaiian or other Pacific Islander, and 0.3% American Indian or Alaska Native. Prior to working at her high school, she was a longtime middle school teacher teaching science, also in Southern California. Her background is in marine biology.

When reflecting on her experiences teaching integrated mathematics and science lessons, Susie shared that she finds it especially important to make explicit connections between the two disciplines for middle school students. She found that it was important to explicitly name when integration was happening to help students see the subjects as integrated and not as disconnected. For example, she would call out the name of a concept that students learned in their mathematics class (e.g., analyzing graphical information), which encouraged students to think outside of disciplinary silos and to use their mathematics knowledge in the context of science. However, she acknowledged that calling out mathematics concepts like this required her to know what mathematics students have covered or know, which is difficult since she is not their mathematics teacher. She explained how she uses exit tickets from her classes to gauge where students are at in their mathematical understanding for content related to what she plans to cover the next day.

Susie said that she was given collaboration time at her prior school with other science teachers and some teachers from other content areas, which helped with cross-content collaboration. However, "the reality of the master schedule is that we only shared 60–70 percent of the same kids. The reality of day-to-day life is that everybody is in survival mode most of the time." Further, this collaboration time, although intended for collaboration, was also the time they were given to do everything else teachers need to do (e.g., phone parents). This meant that collaboration time was impinged upon by other necessary tasks. However, she described the situation at her new school as even more dire. She said, "The resources aren't even there" and "the only conversations I have with the mathematics department people are at the copy machine."

Susie also reported a lack of integrated curriculum as a challenge for her integration of mathematics and science. Susie described not having access to curriculum that authentically integrated the disciplines, was project-based, and did not require a lot of teacher time to adapt for students.

Susie encourages students to bring their knowledge and experience from mathematics class into her classroom by prompting them to identify areas where it can be used in the science they are learning. Susie explained how her students are accustomed to only using mathematics in mathematics class and are not used to applying their mathematics knowledge or skills in other contexts. This poses challenges for science teachers like her who must find ways to make connections for students, which often requires pedagogical content knowledge of the other domains (Ní Ríordáin et al., 2015). Integrating these subjects is also difficult because teachers face many challenges and structural barriers when trying to integrate mathematics and science in their classrooms. In contrast to the two teachers described above, Susie largely talked about challenges and barriers despite her attempts to want to integrate mathematics and science. Her description was, however, representative of most teachers we talked to in focus groups.

Challenges to Address to Support Integration

While our literature search, interviews, and focus groups identified examples of teachers' dedication to and perseverance in delivering integrated mathematics and science lessons, various challenges were identified as well. These challenges are important to consider as educators strive toward the kind of integrated mathematics and science instruction that may provide the most promising outcomes for students. Addressing these challenges should be at the forefront of questions around how to support teachers in implementing integrated instruction. This section outlines some of the main challenges that need to be addressed, as identified in our literature review and discussions with teachers.

Academic disciplines are structurally compartmentalized

Layla, a middle school science teacher we interviewed, described a challenge she has when integrating mathematics and science content in her science classroom. The challenge is related to students' understanding of the disciplines as being distinct and/or unrelated:

> *"I often feel like students compartmentalize what they learn. So, what students learn in their other classes like math…doesn't transfer over when they are in science class. For example, students may be graphing in math but when asked to graph in science, they can't apply that same learning from their math class."*

This challenge, brought on by the separation of mathematics and science as distinct subjects by school systems, made integration difficult for Layla, even when the topics being covered in mathematics had already been covered in science.

However, it is not only students who often view mathematics and science content as distinct and separate from each other. Rose, a high school chemistry teacher, succinctly described this challenge with her fellow teachers as "a mindset of silos." The separation of mathematics and science classes, teachers, curriculum, professional learning opportunities, and resources reinforces the widespread belief that these disciplines should be taught and supported as separate disciplines. As will be described later in this report, the disciplines have a long history of overlap and integration but have been siloed by the education system. Rose says that in her teaching practice, she tenaciously "seeks out collaboration with mathematics teachers to be able to align mathematics with science." To support mathematics teachers' self-efficacy in science, she explains to these teachers that "science is just math with toys."

School structures and policies can inhibit integration

Lack of cross-disciplinary planning time. One of the school structural factors identified most by teachers in our focus groups—and explicitly mentioned above by Susie—as something that impedes integrated instruction was the lack of planning time with other teachers.

