The Social and Conceptual Function of Uncertainty in Open-Ended Project-Based Learning

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Introduction

In this research paper, we report on a study of collaborative work in a high school-based maker club. There is growing interest in project-based learning (PBL), makerspaces and other relatively open-ended learning environments that afford many entry points and pathways into and through engineering. Though often focused on engineering design and digital fabrication, these spaces often support a range of activities and technologies, from laser cutting and 3D printing, to electronics and e-textiles, to carpentry, sewing, painting and digital media, and so have the potential to attract students who may not have yet identified an interest in engineering.

Unlike more traditional curriculum, open-ended makerspaces elicit many sticking points and moments of uncertainty which can serve as rich contexts for conceptual development and disciplinary practice. In these open-ended spaces, students experience uncertainty about project goals, roles and designs, and how learning paths take shape moment to moment is unclear, often differing student to student.

In project-based curricula, much is unknown, unspecified, and ambiguous, conceptually and relationally. Learners must tolerate much of this ambiguity and select what and when they call attention to uncertainty – places where they see fault or limitation in their own or the group's designs, knowledge, or plan. In this analysis we saw that when facing much uncertainty - often across many aspects of a project - how students select what to bring attention to, and how they respond when uncertainty is raised by others, cannot be well predicted by the material problems, knowledge, and material resources, as we as outsiders might see these.

Using interaction analysis, we analyze and report on the interactions within one group as they worked through design phases of a long-term project - a light-up class portrait. We bring attention to moments of uncertainty and found that they act as pivot points that learners can use to position themselves and others, to control problem-solving discourse, and ultimately to direct projects toward features, resources and practices that served their interests. We also saw that while some students were able to use their projects to pursue personal learning goals and identities, others were not.

Background

Development of expertise requires learning over long periods of time [1] and within engineering disciplines can be particularly difficult for young people who face barriers raised by forms of systemic discrimination at many points along the way [2], [3]. To forge learning pathways that are personally meaningful, marginalized students in particular often have to exercise agency "as they construct, leverage, repurpose, and transform social and material arrangements" [4]. While this is a daunting task, the idea that learners actively shape the environments in which they learn is central to sociocultural theories of cognition, ,and studies of engineering trajectories show that in addition to gaining the conceptual and practical knowledge to participate in engineering, people must come to *identify* - aligning personal interests and communities with the practice of

engineering - and must learn to *navigate* institutions through both formal and informal, flexible, even idiosyncratic means [5].

PBL and makerspaces in particular - as one kind of PBL and design-based learning increasingly common in schools - have been posed places with the potential to open space for young people to do this work of identification and navigation in generative and equitable ways [1], [3], [6]. Makerspaces vary but are typified by fluidity of roles, products, audiences, and values [7]. There is evidence that such fluidity creates opportunities for greater student autonomy over learning products and that such arrangements can support positive identification with STEM disciplinary practices and communities [8]. However, PBL can also exaggerate imbalances of power and knowledge as students learn to navigate new spaces, new tools and the social dynamics of collaborative work [3].

In looking at makerspaces to see where and how pathways into engineering practices might develop, WE came to focus on moments of uncertainty in collaborative work. Uncertainty is the "feeling of doubting, being unsure, or wondering" about future events or past meanings [9]. Uncertainty can be productive for learning because it points to places where existing mental models of the material world, or understandings between participants, reach a limit or conflict, and can then be addressed through conceptual or social reorganization.

Raising uncertainty is central to creating scientific knowledge, spurring evolution of representations, discourse, disciplinary equipment and concepts [10], [11]. It is also critical to learning in science and math, necessitating that learners work to align ways of seeing and organizing problems, and driving conceptual development [12]–[14]. Studies of uncertainty document sources of uncertainty as both conceptual and social, necessitating work by participants across these dimensions [15]–[17].

