



Examining shared understandings of design artifacts in upper elementary school engineering (Fundamental)

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Introduction

With the implementation of the Framework for K12 Science Education and the Next Generation Science Standards in the United States, engineering is increasingly prevalent in the pre-college classroom (NGSS Lead States, 2013). A typical way to incorporate engineering into K12 education is through collaborative engineering design projects (NAE & NRC, 2009). This type of project often requires students to present the group's design work in a single representation, usually a co-constructed physical object (NRC, 2009). Though we expect that the physical artifact which a group creates is representative of a shared understanding among the group, from studies of engineering design with adults, we know that coming to this shared understanding of the problem, the team strategy, and the design artifact itself requires intense negotiation. Designers must communicate across all members of a team in order to establish roles and relationships, plan and change activities, gather and share information, generate and adopt concepts, and avoid and resolve conflict (Cross, 2011). Studies of elementary engineering education illustrate the ways in which young children manage these elements of designing together (Jordan & McDaniel, 2014; Roth, 1996; Moore et al., 2019; Wright et al., 2018).

Elementary students, as novice engineers, differ greatly from the populations usually discussed in studies of engineering design. For instance, Bucciarelli's work on object worlds (2002) characterizes the complexity of communication in interdisciplinary design teams of expert adults. How does this translate to the case of children designing together? Roth, in his work with school-aged children found that the artifact was central, as well as tools, materials, teacher-set constraints, and current trends. In his words, "Materials, tools, and artifacts serve in important ways as structuring resources to design and make sense of the learning environment and as backdrop against and with which students can construct individual understandings" (Roth, 1996). These works serve to center the design artifact amongst the social process of engineering, "the business of groups of individuals" (Bucciarelli, 2002).

These groups of individuals must communicate across difference to come to shared understandings of their design product and process. Questions remain about this undertaking, especially in the case of novice engineering students. For instance, is it necessary to come to a shared understanding to create a design artifact? How do teams composed of novices collaborate to design solutions? What is the role of a physical design artifact in mediating intragroup understandings?

In this comparative case study we analyze student discourse and student work from two groups which had different degrees of shared understanding of both the design process and artifact in order to address the following research questions:

- 1) *At the end of a design project, to what extent and in what ways do individual elementary students of the same design team have shared understandings of their design solution?*
- 2) *To what extent are the similarities and differences in their individual understandings influenced by their interactions and the characteristics of the design challenge and learning environment?*

Context

Data for this study come from a large, university-district partnership project to create and implement curriculum units that integrate science and engineering through design challenges set in the students' local communities. In this study, we seek to describe two cases, Group A and Group B, from upper elementary school classrooms in the same socioeconomically, ethnically, and linguistically diverse suburban school district in the Northeastern United States.

Group A comes from a 3rd-grade classroom that was implementing our “Animal Habitats” unit. The design challenge in this unit centers on a large commercial development in the students’ town and the habitat destruction and fragmentation that it caused. Students aim to aid animals that have been displaced by the development by moving them to a more natural habitat. To support their thinking in the design challenge, students study related science phenomena about animal habitats and survival. Group B comes from a 4th-grade classroom enacting our “Bird-Friendly Highway” unit. This unit blends the life and physical sciences around a problem facing migrating birds: light and sound pollution near highways. Students aim to aid migrating birds by building a structure to shield the natural area near highways from disruptive light and sound. To support their design work, students learn about the physical properties of light and sound as well as the biological structures that allow birds to see, hear, and generate sound. The two groups and their members are described in Figure 1 below.

Group A



Kai

Sam

Henry

Isaac

- 3rd grade

- Challenge: Design and build a way to relocate animals to a natural habitat after their habitat was destroyed by a commercial development.

Group B



Nathan

Yuri

Nico

Leo

- 4th grade

- Challenge: Design and build a structure to shield migrating birds from the lights and sounds of a highway.

Figure 1. Case study groups (all names are pseudonyms).

In both classes, students were first introduced to the context of the design challenge. They then completed 3 to 4 sessions of science inquiry on related phenomena followed by 3 sessions of engineering work on their prototypes, concluding with an engineering expo to share their solutions with the rest of the class and a few outside visitors. Table 1 below summarizes the flow of the class time for both classrooms. This paper only focuses on the portions of the design challenge days when students were actively working on their prototypes, highlighted in Table 1.