A teacher in our focus group recounted that decades ago, early in her teaching career, "math and science teachers were not even in the same building and never saw each other." She said that some of this physical separation has since been ameliorated, but that there was still a lack of cross-disciplinary collaboration. This teacher explained that at her school site, there is usually only one other teacher available during the same preparation period, and that, by design, the other teacher is usually someone in your same subject area. This means that a science teacher may never actually see a mathematics teacher during prep time. Another teacher in the focus group, Sam, agreed with this description, saying:

> *"Collaboration is key in doing integration very well [but] we do not have common prep periods, which means we're meeting before or after school on our own time."*

The day-to-day structure of prep time means that teachers across disciplines are not given the time to collaborate together on how to integrate their disciplines. If the only option for cross-disciplinary collaboration is for teachers to coordinate and meet outside of school hours, then, more likely than not, this collaboration simply will not happen (Banerjee et al., 2017; Ronfeldt et al., 2015). Mindy's unique situation— in which she was both the mathematics and science teacher for a group of students— is not typical. Nor is it ideal for one teacher to be responsible for teaching so much content, since most teachers do not have this breadth of professional preparation or time for proper planning of instruction covering multiple subjects.

Gatekeeping courses. A set of structural barriers discussed in the literature were the historical norms around gatekeeping courses. These were somewhat described by Calvin above when he said that students are afraid of mathematics in science because of their performance in mathematics courses. Historically, students have been kept out of advanced science courses depending on their performance in mathematics (Douglas & Attewell, 2017). Prior research has shown that taking higher level mathematics classes in high school is related to whether students attend and finish college and, eventually, what jobs they are offered. Using mathematics performance as a deciding factor in what classes students take reifies patterns whereby students are segregated along racial lines (Berwick, 2019).

There is a lack of alignment between mathematics and science standards

Participants in our focus groups cited the misalignment between mathematics and science standards as a major challenge they have encountered when trying to integrate mathematics and science in their teaching. Kyle, a middle school science teacher, noted that the Common Core State Standards in mathematics and the Next Generation Science Standards do not "chronologically line up well." He described one lesson early in the academic year in which he had students calculate averages in his science class. However, because in 6th grade averages are not covered in mathematics until the end of the year, many of his students said, "What's an average? We don't know." He expanded on this by saying that "misalignment makes it difficult when standards exist but are not in sync with each other."

Layla echoed these sentiments, explaining that averages and scientific notation are a big challenge for middle school science teachers because their science standards include these topics early in the year, but in mathematics classes, these topics are not covered until later in the year. She explained that she tries to frontload these topics as much as she can, but

> *"To add more math would mean to stretch out where we are. We try to embed as much as we can, but we don't have time to even pre-assess math skills because of when testing happens."*

Finding content for integrated instruction is challenging

Teachers need curricular materials that support integrated mathematics and science instruction. A fully integrated curriculum has been more easily achieved in primary grades where students remain with a single teacher for a large portion of the day (Tekerek & Karakaya, 2018). However, at present, the same is not true for secondary education. A study by Brown and Bogiages (2019) found that there was a dire need for integrated mathematics and science activities that can be easily implemented by secondary teachers. They determined that there is currently a lack of curricular materials that teachers would like to use and would feel prepared to use with students. Importantly, curriculum needs to account for the fact that, when implementing integrated instruction, teachers may have little to no content or pedagogical content knowledge in one of the disciplines (Aguirre-Munoz et al., 2021). Research has called for integrated curriculum to be developed that teachers can use to deliver integrated content (Brown & Bogiages, 2019).

Historically, minoritized perspectives have been rejected in mathematics and science

Lastly, a shift is needed from thinking about the disciplines as siloed from each other toward viewing the disciplines as integrated in authentic contexts. To do this, what counts as meaningful or legitimate ways of figuring out or knowing in mathematics and/or science needs to expand to include other ways of knowing and viewing phenomena, especially those ways that are affiliated with indigenous or minoritized perspectives and traditions. Barajas-López & Bang (2018) discuss three approaches to taking an expansive stance toward the disciplines: (a) taking an approach to environmental education that recognizes the symbiotic nature between Indigenous peoples and land (known as land-based education), (b) noticing and wondering about relationships or patterns by exploring in nature, and (c) embracing storytelling as a legitimate practice for learning about mathematics and science. The authors argue that historically,

> *"[Mathematics and science] ha[ve] simply ignored the existence of other ways of knowing or more actively den[ied] their legitimacy, reifying historically saturated claims to epistemic superiority and deficit models of non-dominant students and communities."*

Taking an expansive stance toward mathematics and science education can advance both teachers' and students' understanding of equity. For instance, teachers should broaden the types of inquiry that are deemed appropriate or worthwhile to engage in. They should also place more focus on knowledge systems that have historically been considered peripheral, shifting these systems to become foundational aspects of disciplinary practice. In other words, when students and teachers embrace different ways of knowing (e.g., storytelling), they expand the discipline toward more inclusive approaches to mathematics and science.