We focus on uncertainty as intersubjective, produced through interaction in ways that likely resemble, but cannot be assumed to represent, the "cognitive feelings" of those who express it. In open-ended learning environments and particularly those that engage learners in design, uncertainty can be ubiquitous. Learning in makerspaces can involve not just taking a problem as given and trying to solve it (with resources as given), but rather it involves looking for problems to address, identifying and evaluating potential solutions, then working over the course of a project to find relevant resources (sometimes going beyond the given) and work toward products and prototypes that enact a solution.

Beginning from the question of how youth shaped opportunities to learn in collaborative work in a school-based makerspace, WE came to examine not how questions and uncertainties were *resolved*, but why they were *introduced* and *taken* up, or not. How was uncertainty produced in the group's interaction, and what effect did this have on opportunities to learn for participants?

Study Context

This study was part of a long-term design-based research project in which we, as part of small research team, co-developed a "maker club" that operated during the school day at a public charter high school. With a variety of traditional tools (sewing machines, saws, etc.) and digital fabrication tools (laser cutter, 3D printer, microcontrollers) available, we designed the club to

give youth participants a chance to choose projects of interest. The maker club met once a week for the last 3 months of the school year. We met with the students for approximately five hours each time, on a day when they otherwise would be at internships. This meant there was time for significant development of the group projects, across the club and even across each day.

Participants & the Class Portrait Project

Fifteen students, ages 14 to 16, at a public high school participated in the maker club – 7 boys, 7 girls, and 1 gender non-binary. The club demographics reflected those of the school as a whole – 5 African-American, 3 Latinx, 3 White, and 4 multiracial. Most students were from low to middle income families. In this paper, we focus on the work of one group, in which there were three young women -- Casey, Deonne and B -- and one young man -- B's brother Isaiah.

Three members of the group – Casey, Deonne, and B[i] – shared a homeroom, and decided to create a light-up Class Portrait. The portrait as initially envisioned would include a photo of all students in the class and use LEDs embedded in the border to make it "unique" and "interesting." Isaiah wanted to help B and thought the project would allow him to learn more about digital design software. Deonne had hoped to focus on sewing and planned to work with B on a skirt that would light up. However, when B switched into the Class Portrait group, Deonne did as well.

Of approximately six groups in the Maker Club, this group was representative in type of project – a mix of traditional and digital technologies – and problems that arose – technical and social. We selected them for closer analysis in part because they were among a subset of groups for which we had consistent interview and interaction data across the duration of the maker club, because the group members had a range of interests and levels of experience with STEM practices and technologies, and because the four members seemed to each have different experiences in the group and we were interested to learn more about how their experiences came about.

Data Collection & Analysis

During the maker club, we acted as participant observers, leading workshops and mentoring youth, while also recording audio and video data, collecting field notes, and debriefing with our research team and the partnering teachers. We conducted brief, 3-8 minute interviews with the students at the end of each session, and a longer retrospective interview at the end of the year. For this analysis, we rely primarily on audio and video recordings and focus on interaction from one day early in the maker club. Analysis of field notes and interviews were used to understand the days' activities overall, to ensure that audio and video data did not miss anything researchers had flagged at the moment, and to put the youth participants' actions in context.

To analyze the way that discourse structured opportunities to learn, we turned to an articulation of framing theory [18], which helped us understand how understandings and social expectations are carried into interactions, making visible and legitimate the roles, goals and resources of some students at the expense of others [17], [19].

As we simultaneously conducted analysis of the students' participation in the maker club over time, we selected sessions for close analysis. After reviewing observational data from across the

project timeline, we focused on the third session of Maker Club, when students moved out of skill-building workshops, finalized group composition and began work on their project ideas. This was a time of some conflict and it captured much of the negotiation that directed the project and set in place roles or areas of focus for the group members. It was a day where the group worked to consolidate vision, settle group dynamics, and create a shared understanding of design and construction. We created a transcript of the entire day (4.5 hours), drawing from multiple audio and video files and including verbal discourse as well as non-verbal details of interaction and work on the project.

