What is Engineering? A Comparative Case Study of Elementary Students' Conceptions of Engineering Across STEM and Non-STEM Schools

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Introduction

With the inclusion of engineering practices in *A Framework for K-12 Science Education* [1] and engineering standards in the *Next Generation Science Standards* [2], engineering instruction is growing increasingly common in elementary classrooms in the U.S. One approach to increasing engineering instruction is through schools with an explicit focus on science, technology, engineering, and mathematics (STEM), and national policy documents in the U.S. have called for the development of such schools [3]. However, a clear vision for what K-12 engineering education should include and how it should be implemented is lacking [4].

The responsibility for implementing engineering education in elementary settings often rests on classroom teachers who are also responsible for teaching other subjects that have historically had a stronger focus in elementary education and teacher preparation programs (e.g., language arts and reading, mathematics, science). Because of this, elementary teachers often have no formal training in engineering and may be uncomfortable teaching engineering [4]. Research has shown that teachers have varied conceptions of engineering [5] - [7], yet little research has explored students' conceptions of engineering. This study fills a gap in the literature by addressing the following research questions:

1. How do elementary students conceptualize engineering?
2. How, if at all, do elementary students' conceptions of engineering vary based on whether they attend a STEM-focused school or a school without an explicit STEM focus?

Brief Literature Review

Engineering presents a unique opportunity for integrated learning experiences because of its interdisciplinary nature. Engineering requires the application of science and mathematics content, and it has the potential to transform instruction to hands-on learning related to a central problem or question, with opportunities for critical thinking and collaboration [8]. Engineering design contexts are a common approach to teaching engineering to young students [4] and have been associated with a number of positive outcomes. For example, children are naturally curious, and engineering curricula can capitalize on this curiosity through the use of engineering design contexts to motivate and engage students in the classroom [9]. These engineering design activities can be situated in real-world contexts, which help students see connections between what they learn at school and the real world [4], [10], [11], and engineering design experiences can also help students develop critical thinking and problem-solving skills [12], [13]. Some studies have even demonstrated deeper learning of science concepts through engineering design contexts [14], [15].

However, despite the potential promise that engineering education holds for a range of student outcomes, teachers face significant challenges to implementing engineering instruction at the elementary grade levels. Teachers, like the general public, often have narrow views of engineering, focusing on vehicles, buildings, and digital technologies [16]. Elementary teachers

often lack formal preparation to teach engineering [4], and they may have fear or anxiety about teaching engineering [17], [18]. Further, resources that are intended to support teachers in planning engineering instruction, such as the *Framework for K-12 Science Education*, may actually misrepresent engineering practices [19]. In addition, although engineering contexts present opportunities to apply science and mathematics, students may not recognize these opportunities themselves [12], so teachers must make these connections explicit.

Given the barriers to effective engineering instruction at the elementary level, it is important to consider students' experiences with engineering. As STEM schools develop, it is also important to consider whether students have different engineering experiences at these schools compared to those without a STEM focus. This study explores students' conceptions of STEM and whether their conceptions differ based on whether their elementary school has an explicit STEM focus.

Methods

This study took place within the context of a school district in the Midwestern U.S. that was developing a district-wide STEM mission. Approximately 5,000 students, 17% of whom were students of color, attended the district's schools. The district included a total of four elementary schools. One elementary school had been a STEM-designated school for five years prior to this study. The other three elementary schools did not have a STEM designation at the time of this study but were planning to convert to STEM schools in the coming years. Though the state had not adopted the NGSS, the state's science academic standards included engineering standards, so elementary teachers were expected to include engineering instruction in their classrooms.

This study used a comparative case study design [20] and semi-structured interviews to examine students' conceptions of engineering. Participants were 125 students in fifth grade (10-11 years old) at the district's four elementary schools. School demographics are shown in Table 1, and participant demographics at each school were representative of the school's demographics.

