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Innovate to Mitigate: Microgenesis of student design and rationale in a crowdsourcing competition to mitigate global warming

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Abstract

The Innovate to Mitigate project adapts crowdsourcing to support project-based STEM education, posing design challenges for secondary-school students. Students are charged with designing feasible innovative strategies to mitigate CO_2 emissions and thus global warming. The paper draws on data from 3 project teams. The paper presents evidence that a web-mediated community of practice supports STEM learning of concepts and STEM practices and examines conditions under which the environment can enable an account of microgenesis of that learning.

Introduction

When science education relates to problems students see as relevant, their funds of knowledge and motivation can serve as resources for inquiry that both draws upon and increases students' 3-D learning (*sensu* NRC 2012). Climate change is increasingly seen to affect everyone's lives (Leiserowitz et al. 2021, Richels et al. 2020, NRC 2010, IPCC 2018), and many young people are eager to respond (e.g., Thunberg et al. 2020). Engaging the issue constructively ("active hope") can counteract the anxiety and depression such an overwhelming problem elicits (Hayes et al. 2018, APA 2009). The I2M project poses design challenges in climate change mitigation for middle- and high-school students. Our initial research suggests that an open but well-structured challenge to develop mitigation strategies can galvanize creativity and engagement among young people, and support 3-D learning (Puttick et al. 2017).

This paper presents evidence that crowdsourcing and community dialogue led to changes in students' design rationales and STEM knowledge during an Innovate to Mitigate (I2M) competition to address reduction of CO_2 emissions.

In the paper we address four research questions:

(i) What evidence is there that crowdsourcing led to changes in students' designs and rationales, generated during an I2M challenge? What kinds of changes are seen?

(ii) How are these changes related to students' use of ideas generated in dialogue?

(iii) To what extent does the composition of the community of practice contribute to the dialogue or to students' uptake of discussion inputs?

(iv) Finally, to what extent do the data allow investigation of microgenesis of students' design and rationales?

Theoretical framework

Crowdsourcing for STEM learning

Crowdsourcing and social media are increasingly common media for participation in society (Hossain & Kourainen 2015, Arelas & Ladrón-de-Guevara 2011). The crowdsourcing communities in I2M (students, teachers, scientists) are designed as learning environments in which students can iteratively improve design ideas and STEM knowledge. Such heterogenous communities of practice offer a diversity of inputs, including insights about practice from more experienced participants (Vygotsky 1978, Wenger 1998). Dialogic knowledge-construction is facilitated by the division of labor within the team (Puttick et al. 2017, Drayton & Puttick 2018).

Dialogue within the community of practice comprising all teams and mentors, scientists, and teachers, is central in our model. Students' use of ideas generated in dialogue can provide insight into students' reasoning and understanding of concepts and practices (Ketonen et al. 2020, Samarasekara et al. 2020, Anker-Hansen & Andrée 2019, Cheng & Tsai 2012). Other impacts may include growth in quality and depth of student argumentation, and in metacognitive effects such as students' capacity to evaluate their own reasoning and evidence (Anker-Hansen & Andrée 2019).

Argumentation, rationales, and rhetoric

Because student-driven projects are likely to address a broad diversity of subject matters, in this study we focus on the kind and structure of rationales that the students constructed in the course of the project and examine whether and in what ways dialogue with peers or adult experts might affect their argumentation. The NGSS, in advocating that students learn the science practices of argumentation and communication, several times suggest that students should learn to communicate and argue about information and findings "clearly and persuasively" (NRC 2012 pg. 53). Instantiations of such standards overwhelmingly construe "argument from evidence" in terms of question-claim-warrant-backing, or some variant of that, building both on the ideas of such philosophers as Stephen Toulmin, and on the vast literature on scientific reasoning in educational psychology and the learning sciences (McCarron 2021, González-Howard et al. 2018, Duschl & Osborne 2002). Other ways of thinking about scientific argumentation and communication are generally not discussed in the literature — two important ones being rhetoric and narrative. Both have prominent places in scientific discourse but little formal place in STEM education (Wickman 2012, Nielsen 2012, Wilson 2002).