We coded the transcript for work being done at positional, epistemological and conceptual levels. As themes within these categories emerged, we began to notice moments of uncertainty as key sites at which ideas and social positions were often asserted or contested, shifted or reinforced. Using verbal and non-verbal markers of uncertainty, such as questions, hedges, and hypotheticals [9], we re-analyzed the transcripts, identifying places in the day where uncertainty was raised. We coded these places for how uncertainty was raised, content of issue raised, framing work evident during these moments, and issues of power that were evident. To understand more completely what was happening during these moments, we identified and summarized thirteen key moments – moments at which framing work evident in the student profiles was introduced and/or contested. In this closer analysis, we identified themes in how moments of uncertainty functioned in framing work students were doing and refined these using codes for framing work that had been applied across the day. Due to space constraints, we present interaction from only one of the thirteen key moments, then provide a summary of themes identified across the entire analysis.

Findings

To illustrate the nature of work and interaction in this group and to provide a sense of how uncertainty moved across the participants and project, we first describe one brief interaction.

Episode 1: Shark waves and bubble letters

In this episode, participants use uncertainty as a way to control access to project vision and project and roles. At this point in the day, the group had been working through ideas for the portrait, figuring out how features they wanted might get built, and what limitations of materials and tools (such as the laser cutter size) they needed to account for. Unsure of how they might integrate LEDs into the structure of the portrait, the group had begun to look on the internet for examples. At the point we begin, Casey and B, the project leaders, had stopped research and begun talking about the portrait dimensions. Deonne, who up until this point had been kept out of some of the project planning, continued the internet search and was starting – as evidenced by brief exclamations – to get a clearer sense of what Casey and B had in mind for the LEDs.

As this episode began, Isaiah and Deonne were both seated at a round table, with laptops in front of them. Casey and B were near them at a large whiteboard, redrawing plans for the portrait, struggling to figure out what dimensions its component pieces should be and how to make their drawing reflect these dimensions. Isaiah stopped working on his computer and raised his head to ask a question of the group.

1	Isaiah:	What are the measurements of this box going to be?
2	Deonne:	I have no idea
3	Isaiah:	[turning toward B and Casey] What are the measurements of the
4		box going to be? [pausing, he looks at the whiteboard sketch] 36
5		by 24?
6	Casey:	Yeah, we're making it three separate pieces
7	B:	Yeah 'cause the laser cutter only goes to 12 by 24
8		[B and Casey turn back to the whiteboard]
9	Casey:	[to B] It [the sketch] says one, inch.
10	Deonne:	[looks up at Casey and B] see! something like this? [she points to
11		an image on the computer screen] a frame like this, with lights,
12		going around it - ya a ya a / ya a [she points at each LED as she
13		says this]
14	B:	/ but are we going to /have it, like/ *that*?
15	Deonne:	/but
16		they'll [the LED lights] come out, like this [she points to another
17		image on the computer screen]
18	B:	But are we going to have it, like shark, waves, bites, things?
19	Deonne:	no! I'm just, I wasn't really going to do that. [1 second pause] I
20		was thinking maybe squares though. Or I don't know.
21	B:	but like, what should the pattern be?
22		[3 second pause]
23	Deonne:	I could make that / part/ [last word trailing off]
24	Casey:	/ it should be "good job' in big bubble letters"
25	B:	yeah.
26	Deonne:	[in a high voice] can I cut that?
27		[2 second pause]
28	B:	just / draw it out, then like / cut, out
29	Casey:	/ the letters [inaudible as Casey and B
30		talk over each other]
31	Deonne:	/ like I don't even know how to cut in
32		bubble letters, I don't think. I could try right now. / I'll make a G
33	Casey:	/ you write them
34		out, and then you cut them – no, use a pen!