Table 1. Classroom flow for each of the units. Focus days for this paper are highlighted for each classroom.

	Group A: 3rd Grade Animal Habitat Problem	Group B: 4th Grade Bird-Friendly Highway Problem
Day 1	Unit launch: introduction to problem, animals displaced from habitat due to local human development	Unit launch: introduction to problem, light and sound pollution affecting birds near highway
Day 2	Inquiry: animal needs for survival	Inquiry: physics of light and sight
Day 3	Inquiry: animal population fluctuates with surrounding resources	Inquiry: physics of sound and hearing
Day 4	Inquiry: variation between individuals of the same species	Inquiry + Design: revisit sound, begin ideating
Day 5	Inquiry: human impacts on habitat destruction	Inquiry: bird anatomy, how do birds see, hear, and generate noises?
Day 6	Design Day 1: define problem, plan prototype, plan how to test	Inquiry: bird anatomy, how do birds see, hear, and generate noises?
Day 7	Design Day 2: build, test, iterate	Design Day 1: define problem, plan, build
Day 8	Design Day 3: build, peer feedback, iterate	Design Day 2: build, test, iterate
Day 9	Design Day 4: prepare for expo	Design Day 3: build, test, iterate
Day 10	Engineering Expo	Design Day 4: prepare for expo
Day 11		Engineering Expo

Methods

Data sources for this descriptive study include video records of whole-class and team discourse, interviews with individual students, notebooks and other written artifacts, and photos of design constructions. Both classrooms come from the same socioeconomically, ethnically, and linguistically diverse suburban school district in the Northeastern United States.

As part of the larger project within which this study is situated, interviews with consenting students from every classroom were collected using an identical protocol. The interview protocol consists of three phases: 1) exploring student design solutions, 2) comparing design solutions, and 3) reinforcing the real-life problem context. We close the interviews by asking students to share two things they enjoyed and any questions or comments they may have. The focus of this study is on Phase 1, where we ask students to describe the design solutions they created, how they came up with them, what they valued about them, how they solved the problem, difficulties they faced, and how their design ideas changed throughout the unit. The full interview questions can be found in Appendix A.

We employ qualitative case study and microethnographic analysis techniques to explore the differing conceptions of the design artifacts (Merriam, 1998; Bloome et al., 2004). The interviews were transcribed verbatim, using the Jefferson transcription notation system (Jefferson, 2004). The first author reviewed the set of four interview transcripts for each case group and wrote a memo summarizing similarities and differences among team members concerning their design ideas, construction plans, and prototype functionality. These memos, along with transcripts and video records of the interviews, were reviewed on several separate occasions by members of the lab group.

Classroom video data was not fully transcribed. Instead, the first author and another member of the research group watched each video and used a video analysis software to track when new ideas were introduced and repeated or agreed with. To ensure similar results, both analysts coded the same 10 minutes of video and compared. Then, each analyst examined 80 minutes (Group B) to 160 minutes of group work. This analysis yielded a timeline of ideas across the design challenge days. Each introduction or repetition of an idea was transcribed. This process generated a partial transcript for each of the video records. We then cross-referenced this timeline of ideas with photos of the students' prototypes over time in order to create Figures 2 and 3, discussed further in the Findings section, *Influence of interactions and learning environment*.

Findings

Similarities in understanding across design teams

To address the first research question, *At the end of a design project, to what extent and in what ways do individual elementary students on the same design team have shared understandings of their design solution?*, we turned to the interview data. These provided insight into each student's individual understandings of their design solution. In Group A we observed agreement among team members about how the artifact came to be, whose ideas it comprised, and what each physical component represented. For example, in response to the question "How did you come up with this design?" we saw a coherent story of the group's design evolution emerge (Table 2).

Table 2. Group A: responses to the interview question "How did you come up with this design?"

Student (Group A)	Response to "How did you come up with this design?"
Kai	"Um, we came up with it about Henry, because Sam thought about transportation with the car, but Henry was like no, we should do a bridge instead. And so we did a bridge."
Sam	"Well, Henry, in our group, he said, let's just do a bridge that animals don't go over, under, so the animals are safer. Cause like a bird could just like pick them up, but then they're under so then birds cannot. So then we agreed to the idea and then we just started building it."
Henry	"I was thinking of cars going over the highway and- there's a ton of those designs. So... the green part looks like vines and trees and there's water for the bears and animals to drink so they think it's their home and their habitat."
Isaac	"Uhhhh, Henry. Well, Sam first wanted to do, like, a transportation vehicle, but then Henry said we should do a bridge where the animals go under and the cars go over."