Yet we conjecture that rhetoric and argumentation, as methods of socially situated sense-making, can serve pedagogically as pathways into effective, evidence-based reasoning about research design, data collection, and data interpretation, as students advocate for a solution to a problem, and then are challenged in dialogue to justify their claims, their methods, their theoretical framing, and their data. This is thus a socially situated construction process, in which the development and defense of a proposed design and its rationale are critiqued and developed in the dialogue, drawing on the variety of knowledge and expertise present in the community of practice.

A common "anatomy" of rhetoric, based in Aristotle's classic analysis (See http://humanities.byu.edu/rhetoric/silva.htm) distinguishes three general strategies: *logos* (arguments from reason), *pathos* (arguments appealing to emotion), and *ethos* (arguments establishing the authority or credibility of the speaker). Such a simple categorization of rhetorical strategies can provide a framework within which to identify instances of rhetorical argumentation.

Microgenesis

In Vygotsky's model of how people learn higher-order thinking skills (Wertsch 1985), the learning community plays an indispensable role: new skills and concepts emerge from social activity around problems that require such capacities before they are internalized by individuals. Thus, the acquisition of such higher-order thinking follows the familiar pattern in which *contextualized* understanding, a group property, is internalized by individuals participating in the learning group (scaffolded by more expert community members). When the new capacity is thus internalized, the individual can apply it in new contexts (*decontexualization*) — it thus becomes an individual property. When the individual, in a new social setting, applies the cognitive tool to a new problem, it is thus *recontextualized*, and the constraints offered by the new use add meaning to the cognitive tool, enriching the capacity of the group.

At each step along this process, individuals make progress by formulating provisional accounts, provisional models, of the concept or skill in question. These provisional models are typically incomplete and temporary, as continued thinking and activity within the learning community lead to their revision or replacement. As Kuhn (1995) commented, in a review of literature to date, "multiple strategies are present in an individual's repertory...Initial appearance of a new strategy...does not mark its consistent application. Instead, less adequate strategies continue to compete with it, and, indeed, the more formidable challenge appears to be abandonment of the old, rather than acquisition of the new... (Kuhn 1995, p. 133)."

Vygotsky called the history of these intermediate understandings "microgenesis," and saw that if one could record and analyze such learning events, they could provide valuable insights into learning processes and learning challenges (Chinn & Sherin 2014, John-Steiner & Mahn 1993, Vygotsky 1978). But it is evident that this research approach encounters important challenges in methodology. How to capture fleeting thoughts, half-formulated conceptions? The "think aloud" protocols, originating in the last century (Güss 2018) and used in a variety of fields since the 1980s, as for example in artificial intelligence or cognitive research (van Someren et al. 1994, Weir 1987), represent a kind of clinical interview designed to capture the flow of thought in the performace of a task, but they have primarily focused on a specific individual's thinking-while-doing.

Text-based exchanges such as occur in an on-line discussion forum have the potential to capture microgenetic data as they are generated within a community of practice, while preserving the individual voices of participants. They emerge from shared design work and discussion and debate about proposals and claims; they can occur at a suitably rapid rate to provide insight on the necessarily short-term and fine-grained developments by which intermediate formulations emerge, are evaluated, and either supplanted or refined (Siegler and Crowley 1991).

We have not found any evidence that such discussion forums have been used for an investigation of microgenesis to date. We conjecture that I2M, situating discourse in an active if short-lived community of practice where interaction is strongly incentivized, can provide evidence of the value of such environments for microgenetic studies. In this paper, we examine conditions under which the environment can enable an account of microgenesis of that learning.

Methods

Structure of the competition

Student teams submit the abstract for a proposed design based on a mitigation strategy such as energy conservation, alternative energy generation, agricultural methods, or social/behavioral change. Since abstracts scaffold the whole investigation, students are given a rubric of elements to address (Table 1).