As seen in this episode, given the open design space and multiple project dimensions that need to be figured out, the group's discussion jumped frequently across aspects of the projects - from size, to construction methods and materials, to electric components, to how the portrait would be received by the intended audience. The group's off-and-on discussion of questions and problems revealed that uncertainty was not inherent to a material or social problem, nor is it based solely on the limitations of knowledge and resources that are, or should be, accessible. For example, at the beginning of this excerpt, Isaiah is asking a question about the project size that he himself had earlier refused to answer when Deonne asked, claiming at that time that it was not important to determine the project size because they were prototyping. While Deonne's question about portrait dimension was initially ignored (and therefore she cannot answer, line 2, Isaiah's here is answered immediately by Casey and B, who also offers a rationale for the size they mention.

As the interaction continued, Deonne finds a picture that finally gives her an idea of how the LED lights might be integrated into a picture frame, something she had struggled to envision and something others in the group had not yet made a plan for. Deonne shows this picture to B, focusing on the structural features of the example. However, B does not engage with Deonne's question about structure, instead challenging her with a question focused on the graphics on the surface of the frame, "shark, waves, bites thing." Deonne clarifies that she is not showing her the graphic design (line 19), but B does not respond to engage with Deonne's initial question.

B's question reframed Deonne's suggestion to the group and served to both position Deonne as an advocate of the "shark" design and, at the same time, to resist that design, in turn resisting Deonne's bid to participate more fully in the group's process. When B did not engage with the question about the project structure and light design, Deonne seemed to recognize an opportunity to play a role in the project - graphic designer, a role that fits a prior interest in drawing and fashion design. Deonne tentatively suggested an idea for the graphics, then qualified the suggestion by saying, "or I don't know" (line 20). This is the first of three bids to take responsibility for the graphic design of the frame (lines 20, 23, 26), each of these posed as a question and with increasing hesitancy. The first two bids are ignored and when at last B and Casey seem to grant Deonne responsibility, they have already dictated what the design will be (bubble letters) and proceed to regulate Deonne's process. Deonne accepts the responsibility, yet is still tentative, saying she "could try," with an implication and intonation that Casey or B could stop her.

Rather than being determined primarily by the nature of the material or conceptual problem they encountered, uncertainty in the group seen, marked (or not), and taken up (or not) depending on situation. In this episode, we see (1) how uncertainty about project dimensions is taken up differently at different times in project development, and for different participants, as well as (2) how uncertainty can be used as part of bids for responsibility or control over aspects of the project.

In the make club, a space with a high degree of student autonomy, resolution of uncertainty was often non-linear. The students in the Class Portrait group began without a clear, let alone shared, idea of what the Class Portrait would look like and how it would be constructed, and without sufficient experience with the systems (circuits, microprocessors, laser cut joinery) and tools (laser cutter, electronics tools, design software) their rough designs would rely on. As the group worked across the day, questions about lighting, portrait dimensions and graphics, and construction and logistics, electronics, and other issues, were raised. Yet these were often left unresolved as group members led discussion on tangents, got distracted, hit dead-ends due to lack of ideas or interest, or simply ignored or shut them down.

The uncertainties the group did address, and the subset they worked to resolve, determined to a large extent how they spent their time, the ideas with which they were engaged, and the positions they took. In the closing discussion, we consider four overlapping functions of uncertainty demonstrated in these cases: *establishing positions and purposes, pursuing areas or topics of interest, directing activity toward personal resources*, and *creating or limiting space for new perspectives*.

Establishing positions and purposes

Moments of uncertainty that arose in class portrait work played an important role in negotiating power and position in the group. Highlighting or downplaying uncertainty provided a means to establish authority, reinforce relationships, or attempt to establish oneself as a central participant. This could be seen in whether or not the participants introduced uncertainty when bringing ideas or concerns to the group, or making a bid for responsibility for a project feature. For example, Deonne, who was positioned as a technological novice and outsider throughout much of the group's activity, used questions and statements when bringing issues to the group. In contrast, Casey, who was positioned as a group leader, presented concerns and ideas about the projects – such as her idea for bubble letters – more often as statements.