Across these responses, we see a similar narrative unfold, one that was corroborated with the classroom video: Sam had an initial idea to create a transportation solution, then Henry introduced the idea to build a bridge for cars to go over the animals. The individual student responses add more depth to the story and give insight into their personal stances. Kai's answer positions Henry with veto power ("Henry was like no") and sway over the group direction ("so we did a bridge"); Isaac's answer presents the two options more neutrally. Henry himself doesn't mention Sam's transportation idea and explains his own thinking for his bridge idea. Sam also doesn't mention his own idea, instead describing Henry's idea and his reasoning for it: that it

would be safer for the animals and that the group (“we”) somehow “agreed to the idea.” The interviewer followed up on this statement, asking:

Interviewer Ok, so you all thought that was a good idea? [*Sam nods*] Ok, cool. So did you ever do or see something before that made you think of this?

Sam No, we were thinking about transportation, before with car. But then Henry told us.

In his response, Sam brings up the transportation idea, which Isaac and Kai had both attributed to Sam, framing it as the idea of the collective “we.” His statement “Henry told us” echoes the sentiment in Kai’s interview that Henry ultimately decided the direction of the team’s solution.

Conversely, in the interviews with the students from Group B, we observed conflict and confusion about their artifact; students among the same group described the functionality and evolution of their prototype differently. Table 3 below shows the answers to the same interview question, “How did you come up with this design?”

Table 3. Group B: responses to the interview question “How did you come up with this design?”

Student (Group B)	Response to “How did you come up with this design?”
Nathan	“Um... well we... so at first when we were thinking about doing our design we were thinking about like a tunnel. So that's sort of how we came up with this cause it sort of resembling a tunnel and we wanted it to be environmentally friendly so we just put some like leaves and snow up here to like decorate it so that's basically how I came up with the idea.”
Yuri	“Um... when you gave us the paper to draw on and... and... and see what you creation was like. Nathan wanted to make a roof, but Nico wanted to make these giant stairs. ... So we just combined them together. Um mine was about cars because I didn't know we were going to be doing this. So I thought if I add something to the cars that it would work.”
Nico	“Yeah we decided to have the sticks and sponges first so then there could be like a little roof just in case there's any animals that can't fly because there's like tape guarding an entrance or something. So then the birds could like go on top and the animals that can't fly they could like um like I said the stairs are for like the cups are for stairs. So then the other animals could walk on the stairs and go on the top.”
Leo	“We just built and it... we pretty much didn't plan it. We just grabbed supplies and then as we were putting it we just kept saying what to put on.”

In general, these answers were longer (except in the case of Leo) and less obviously consistent than those from Group A. Only Yuri attributed particular ideas to particular group members; Nico and Leo talked about all of the ideas and decisions in terms of the team, “we,” and Nathan used both the collective “we” and personal pronoun, “I.” The evolution that Yuri describes, as a combination of Nathan’s idea to make a roof and Nico’s idea to have a large staircase, accurately reflects what we observed in the classroom video. Yuri also distances himself from this group idea in the second part of his answer, alluding to one of his own ideas about cars. Nico, in his interview response, tells a similar story to Yuri’s, though providing more details about particular materials and without attributing the ideas to any particular group members. Nathan doesn’t acknowledge the stair idea in his response at all, though it does come up later in his interview. Leo’s response, which ascribes a certain haphazard nature to their design process, is an interesting outlier. Turning to the classroom video to better understand this position, we observed that it was, in fact, characteristic of *his* approach to the design process. Leo often worked parallel to the team, initiating and constructing most of the “decorations,” or as he calls them, the components that make the design “environmentally friendly”; things like trees, leaves, snow, and clouds. This divergence between team members was typical for Group B; they often seemed more like four students working in parallel than a genuinely collaborative team. This point is elaborated further later in the results.

In addition to these inconsistencies in understanding of the design process, the students in Group B revealed contradictions in their conception of the design *functionality* as well. In response to the prompt “Tell me about your design,” the fourth-graders recounted their understanding of the prototype: what it was and how it worked. These responses are reported in Table 4.

Table 4. Group B: student responses to the interview prompt “Tell me about your design.” Student responses have been shortened and punctuation added for clarity. When unnecessary, interviewer follow-up questions such as “why?” and revoicing moves have been removed. Portions of interest have been bolded.