Innovate to Mitigate Abstract Rubric

Student teams submit a brief statement (250 words) describing their idea(s) for how to reduce greenhouse gases. The statements are open for crowdsourced discussion on the Edmodo community learning site. Students use feedback from peers to revise and resubmit abstracts. Ideas presented in the abstract should be innovative (i.e., adapting an idea from someone else rather than just copying it).

An innovation can:

· Be an entirely new idea
· Build on an existing idea in new ways
· Use common materials in new ways.

The abstract should:

· Go beyond a generic statement such as “everyone needs to save energy” to present a specific idea that will become an investigation

· Clearly describe what is innovative · Include scientifically accurate information · Describe an investigation that is feasible to execute within the timeframe of the challenge.

Table 1. Abstract guidelines

Teams post their abstract to the project's EdModo page. All students can post questions and comments on each abstract. TERC scientists also post comments & questions. Teams have 2 weeks to use the comments received, and then post revised abstracts. The teams conduct their project over the next 3 months and produce a final paper and a short video presentation. When the final paper is submitted, it is posted to the EdModo page, where all the students participating in the competition can comment, as can the judges. Each team can reply to these comments or questions. In the judging for the competition, points are awarded for participation in the discussions in addition to points awarded for quality of submissions.

Participants

For this paper, we analyze the data generated by three I2M teams during the 2020-2021 competition: “LaGrazia” (four 8th graders), “Pedalpushers” (two high school students), and “Pranav No-Till” (one high school student working alone).

Data sources

The data in this case study include:

- The teams' initial abstracts
- All discussion posts from students and scientists for initial abstracts
- The revised abstracts
- Final papers
- All discussion posts from students and scientists for final papers.

Analysis

Units of analysis. In the abstracts and discussions, researchers coded each sentence. For the final research paper that each project had to submit along with their video, researchers coded each paragraph.

Coding. In developing codes (Table 2), we took a grounded approach (except see "Argumentation codes" below).

Code	Subcodes	Definition
Descriptive	School	Basic identifiers
	Grade	
	Team demographics	
	Teacher/mentor	
*Goal		Refers to intent or purpose of the proposed idea
*Design		Details about mechanism, process, or implementation
*Innovation		Claims about how innovative the proposal is, and what the innovation consists of.

*Advantages		Benefit forecast (e.g., ecological, social, economic)
*Scale		Refers to potential for scaling up the proposed idea
†Rationale	Authority	Explicitly cites an authority, whether teacher, text, article, Web, etc.
	Causal	Argument relies upon some explanatory theory or concept
	Empirical	Argument is based on empirical data, cited from authorities or students' own data
	Factual	Asserts the claim as fact without citation, reasoning, or data
Rhetorical		Aims to persuade, frame; engage reader; may include figurative or descriptive language, etc.
Other	Affective	Affective comments on proposal quality, e.g. "Great job!"
	Science content	Questions, or provides additional information about, science content
	Agreement/disagreement	Agrees or disagrees with claims being made

Table 2. Coding scheme. * indicates inductive codes. † indicates argumentation codes, adapted from Sandoval & Millwood (2005).

Inductive codes identified statements referring to or articulating the goal of the project, the ways it is innovative, technical/science content, design elements or strategies, scaling or broader use, and affective statements (Table 2).

Argumentation codes. Other codes were more specifically intended to capture students' rationale for their choices, and the kinds of statements that they used to make their case. We adapted a coding scheme from Sandoval & Millwood (2005) to characterize categories of argument in teams' rationales. In addition to these, we developed a "rhetorical" code to label statements that were judged to reach the reader's feelings or values, or to shape or direct attention to some specific aspect of the argument. (In relation to the classic *logos*-*ethos*-*pathos* framework alluded to above, our "rhetorical" code captures statements in the range of *pathos*-arguments appealing to emotion.) As we discuss in the Conclusions section, coding of individual statements (or even paragraphs) could not capture rhetorical structures or techniques at a larger scale than the unit of analysis. These structures are simply noted where they occur.