Table 1. School Demographics

	School 1 (STEM)	School 2 (non-STEM)	School 3 (non-STEM)	School 4 (non-STEM)
Total Student Enrollment	609	585	464	529
Gender				
Male	51.6%	47.2%	46.6%	51.4%
Female	48.4%	52.8%	53.4%	48.6%
Race/Ethnicity				
White	63.2%	85%	78.2%	57.3%
Latino	17.6%	8.7%	13.4%	22.3%
African American	15.6%	2.4%	3.5%	14.6%
Asian American	0.8%	0.7%	0.9%	1.5%
American Indian/Alaska Native	0.0%	0.0%	0.4%	0.2 %
Native Hawaiian/Pacific Islander	0.0%	0.1%	0.6%	0.2%
Two or More Races	2.8%	3.1%	3.0%	3.9%
Free and Reduced-Price Lunch				
Eligible	53.2%	34.4%	43.8%	65.0%
Not Eligible	46.8%	65.6%	56.2%	35.0%

Students were interviewed in school-specific groups of three to four students, and each interview lasted approximately 25 minutes. Over 20 hours of audio data were transcribed and analyzed using inductive coding methods originating from grounded theory [21]. The authors developed the initial codes together to ensure calibration in their coding [22], and they met to discuss any coding discrepancies. The codes were collapsed into themes, and cross-case analysis between students from the STEM school (n=40 students) and the three non-STEM schools (n=85 students) was conducted to identify similarities and differences between students' conceptions across schools. In order to highlight both similarities and differences in students' engineering conceptions, the findings section below first describes conceptions that were common across all four elementary schools, then identifies ways students' conceptions differed based on whether they attended the STEM-focused elementary school.

Findings

Similarities in engineering conceptions across schools.

In general, students across all four elementary schools held some similar conceptions of engineering. First, they viewed engineering as fun. They cited hands-on activities, student choice, and opportunities to be creative as enjoyable aspects of engineering, illustrated by the student quotes in Table 2.

Students across all four elementary schools also viewed engineering as important. They discussed the importance of engineering in terms of school success and getting jobs in the future. They also talked about engineering as a way to solve problems and make the world better for all people or for certain groups of people. For example, one student said, "If I was smart, I could

engineer something for the elderly to help them get around faster," recognizing the potential of engineered solutions to solve problems for the elderly.

Finally, students across all four elementary schools equated engineering to building and fixing. They consistently and repeatedly referred to building and fixing throughout the interviews, but some nuanced differences were also apparent between students who attended the STEM school and those who did not. Students who attended the non-STEM-focused schools frequently referred specifically to cars and vehicles, equating engineers with auto mechanics. In contrast, students who attended the STEM school had a broader view of the type of work engineers do, often saying that engineers can build or fix anything.

Table 2. Student Quotes for Similarities in Engineering Conceptions

Finding	Illustrative Student Quotes: STEM School	Illustrative Student Quotes: Non-STEM Schools
Engineering is fun.	My favorite part of really just about all of it is when we get to do hands-on stuff, and actually do this stuff. After you're done drawing or creating it, then you get to move on and you actually get to build it. And that's what I think is really fun because then you can see what it actually looks like and how it would work and everything, and see if your prediction or something was right. Engineering is kind of cool because we get to make our own things, like we get to make whatever we want. I love engineering, being honest. I think it's so cool that you get these opportunities at school to make all these new creative things, then you get to take them home and show your families and use them in the future. When we engineer, I feel that it's more creative than what some schools get to do. Because I've moved schools a lot, I've been in two other schools, and so I know the difference sort of. Another thing about engineering that I like is there's no end to it. You can use your imagination and build anything.	I love engineering because you get to be creative all around and just get to work with your hands. I think [engineering is] really cool because you can do a lot more stuff than sitting in a room, or go out and do stuff like experiment with it. You can build a bunch of stuff, go hands on, and do anything your mind thinks up. I think it's really cool since a lot of people put their creativeness into it, and think about all the ways to do stuff. And with engineering, that's fun and stuff.