Student (Group B)	Response to “Tell me about your design”
Nathan	“So our design we wanted the least amount of light and the least amount of noise so the warblers could fly. So at first we were thinking of sponge walls and sponge roof [<i>hand motions a cube shape</i>] but we didn't have-- but the sponges were already out. So then we got one of those turf roofs and we stuck toothpicks into it so it would stand up so that got rid of our light. But then we needed to get rid of the noise so we put sponge walls like we were gonna do before, but didn't cover up that much of our roof so then we put some tape around it and then the noise would bounce off of the tape so that reduced our noise. And when we tried out our design we got zero light [<i>lumens, measured on the light meter</i>]... and like... like 53 noise [<i>decibels, measure on the sound</i>]

	<i>meter]</i> maybe.”
Yuri	“So we used cups as stairs... um... we made this giant roof... so birds can go on the roof and (pigs) can go up the stairs. Um... Um we used a bunch of green and fluff and... um... green roofs because we thought that if it look good to the environment the closest thing is to make it look like a tree and leaves and we put that on top, we didn't put real leaves. Um... and... we also have to put a wall. Um... so first off we were gonna use a sponge but there wasn't enough sponges. We go two sponges, but we needed about four and we didn't have those. So then we started putting toothpicks and we didn't take away the sponge and we put a bunch of duct tape onto the walls. Um... for lights. Just stuck to the wall and the sponge and we did that so that if any light was coming in we could block it off with some tape. Um... We had snow because the birds migrate in the winter and the fall and it might snow then.”
Nico	So um for our design we um we first like started out with just a board um... and some sticks and then we thought we could make a roof if we could like put the sticks through the wall and then we put some more details to make it look like a real forest and we put some um cotton on it to make it look like it's snowing and we first started out with just tape and... sponges, two sponges on each side, but then we um we knew that the [masking] tape wasn't strong enough and the sponges wouldn't hold up so then we got duct tape and then we placed duct tape over the sponges and we after that we added some trees to make it look like a real like forest. So then it looks like real animals could like live there and stuff and it looks like there's actually a sky and stuff. That's why there's clouds right here. Yeah we decided to have the sticks and sponges first so then there could be like a little roof just in case there's any animals that can't fly because there's like tape guarding an entrance or something. So then the birds could like go on top and the animals that can't fly they could like um like I said the stairs are for like the cups are for stairs. So then the other animals could walk on the stairs and go on the top.
Leo	So the tape is like the walls cause we didn't have any sponges or like these green stuff [<i>points to picture of project</i>], so we used some of the tape for the walls. And so it wouldn't be dark left in these spaces. And these cups are supposed to be stairs I guess. And these toothpicks... I think those are... we put cotton to these um to make them the trees and then we put like... yeah, pompoms, we put them on top just I don't know why though. And since um... since we did it, we made this [<i>points to picture</i>] in like the winter time like... um... so we put some snow on it. And... uh... this is.. this sponges were supposed to be some walls too, but we didn't have enough.

Nathan’s response addresses the functionality of their design in terms of how well it met the criteria: reducing the light and sound measurements (“least amount of light and least amount of

sound”). In the classroom video and at other points in the interview, he calls their design a “tunnel,” with “sponge walls” and “turf roof.” The last element of their design that he lists is the duct tape, again describing it in terms of its function, as something that “noise would bounce off of.” During class time, Nathan was most concerned with the light and sound element of the design functionality, and he shared his reasoning with teammates and the teacher in the classroom. Yuri, in his response says “we put a bunch of duct tape onto the walls. Um... for lights”; this echoes the reasoning that Nathan describes, but in less detail, perhaps indicating a less sophisticated understanding of the intended purpose of the duct tape. The other three members of the group were not as concerned with how the materials interacted with light and sound; instead they focused on the structural capabilities and how the design served the animals. For instance, Nico talks about the duct tape as serving to support the sponges (“the [masking] tape wasn’t strong enough”), and Leo says they used the duct tape because they “didn’t have any sponges.” Like his response in Table 3, Leo expresses some hesitancy, ending many of his statements with “I think” and “I guess.” In the following section, we discuss the potential influences on these varied coherences of design product and process in the two case groups.