Questions also allowed participants to check in with the group, to jumpstart activity when they were present. Because participants in the Class Portrait group sometimes wandered around, talked to friends, or worked on different aspects of the project, this happened frequently. These include questions like Isaiah's above, "What are the measurements of this box going to be?". These questions served to re-center activity around the speaker's perspective – the feature they thought most needed immediate attention – and to reconstitute the group in terms of who was within earshot and willing to reply. In addition to being used to rejoin activity (as Isaiah and Casey did with their questions), they could be used to pull others in, positioning them as important to group decision making.

Using uncertainty to re-center activity in this way was not always successful or empowering. Bids to enter or refocus activity with a question could be rejected. Here and across the project, when Deonne raised a question that could open a discussion in which she could participate as knowledgeable, or that might allow her to pursue an aspect of the project in which she had expertise, her questions were often ignored, refuted directly, or encountered scrutiny in ways that others' contributions did not (such as in B's focus on the "shark waves"). Across the day, these responses served to frame Deonne as an outsider, to both the social group and to a space of technological expertise and exploration.

Pursuing areas or topics of interest

Simply raising areas of uncertainty provided a way for participants to pursue areas of interest. Raising uncertainty about a particular feature exposed unfulfilled needs that then allowed participants to make bids for responsibility, often by framing their own expertise or, at minimum, interest and availability. Raising uncertainty seemed to be a way of reinforcing particular project features that aligned with personal interests, helping keep them in the foreground of design decisions and thereby to ensure that the features remained part of the eventual design. As we saw here and across our analysis of the project, a major focus of Deonne's questions were about engraving, decorating or other aesthetic aspects of the portrait – an area that in interviews she said she had experience in and wanted to learn more about. Other students displayed similar patterns, raising uncertainty in the areas of the project they knew most about and should have had the fewest questions.

Directing activity toward personal resources

Though the maker club was designed to encourage connections between the engineering, design and home- or community-based practices, this did not happen consistently across the project and across groups. In the group's interaction, however, we saw management of uncertainty play a role in students' work to bring outside resources – material, conceptual and cultural - to bear. Rather than build connections into a project from the beginning (as we had thought might happen), moments of uncertainty allowed group members to frame project priorities in ways that directed emergent solution paths toward toolsets with which they were familiar, and that allowed them to participate centrally and knowledgeably.

Creating or limiting space for new perspectives

In the group, we saw that when participants resurfaced issues of uncertainty they had previously let drop (or willfully shut down), the framing of these issues shifted. Though many times these shifts were subtle, shifting the frame in some way meant that different resources, constraints, and epistemologies could be brought to bear. Students might leave an issue unresolved – because of lack of understanding or lack of consensus – but re-engage the question when there had been a shift in context, due to changes like mentors or peers joining the group, questions getting posed in new ways or by mentors or friends, new materials being introduced. These shifts directed attention toward new information (or new attention to old information), made resources newly available, or shifted the basis on which the students evaluated ideas – and each other.

For example, Isaiah's question about portrait dimensions is one he had refused to answer early in the day, when Deonne first raised it. At that time, he made the claim that because they were prototyping, they did not need to answer it. Isaiah reintroduced the question for the group, only after he had a chance to explore the software he was interested in learning, and after the group had been told by a mentor that the limitations of the laser cutter would impact their design. Very little prototyping had been done, but the context for the question had changed: the portrait dimensions were no longer question of aesthetics, but a question with technical, structural implications and one that was necessary to answer in order for Isaiah's' work on digital design to continue.

Conclusion

We have examined how young people, starting from different places, navigate collaborative work in an engineering-oriented but student-driven space. We describe processes that are central to interest-driven learning, but we also shed light on how learning can break down and reinforce existing imbalances of social and academic power. As co-designers and educators in this setting, we set out with a goal to support a broad range of youth identities and to allow young people to bring in and build on areas of existing expertise, while layering on technical tools and connecting to design and engineering practices. We expected encountering uncertainty to be a central part of this process [12], as young people learned to deal with unexpected problems, navigate constraints on time, materials and expertise, take risks, and persist through failure [20], [21].