Engineering is important.	Engineering is actually necessary for the future of us, like planning the design for buildings that can make our lives better. Engineering may not have its own subject, but you still use it a lot in school. [Engineering] is important for stuff in the future. [Engineering is] important because you'll need to learn this stuff if you want to have a job in the future.	Engineering is gonna make me be a good person. If I was smart, I could engineer something for the elderly to help them get around faster. I like engineering, 'cause when people engineer, they can build things that are very helpful to the world and can really help people. And just build something new and better for the world. If you learn [engineering], you can clear out real-world problems.
Engineering is building and fixing.	I think [engineering is] fun. You can build anything. I really like engineering 'cause you get to create what you want with the materials given. You can use your imagination and build anything. There's a lot of steps to eventually get to the finished product.	Engineering is pretty much like building stuff. When I hear engineering, I just think you work on cars. My dad's a mechanic, so I think of cars all the time with engineering. I think about mechanic or something like that. Well, my grandpa would do some of that [engineering] stuff too, and my dad, and so I would help them with my dirt bike or my snowmobile and stuff. I helped my uncle work on his truck that he just got, and I just kind of like helping with engineering and stuff.

Engineering conceptions of students attending the non-STEM schools.
Among students attending schools without an explicit STEM focus, several additional conceptions of engineering were evident (see Table 3 for illustrative student quotes). First, when considering the connections between engineering and science, mathematics, and technology, students were uncertain of how the disciplines fit together. They often referred to STEM disciplines being grouped together because they are challenging, important for the future, or things that should be learned. When they spoke of the integrated nature of STEM, they either made vague statements, like "They all just kind of work together," or conflated engineering and technology while ignoring the other disciplines. They referred to engineering as creating, helping, or being the same as technology.

Second, the students attending non-STEM-focused schools revealed that they do not see many opportunities to do engineering at school. They repeatedly said they had not done much engineering at school, often referring to a single occasion. Some students did acknowledge that they were required to participate in a science and engineering fair. For example, one student said, "One time we had a science and engineering fair that every fifth grader had to do. So, we each came up with our own project with two other people or one other person. And we actually made our own project." Another student explained, "For our engineering project we had a group of three, and we would have to go over to their house… and you'd have to get it done by a certain day." Thus, even though the engineering fair opportunity was provided through school, students viewed this as an aberration and discussed completing significant portions of the project at home.

Finally, when considering whether they participated in engineering, students attending schools without an explicit STEM focus primarily saw opportunities to do engineering projects at home. Some of the opportunities reflected more accurate conceptions of the work of engineers than others, but students often described key people who served as informal mentors in engineering by inviting them to help with projects. Notably, these key individuals were often male family members: fathers, grandfathers, and uncles. No student provided an example of doing something they saw as engineering with a female family member. Although boys referred to these experiences more often, they were not exclusive to boys. For example, one girl said, "Well, my grandpa would do some of that [engineering] stuff too, and my dad, and so I would help them with my dirt bike or my snowmobile and stuff. Because I'm like a tomboy, but I'm also a girly girl too." She saw at-home opportunities for engineering with her father and grandfather, but her follow-up explanation of being both a tomboy and a girly girl suggested that she maintained a view that engineering is more suited to males.

Table 3. Student Quotes for Conceptions of Engineering at Non-STEM Schools

Finding	Illustrative Student Quotes
Connections between engineering and other STEM disciplines are unclear.	STEM, they all have something in common. They have to make you think hard.
	Maybe it's because we get to learn about science, technology, engineering, and math, and they all go together.
	They're like the big things that people study on and stuff.

	They're all like four different types of subjects that will help you get farther in life.
	They all like are helping people learn more things.
	They're all very important for stuff in the future.
	Well I think they're all part of the education, you're all supposed to learn that.
	They all just kind of work together.
	Engineering and technology are kind of the same because they both use like batteries and stuff to make them work.
	It basically just all fits together because engineering creates the technology.
	Without engineering you can't have technology.
	Engineering helps the technology.
Students do not do engineering at school.	We don't really do technology or engineering, that's probably gonna be in junior high or high school.
	There was only like one engineering.
	They don't think they can trust little hands with metal.
	Our school just does science and math, but you should do technology and engineering.
	We haven't really done it [engineering] much.
	We haven't really talked that much about engineering.
	We haven't worked a lot with engineering
Students see opportunities for engineering at home.	My dad's building a shed in our house right now, so I like helping him.
	I like to do [engineering] with my neighbors because we can make cool toys out of it and make our toys sound louder and stuff.
	My uncle, he gets parts and makes something cool, so I liked helping him doing that, and it’s really, really fun because you’re just taking all kinds

of stuff and making it into something really cool.