Influence of interactions and learning environment

Our dive into the classroom video records and student artifacts themselves allowed us to address the second research question, *To what extent are the similarities and differences in their individual understandings influenced by their interactions and the characteristics of the design challenge and learning environment?*

At the most basic level, these two classrooms were different: the students were completing different design challenges, rooted in different scientific phenomena; Group A was composed of 3rd-graders and Group B, 4th-graders; the class time was structured differently. Though both units allowed four class sessions for the design challenge (see Table 1), Group A spent 120 minutes on building, testing, and iterating while Group B only had 80 minutes of dedicated group design time. That extra time alone spent discussing, planning, building, and testing may have provided Group A with more opportunities to negotiate their shared understandings. Their time also differed in the way it was spent. Group A had 30 minutes dedicated to peer-to-peer feedback that Group B did not (see Table 1, Day 8). During this time, students from Group A were able to show their design to multiple other groups, ask for help, and be inspired by other solutions in the classroom. Group A also had many interactions with adults in the classroom, both during this feedback time, as well as on their initial planning day, on Day 6. It is probable that describing their design concept multiple times to people outside their group helped them to solidify a narrative of their design concept, shared and repeated across group members.

Another key difference between the two learning environments lies in the structure of their planning time. On Design Day 1 (Day 6 for Group A, Day 7 for Group B, Table 1), both groups

were given dedicated time to talk amongst themselves and sketch a plan of their design. However, Group A was provided one large piece of chart paper to sketch on collaboratively. In Group B's classroom, each student had an individual piece of paper and was asked to sketch individually, then compare. Though both are valid pedagogical choices and have their own pros and cons, the unique combination of this choice and the team interaction styles may have contributed to the difference in shared understanding across the groups. In Group B, this led to a strong association of a design idea with an individual. Consider the following exchange:

<i>Yuri</i>	I'm doing Nico's idea 'cuz I think it's good.
<i>Nathan</i>	Me and Nico have like the same thing except with stairs. But mine's [inaudible] because mine has leaves so it's more environmentally friendly.
<i>Leo</i>	[scoots closer to Nathan] I'm with you, don't worry I'm with you.
<i>Jayden</i>	Leo we're not doing <i>with</i> each other we're just doing ideas. [Leo begins protesting] Yeah but [mockingly] 'I'm with Nathan.'

In this brief conversation, each student from Group B attributes certain ideas to particular individuals, putting themselves into different camps. In the next section, each group's particular interaction style is examined to tease out how these differences in the learning environment may have influenced the cohesion of the groups' design conceptions.

Characterizing student-to-student interactions around the design artifact

Because this study centers the design artifact as the mediating object of the student's design work, we chose to examine student discourse as it pertained to their construction. As outlined in the Methods, we generated timelines (Figures 2 and 3) that trace the features of each group's artifact from conception to completion.

For Group A, we identified three main features: 1) the bridge structure, where animals move freely underneath and cars travel overtop; 2) pillars as support for the bridge, constructed from two Dixie cups taped end to end; and 3) a "no polluting" sign, announcing a fine of \$1,000 for pollution. Figure 2 shows the group's final prototype and the evolution of each of the design features over the three design days (Days 6, 7, 8 on Table 1).