Strategies to Promote Integrated Instruction

In this section, we outline several practices that were discussed in the literature and/or mentioned in teacher interviews and focus groups. We found that while the literature has identified the strategies below as important to supporting integrated instruction, teachers in interviews and focus groups mentioned not having access to many of the resources to support these strategies. These strategies are organized below around three perspectives: integration strategies that support teachers, strategies that support students, and strategies that support diverse students more specifically.

Strategies that support teachers

Provide opportunities for teacher peer observation and learning. Previous research has found that providing teachers with opportunities to observe and reflect on peers' integrated lessons supports teachers to integrate the two disciplines (Aguirre-Munoz et al., 2021). This type of observation can be helpful for teachers who might not only be learning the content of mathematics or science, but who are also learning how to teach the disciplines in an integrated way. An important part of this observation process is giving teachers space for reflecting and learning from their peers about how to teach integrated mathematics and science. It is this reflection that supports the transformative learning necessary for reimagining the disciplines as integrated. Further, the teachers we interviewed expressed interest in learning from their peers. Susie described wanting to develop a working relationship with her peers in the mathematics department so that they could co-create lessons that integrate the disciplines.

Offer models of integrated instruction. School and district leaders, coaches, and other stakeholders should also provide teachers with models of integrated instruction (Aguirre-Munoz et al., 2021). Teachers are best supported when they are given examples that explicitly name and illustrate what integrated mathematics and science instruction is and looks like. This might take the form of identifying expert teachers who other teachers can observe, providing example lesson plans, or organizing lesson studies. However, as mentioned previously, providing useful examples may be challenging, given the lack of consensus in the literature around a definition for and hallmarks of integrated instruction. This points to an area of need: more research on defining and providing examples of integrated instruction.

Dedicate time for cross-disciplinary collaboration. Finally, teachers need to be given time to collaborate with cross-disciplinary teams, especially on lesson plans (Riordan & Klein, 2010). As discussed in the previous section, this is a structural barrier that needs to be addressed. Susie, as well as several other science teachers

we interviewed, mentioned wanting time to collaborate with teachers in the mathematics department on lessons but not being given the time. During common planning time, mathematics and science teachers can draw on each other's knowledge and expertise to plan lessons for students that cross disciplines.

Strategies that support students

The literature identifies some strategies for supporting students in engaging in integrated mathematics and science lessons.

Use other disciplines as context. First, teachers can use other disciplines (e.g., engineering, art, technology) as the context for instruction (Boakes, 2019; Valtorta & Berland, 2015; Leszczynski et al., 2014). As an example, we saw Calvin in the story above effectively use engineering to integrate mathematics and science. Integrated instruction works most effectively when the integration comes naturally (Chiu & Linn, 2011). Using contexts like engineering, art, and/or technology for mathematics and science encourages students to think outside of disciplinary boundaries. These rich contexts can support student learning that is authentic to real-life problems and issues.

Clarify the purpose of lessons. The second major theme that arose from the literature was that students need to see mathematics and science as useful—the focus should not only be on teaching the "what" but also the "why" (Valtorta & Berland, 2015). For example, the mathematics in a science lesson should not stop at using a formula but should extend to include the reason for using a formula. Calvin's story above is an example of this: he encouraged students to think about the purpose of their measurements to design a functional parking lot. When his student designed a parking lot that mathematically made sense but functionally did not, Calvin encouraged his student to think through the problem and come to understand the functional purpose behind the measurements.

Strategies that support diverse students

Mathematics and science teachers draw on a range of disciplinary practices that have clear benefits for multilingual learners, such as problem-solving, observing, making claims, identifying evidence, clarifying reasoning, exhibiting perseverance, and noticing and wondering (Delavan & Matranga, 2020; Lee et al., 2013; Zweirs, 2014). Using disciplinary practices as a consistent framework for classroom discourse supports linguistically minoritized students. For example, when using noticing and wondering, teachers ask students to share their initial answers to prompts like "I notice… I wonder… It reminds me of…" Such practices structure mathematical conversations for students and can function as both tools for making student thinking public and scaffolds for developing feedback that leverages this thinking to maximize student learning. Delvan and Matranga (2020) explain, "Noticing and wondering creates a conduit for cultural relevance in the classroom and the recognition of prior knowledge and current assets because students' noticings and wonderings will be expressions of what they find personally and culturally important." Engaging diverse students in these kinds of disciplinary practices thus apprentices students into mathematical and scientific ways of knowing and talking while leveraging their own experiential knowledge in the process.