[I do engineering] in my garage sometimes because my dad has a little work place, and I sometimes help him.

I do it [engineering] in my grandpa's workshop.

I kind of like engineering because me and my dad are diesel mechanics.

The engineering because I made the cat elevator and I try to like make things for my cats because we have four of them [at home].

I like to build stuff at home too.

I really like building things. And I actually have a project that I'm going to do. I'm going to make a moveable armor out of cardboard and I'm going to be able to wear it. And I actually got a ninja costume, so I'm going to use the black cloth that it has on it for the armor base. And I haven't started it yet, I'm still designing.

Engineering conceptions of students attending the STEM school.
Students attending the STEM-focused school also revealed several key conceptions of engineering that differed from the conceptions held by students not attending a school with a STEM focus (see Table 4 for illustrative student quotes). First, the students had a clear idea that engineering is multidisciplinary and that the STEM disciplines can be used together to reach a goal or solve a problem. They spoke about engineering as requiring the application of science and mathematics content both in general statements as well as through connections to specific activities they had done at school.

Second, students attending the STEM school discussed an iterative engineering design process. They talked about the importance of making plans, then carrying out the plans. Testing and iteration of designs were central to students' ideas of how engineering is done, and they discussed this iterative nature as being challenging and sometimes frustrating. Although they described difficulties associated with engineering, they also discussed the need for perseverance and expressed that with ongoing effort, they could reach a successful iteration for their engineering designs.

Finally, students attending the STEM school saw lots of opportunities to do engineering at school. They referred to specific projects and units of study that occurred within their science classroom, acknowledging that even though they did not have a designated engineering class, engineering was still regularly present. The students provided details about their school engineering projects, reflecting on how the engineering design process worked and the revisions they made to their designs.

Table 4. Student Quotes for Conceptions of Engineering at the STEM School

Finding	Illustrative Student Quotes
Engineering is multidisciplinary.	Well, they all connect to each other. We had trout in our classroom earlier this year, and that really connects with science because an animal in your classroom, that's really exciting, but then we used math when we tested the PH, the ammonia, the nitrate and nitrite levels, and when we used mean, median and mode. And then for engineering, we tried to create, if there were to be oil in the trout water, how would we take that out. So, we engineered the environment, and we had rocks on the shoreline, and then sand, and then there was water, and we tried to take out the oil with different materials, and that would be the engineering part. And the technology part didn't have as much to do with it, but we used a trout cam so at home you could go on your computer and you could see what the trout were doing when they were little babies, and they just all connect together. So, that's why I think it shouldn't be some random letters all mixed up, because STEM, it works together in that way that all of it is connected. Because if we were doing one project, we could connect that to technology in some way, or to math in some way. They all fit together. What we do in science… we usually go outside and find something, and we try to connect it to something with engineering. It takes science, math, and engineering to make technology. And it takes technology to engineer with math and science.
Engineering involves an iterative design process, which can be challenging and frustrating.	We had to draw it all out how it was going to be. Sometimes it doesn't turn out as well as you thought so you might have to fix it up. But that's kind of fun too because you can see like, oh yeah, I probably should have done that and then that would have been way better. And then you actually have the chance to do that. It's frustrating when you try it the first time and it doesn't work out so you have to think of what you can change for it to work. I like building things, but I'm one of those people that needs to have the plan in front of me, and the instructions on how to build it. I don't like going from just my knowledge on how things work, because it really disappoints me when my project, or what I'm made, doesn't work. If it doesn't work the first time, just keep on trying again, and you'll end up doing it. Sometimes I get it, sometimes I don't, 'cause it gets frustrating when you do it over and over and over and over and over and over again.