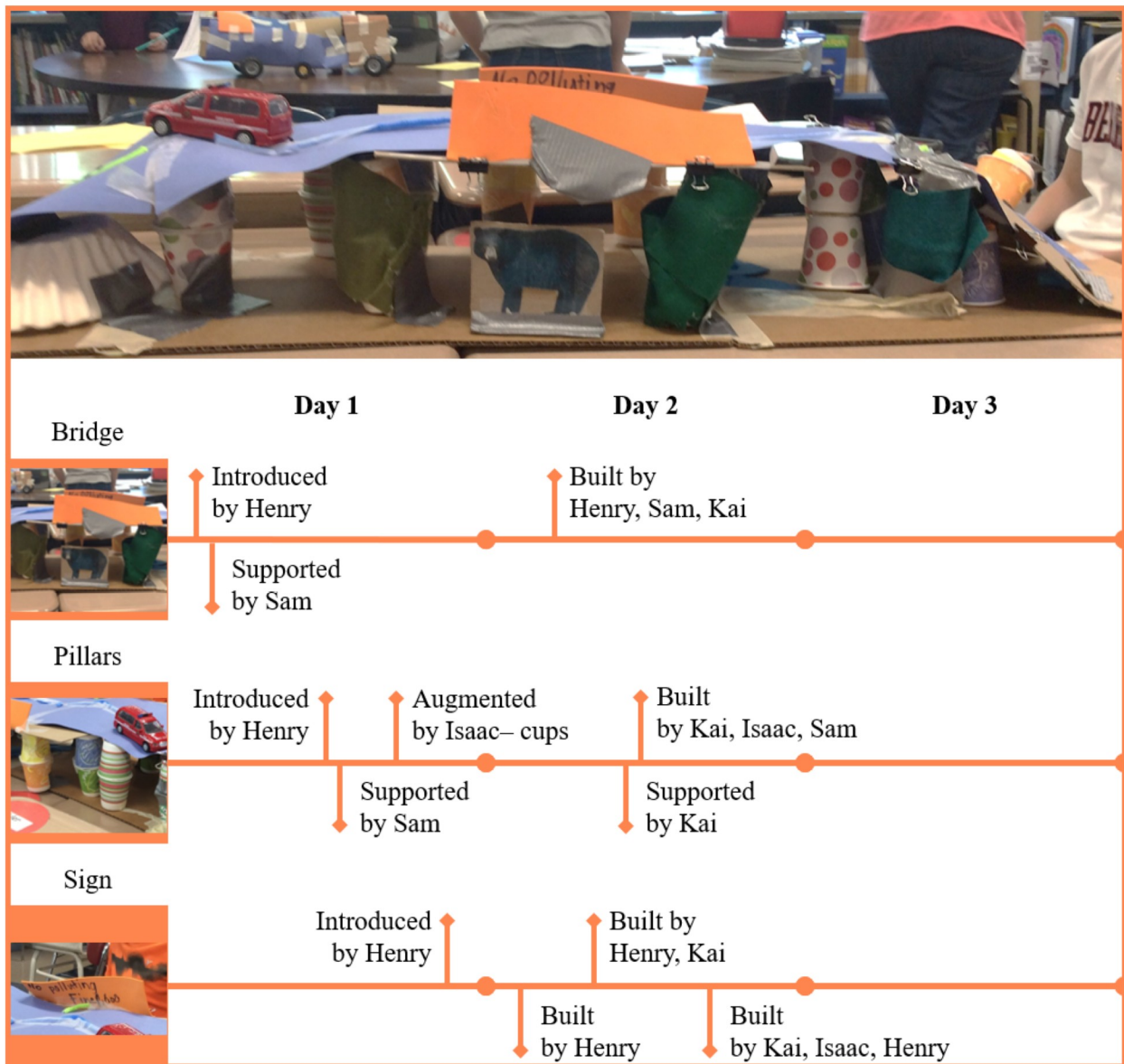


Figure 2. Timeline of development of Group A's prototype, organized by design feature.

All of the features identified were introduced by Henry; this aligns with the views expressed in the interviews, with Henry taking a leadership role in the group. The bridge and pillar ideas were both supported by Sam very quickly after being introduced. When building began on Design Day 2, no one student dominated and all four students had their hands on the project, often working together. Nothing was built in parallel by different members of the group; the entire team changed gears together.

In Group B's final prototype, we identified six distinct features: 1) stairs for animals like pigs or birds with broken wings to cross over, made from cups; 2) trees, made from skewers wrapped in pipe cleaners and topped with pompoms; 3) a flat roof, made from a turf-like material; 4) tunnel

walls, made from sponges; 5) additional walling, duct tape; and 6) snow, made from cotton fluff and ripped up paper.

Across the different features of Group B's prototype, their path to existence varied. For example, the "trees" quickly moved from introduction to production, with Leo leading the charge. Only after he had already built the trees was his idea even acknowledged by another teammate. This pattern was similar for the "snow" which was introduced and immediately enacted by Nico, with a bit of help from Leo, in the haphazard way that characterized his interview responses. More essential design features, like the flat, turf roof and sponge walls followed a different trajectory.

The idea to have a roof and walls was embedded in Nathan's overall design direction to build a tunnel. Making the roof flat and accessible by stairs was introduced by Nico, and generally agreed upon. Nico also put forth the idea to construct the flat roof from a piece of turf. When it came time to enact these ideas on Design Day 2, Nathan took charge, with Nico and Yuri assisting the building process. Even so, the way that these students constructed together looked different. More often one student would have control of the materials, struggle, then pass them off to another. Materials changed hands rapidly, but always trying to match Nathan's vision. Even if he wasn't first to try to put something together, he was always the last, modifying the artifact continually.