Key strategy takeaways

In summary, our literature review and teacher interviews identified some important strategies, including

- Give teachers examples of integrated lessons
- Allow teachers to observe their peers
- Use other disciplines such as engineering or art to help students break out of viewing the disciplines as distinct and separate from each other
- The purpose of integrated mathematics and science instruction needs to be contextualized—the instruction should not stop short at surface level formulas or facts

The interviews and focus groups we conducted with teachers illustrate some of these same themes that were identified in the literature. Teachers' stories lend a pertinent perspective on the importance and value of integrated mathematics and science instruction.

Implications for Future Work

In general, much more work is needed around integrated instruction, especially research that attends to defining what integrated science and mathematics instruction is and should be. Given prior research that has been done that shows the benefits of integrated instruction, we recommend that district administrators learn about the value and possibilities of integrating mathematics and science so that schools can potentially move in the direction of co-planning and sharing professional learning opportunities. To allow for more integrated instruction, district and school leaders should consider restructuring school schedules, such as implementing block scheduling, co-teaching, peer observations, and collaborative lesson reflections.

Our review of relevant literature and our interviews with teachers found that approaches to integrated instruction largely focused on how mathematics can be used in science classes, but not on how science can be used in mathematics classes. We found that across all aspects of the education system (e.g., policies, districts, professional learning, curriculum), there needs to be greater attention paid to how mathematics can bring in science. Accordingly, future work should attend to how science can be integrated into mathematics lessons.

Currently, secondary education is artificially segregated by discipline, which leads students to an incomplete understanding of mathematics and science and causes more difficulty in utilizing these disciplines together to solve complex problems as well. There is a great need for further attention to be paid to integrated instruction that brings singular puzzle pieces together to make a complete picture.

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Appendix. Our Approach to Examining Integrated Mathematics and Science Education

In order to answer this project's key questions about integrated science and mathematics instruction, we recruited and spoke with experts in mathematics and science education, reviewed relevant literature, and interviewed in-service secondary mathematics and science teachers.

We began by recruiting an expert team of six advisors. We drew on the authors' knowledge of the mathematics and science education landscape to identify six experts whose work has had an impact on the field of mathematics or science education. Three of these six advisors were experts in mathematics education at various levels from early childhood through secondary and postsecondary, including preservice teacher education and preparation. One of these three mathematics education experts was also intimately familiar with perspectives regarding the intersection of mathematics education and minoritized students' participation in the discipline. The other three advisors were experts in science education at various levels and one was an expert in the intersection of science education and minoritized students' participation in the sciences. We asked these advisors to recommend relevant literature that they were familiar with and to provide suggestions for key terms (as listed in Table A1) that we could use as search terms to identify literature using search engines such as Google Scholar and ERIC. Table A1 provides some of these key terms that we used in our structured literature searches and that are relevant to the discussion included in this report.

Table A1. Definition of Project Terms

Term	Definition
Integrated mathematics and science instruction	(1) Instruction that intentionally addresses mathematics and science standards (content and practices) for at least one grade, 6–12, within the same unit of instruction; and (2) such instruction may occur in classes or programs that are labeled "science" or "mathematics" only, STEM, or other integrated programs (e.g., engineering academies, after-school programs).
Mathematics and science practices	Disciplinary exercises that require both habits of mind and content knowledge; sometimes described as the intersection of the Next Generation Science Standards practices and the Common Core State Standards for Mathematical Practice.
Promising instructional practices	Approaches to teaching and/or learning that integrate mathematics and science and facilitate desired impacts, such as increasing engagement for historically underrepresented minority students.
Historically underrepresented minority (HURM) students	HURM students are persons who are members of racial, ethnic, or gender groups that have been disproportionately underrepresented for a period of more than 10 years. HURM students are members of groups that have historically comprised a minority of the U.S. population (Goforth, n.d.).

Simultaneously to reviewing some relevant literature, we conducted focus groups and interviews with in-service secondary mathematics and science teachers. Through snowball methods of recruitment, we identified eight middle and high school teachers—three mathematics and five science—to participate in focus groups and interviews. To get a sense of the general landscape of mathematics and science education in the United States, we put few restrictions on requirements for participation; teachers simply needed to be teaching mathematics or science at the middle or high school level and could be from any geographic region of the country. These focus groups and interviews, which were conducted using a journalistic approach, are the source of the profiles in this report and informed the themes related to challenges and supports for integration presented in the report.