Students have many opportunities to engineer at school.	Technology and engineering may not have their own subjects, but you still use them a lot in school. Engineering we do in science. The mousetrap project that we did this year was really fun 'cause we got to create our own, like machine. We got to engineer it and see how it works. We did this thing called Scratch, and I felt like an engineer because we were practicing computer programing, and I felt like a computer programmer during that. We did this biomes project where we had to engineer something to make our biome cardboard things [displays] spin. I felt like an engineer when we were doing the wax museum because you had to engineer your activation device and I felt like an engineer trying to figure that out. And also, with the trout thing, I could tell pretty much like when we started doing math in the science stuff, that's when I knew it was STEM. Because we started with doing science and then we did engineering because we had to build. For the portfolios that we built for our trout company, we had to have a blueprint pretty much of our building. And also testing the water with science and we did graphs and stuff. We got to engineer our own mousetrap.

Discussion

The findings from this study revealed both similarities and differences in students' conceptions of engineering based on whether their elementary school had an explicit STEM focus. In general, students at all four schools had limited views of engineering, focusing on building and fixing. Those attending schools without a STEM focus viewed engineering as particularly relevant to work on cars or other vehicles, whereas those attending a STEM-focused school had a somewhat broader view of engineering and its applications. Students' limited views of engineering are not surprising, given that teachers, too, often see engineering in vehicles, buildings, and digital technologies [16]. *A Framework for K-12 Science Education* suggests that design activities for elementary students "should not be limited just to structural engineering but should also include projects that reflect other areas of engineering, such as the need to design a traffic pattern for the school parking lot or a layout for planting a school garden box" [1, p. 70]. Students in the STEM school revealed they had these experiences through the examples of in-school engineering they described, yet when they were asked to define engineering, they still focused on fixing and building.

Although students did not have fully articulated views of engineering, they viewed engineering positively, discussing opportunities for hands-on activities, choice, and creativity as appealing to them. They believed engineering helps to improve things in the world and prepares them for further education and careers. The messaging around students, both in school and out of school, has left them with the impression that engineering is important. This belief may support their ongoing participation in engineering.

Despite some commonalities in students' conceptions of engineering across the four schools, differences between the STEM-focused and non-STEM-focused schools were also apparent. Students attending the STEM school talked about the frustrating nature of engineering extensively, whereas those attending schools without a STEM focus did not. While it may initially seem problematic for the students with more engineering experience to view it as frustrating, it did not seem to hinder their interest or enjoyment of engineering. Rather, they viewed frustration as an inherent part of the engineering design process, with failure and iteration being central to engineering and necessitating perseverance. In contrast, students attending schools without a STEM focus did not speak of frustration, nor did they speak of redesign or iteration. The *Framework for K-12 Science Education* states that "it is the iterative cycle of design that offers the greatest potential for applying science knowledge in the classroom and engaging in engineering practices" [1, p. 201-202]. Thus, without these opportunities for redesign, the engineering experiences at the non-STEM schools limited students' engagement in authentic engineering practices. They did not have the opportunity to see their first design fail and a subsequent design succeed in meeting the criteria and constraints, so they did not get to the point of experiencing frustration. Opportunities to learn from failure through redesign are key elements of K-12 engineering instruction [10], and tolerance of failure is critical to supporting students' ongoing participation in engineering. Shielding students from failure and redesign in engineering does a disservice to these students.

A second key difference in students' engineering conceptions related to where they saw opportunities for engineering. Students attending the STEM school described numerous opportunities to engineer during the school day; in contrast, those students attending non-STEM schools saw their opportunities to engineer primarily outside of school with the support of family members, particularly those who were male. These students viewed engineering as building or fixing, and working on vehicles in particular, and they did not recognize women in their lives as doing engineering because they did not see women doing these activities. Particularly given the desire to attract more diverse students, including girls, to engineering fields [23], it is important to challenge the stereotype of engineering as fixing cars. Broadening students' views of engineering may help them recognize that engineering presents opportunities for people with many different interests.

Conclusion

Findings from this study suggest that elementary students require support in developing more nuanced engineering conceptions. In this district, attending a STEM school influenced students' conception of engineering. Although students who attended the STEM school still demonstrated areas where their conceptions of engineering could be more fully developed, they had a broader understanding of engineering and saw it as relevant to their lives and the world in more ways. As

engineering and STEM curricula are developed, particular attention should be given to exposing students to a range of engineering activities. While structural designs can provide an entry point into engineering, elementary engineering experiences should move beyond building physical items to help students understand the broad range of possibilities within engineering fields.

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