The stairs, built from three stacked cups that were in no way attached to each other, were from the beginning attributed to Nico. Surprisingly, on Design Day 2, they were not constructed until halfway through the class period, with Nathan as the sole contributor. After announcing, "I'm gonna try to make your stairs Nico," Nathan stacks the cups on either side of the tunnel. Though this stack is not secured to anything, continually gets knocked over, and was arguably Nico's idea, no one challenged Nathan's construction. Interestingly, in the interviews the cups are brought up as a source of frustration and a bad representation of stairs, but no such thoughts were aired during class time.

We argue that these feature trajectories characterize two different interaction patterns among the two groups. Interestingly, both groups were observed to have strong leaders, Henry in Group A and Nathan in Group B. However, the leadership was taken up in different ways. In Group A, Henry ended up making a lot of decisions for the group, but he tended to explain his reasons clearly and his team members heard these reasons and had many opportunities to repeat them to peers or adults in the classroom. In Group B, Nathan made decisions without sharing much of his reasoning. He was also positioned more often as the explicit leader of the group, with Yuri, Nico, and Leo often sharing their ideas and questions with Nathan directly. These interactions came across as his team members deferring to him and asking for his approval.

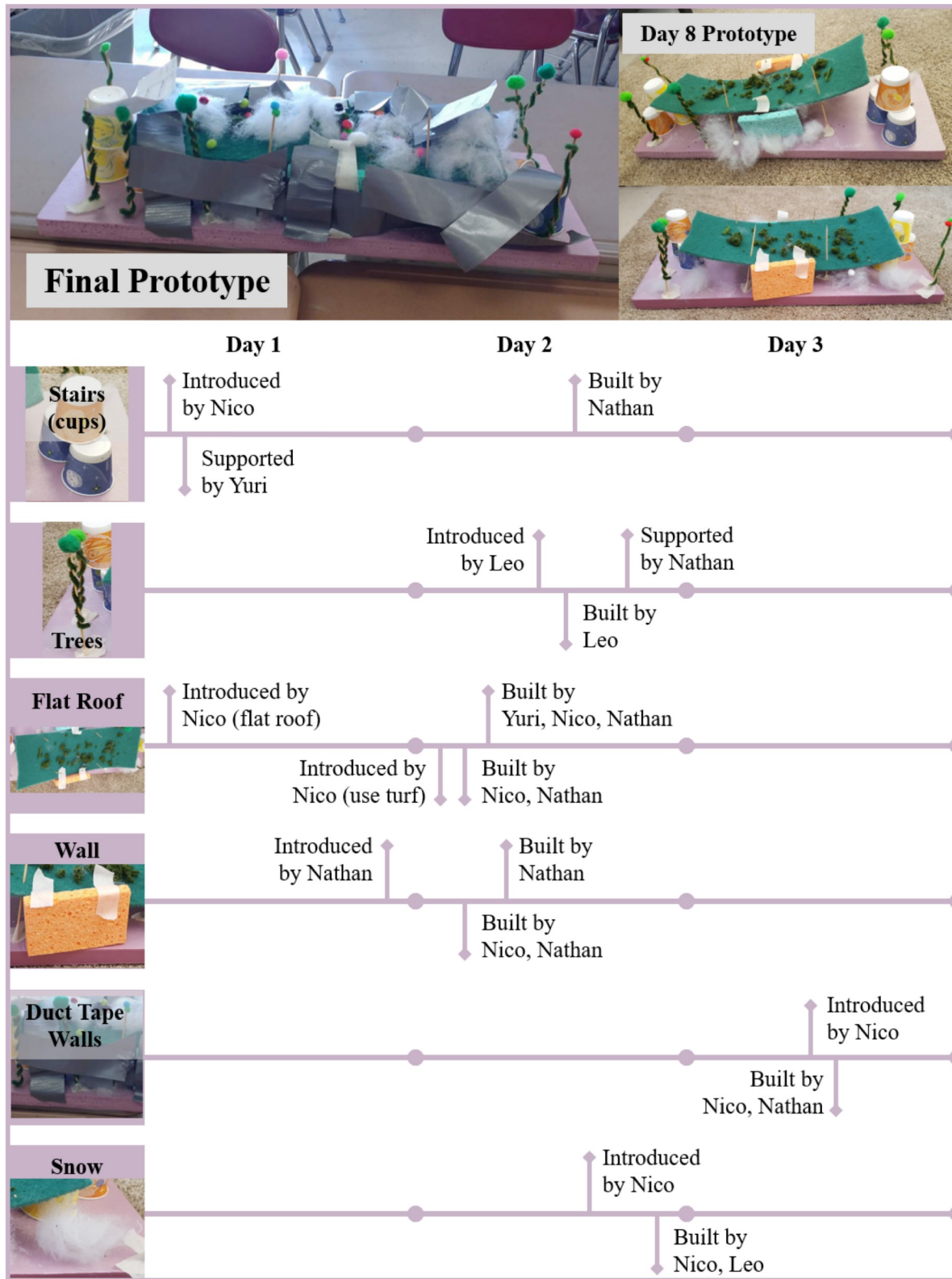


Figure 3. Timeline of development of Group B's prototype, organized by design feature.

Discussion and Conclusions

In this study we addressed the implicit assumption often made when the student design team is the unit of analysis in engineering education research: that a constructed design artifact represents a shared understanding among group members of their design concept. Using video data from groupwork as well as retrospective interviews, we investigated how individual elementary students on the same design team each conceptualized their group's design solution, and we explored how the students' interactions with each other and the learning environment may have influenced those conceptions.

We found Group A, the third graders, to present consistent and coherent narratives in their retrospective interviews about how their animal habitat protection bridge came to be, and these narratives from the individual students matched what we saw in the video of their actual design work together. By contrast, each member of Group B, the fourth graders, described a somewhat different trajectory of how their bird-friendly highway tunnel emerged as their design solution, and the video record indicated that they worked more as four students in parallel than as a collaborative group. Their interview responses also diverged in terms of how they explained the functionality of their design prototype features. Not only did they suggest different purposes for the same component, they also differed in what kind of model they understood the design construction to be. At one end of the spectrum, some Group B team members explained how light and sound were actually absorbed or reflected by the particular physical materials they chose for their construction, while others framed the physical materials as "stand-ins" for what the design would be composed of at larger scale.