However, the way we saw uncertainty arise and get dealt with in the maker club defied our expectations, and to some extent, so did the result. We saw student repertoires and identities

surface in the maker club, but did not see them accessed and utilized in the same ways and to the same effect. Like Casey and Isaiah in the Class Portrait group, some young people in the club were able to use their projects to establish knowledgeable, connected positions and to pursue learning goals, like learning to design for a laser cutter and 3D printer, gaining experience with carpentry or sewing, or figuring out how to use a microcontroller and actuators. Though we heeded warnings about risks of collaborative work in project-based engineering contexts [3], others were not. The analysis helps us understand when and how these experiences differ and diverge.

Uncertainty appeared at the heart of nearly all salient moments we identified. These were moments at which the youth seemed to be doing important positional work – like bidding for a particular role in project work, a social connection, or asserting an identities and values connected to worlds outside the maker club – and conceptual work – like focusing attention on particular systems or features, directing an approach to their task.

In contrast to a view of uncertainty as "immediate and spontaneous," [9], we saw moments of uncertainty functioning like pivot points [22]. Uncertainty functioned in four key ways, allowing participants to: *establish positions and purposes* that could guide development of design decisions and roles; *pursue areas or topics of interest* by bidding for responsibility of particular project areas or focusing the group on issues relevant to learning goals; *directing activity toward personal resources*; and *creating or limiting space for new perspectives* by shutting down issues of uncertainty or picking them up as context shifted and new configurations of people, resources, or conceptual frames arose.

In open-ended, collaborative work, like much PBL, uncertainty can be pervasive and persistent and the fluidity of work in the maker club allowed for uncertain and yet-unplanned issues to be framed in multiple ways as they got introduced and reintroduced. Group members might close down discussion of an issue when raised by one member of the group, but pick it back up when a higher status member, or an adult mentor, raised the issue, adding weight to the issue and bringing to mind different potential connections and levels of emotional investment. Learners must tolerate much of this ambiguity and select what and when they call attention to uncertainty.

As such, moments of uncertainty are not just rich places to look for conceptual development and disciplinary practice, but are places of flux where young people have opportunity to push on what kinds of resources and knowledge are brought to bear. They can reshape the nature of a question socially but also technically, shifting what kinds of solutions seem reasonable, what tools are legitimate, what constraints are perceived and accepted. For some group members, we saw that opening and closing uncertainty could be a tool with which to patrol borders of the project and solidifying status as a leader or as knowledgeable. For others like Deonne who had a lower status position in the group and less assurance that her interests would be served within the group, over-performing uncertainty became a tool for entering discourse, one that recognized the authority of others and reflected that she did not have access to the overall project vision. Moments of uncertainty functioned conceptually to limit participation of Deonne by excluding ideas and setting the shared design space beyond her view or outside of her expertise. Socially, this served not only to position her as an outsider, but to create a feedback cycle in which she moved farther and farther from the meaningful work of making and engineering.

Though Deonne become increasingly marginalized from meaningful work on learning within the class portrait project, in looking across our observational data, we saw within club sessions she began to spend more time away from the group, instead developing small projects that lasted only a session or two, and interacting with mentors in the space. From her case, we learned to pay attention to these "side projects" as sites for important meaning and to look more closely at how questions reflect how a learner is evaluating her status in the space, as well as project [23]

Though we see ways of handling uncertainty as related to practices like troubleshooting, problem framing [20], and organizing a problem space or design space [15], they also involve the kinds of identification and navigation work that are necessary to taking up not just the skills of engineering, but the to joining a professional community of engineering [5]. We believe the analysis helps demonstrate ways in which these social and conceptual processes are inextricably intertwined, and we believe that addressing them as such is essential to supporting more diverse pathways into and through engineering disciplines.

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[i] Pseudonyms used for all research participants and sites