Group A's strongly shared understandings of their design concept were consistent with their more collaborative approach and team dynamics, as can be seen in their design construction chronology. Each member of Group A had a hand in constructing each of the components of their design. While both Group A and Group B had students who emerged as strong leaders, only in Group A did the other students fully engage with implementing each of their leader's ideas. Two differences in the learning environments for Groups A and B may account for these differing team approaches and dynamics. First, design planning in Group A's classroom was facilitated by large shared papers on which team members collaboratively sketched ideas. These group sketches supported joint attention (Barron, 2003) and conversation. In Group B's case, individual students drew fairly similar sketches on their individual papers; they may have assumed that these represented shared knowledge even though they did not (Kittleson & Southerland, 2004). Second, the learning environment in Group A's case involved frequent opportunities for students in a group to discuss their design ideas with adults and peers outside of

the group. These conversations may have surfaced differences in interpretation between group members and supported their conceptual convergence (Roschelle, 1992).

Ideas about the influence of the learning environment, like the nature of planning and opportunities to talk to adults or peers outside of the group, are actionable. The findings seem to suggest that collaborative planning and repeated opportunities to describe a design concept may be beneficial for teams to come to shared understandings of their artifact. Future design-based research could explore how these activities can be scaffolded and fine-tuned to suit the needs of different classrooms and students. This ties in to the third influence, of a strong leader and particular interaction styles. Because every student is a unique individual and every design team is a collection of individuals attempting to communicate across differences, there will always be variables that call for careful teacher noticing in the classroom. These findings beg future work on how to support teachers in crafting learning environments that support students in engaging in this communication effectively to collaboratively create design solutions.

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Appendix A: Interview Questions

The following questions were asked in Phase 1 of the individual student interviews.

- Can you please tell me about your design?
- How did you come up with this design?
- Have you ever seen or done anything before that made you think of your solution?
- What do you consider to be good about your design? Why?
 - *Follow-up:* What things do you like about your design? Why?
- Can you explain how your design solves the problem?
 - *If design didn't solve the problem:* How was your design supposed to solve the problem?
- Did you face any challenges or difficulties while designing?
- After you first started working on this unit and your final design, did your ideas on how to solve the problem change over time? And in what ways?