Data were consensus coded by three researchers. Coded data were discussed by researchers. After coding was stable, a researcher wrote an interpretive research narrative about each team. Narratives were discussed by the research team to test inferences, identify issues requiring further analysis, and maximize the value of the data (Merriam 1988). Finally, cases were compared to identify differences and similarities of interest in relation to the research questions, and to identify hypotheses and initial theories which can inform future research (Stake 1995).

Results and Discussion

Because the three teams varied in age, size, and constitution, we present the three cases sequentially in what follows. After these three treatments, we compare the results across the cases, identifying similarities and differences as they relate to the research questions.

1. The Pedalpushers

This team of two high-school students proposed a design to generate power from individual pedal-driven generators located in classrooms. This system would supply the electricity needed by the classroom, reducing energy use one classroom at a time, and therefore reduce CO_2 emissions.

<u>First abstract.</u> Pedalpushers' initial abstract described a *goal* ("generate clean electricity in a classroom setting"), and a proposed *mechanism* ("use a system of pedals to generate enough electricity to keep plant grow-lights running and other light sources in the classroom"). They claimed that their idea was *innovative* on two counts: the novel way of generating electricity, and targeting plant grow-lights. Only one statement was coded as *rationale* and it was *factual.* One statement was coded as *rhetorical.*

<u>Dialogue with other students.</u> Students from other teams made *factual* claims for potential benefits, but none adduced data to support their claims. One student named a potential benefit (for ADHD students). Another student asked about a technical detail (*design*). In response, the Pedalpushers articulated more constraints that they would incorporate into their *design*. They did not make appeals to an *authority* or make any *empirical* or *causal* claims other than that their design would reduce that locale's fossil-fuel energy demands.

<u>Scientist input</u>. The scientists' questions addressed methods for gathering evidence in reference to a *causal* model: about mitigation impacts, feasibility of the design, measuring energy output and CO2 savings (*empirical*), and scalability of the design. In effect, all the questions assumed that there was a *causal* rationale underlying the team's proposal and gave the team an opportunity to supply or surface more of that rationale.

<u>Second Abstract.</u> In response to the community comments, the Pedalpushers added to their rationale, connecting their idea to climate change and CO_2 mitigation (*causal*, 2 coded occurrences). Though they included two factual claims as part of their argument (2 coded occurrences) they also specified *empirical* evidence (4 coded occurrences) they would need to collect to test their claims and establish impact, promising to collect evidence on amount of energy collected, and how it is used. Furthermore, they also introduced a new *empirical* element: to make a quantitative comparison with their city's power use and its CO_2 emissions as a baseline to help estimate their innovation's impact on emissions. They also incorporated peer questions about design and introduced additional design elements. They achieved a clearer and more complete abstract, better positioning themselves to work out an implementation and testing plan.

<u>Final paper and discussion.</u> The Pedalpushers' final paper reflects the impact of the questions they were asked, and the resultant further R&D work they needed to undertake. They included more information deriveed from studies cited from the literature (*authority* 3 coded occurrences) about electricity generation by various means and estimates of potential power generation using their proposed design. The calculations enabled them to make some quantitative comparisons, in terms of rates of power generation, between their pedal-driven system and other green electricity sources (e.g. wind or solar power). These comparisons and the claims derived from them included causal claims, reflecting a more fully elaborated theoretical rationale (3 coded occurrences). A notable additional feature in this document is the increased use of *rhetorical*

methods, using repetition or iteration to frame the elements of their design and rationale to the overall *goal* of their proposed invention. They repeated the key values and advantages of the design, emphasizing potential scaling effects. They reiterated the relation of their design to the need to mitigate CO_2 emissions and invited the reader to imagine the system in operation, thus presenting a way of prototyping a future with their design present. They bookended their whole argument by pairing what we may call the proximal goal of their proposal in the context of a distal or overarching goal, mitigating global climate change.

A detailed analysis of the sequence and structure of the discourse shows a temporal development of this rationale, which was thus a collaborative achievement.

2. La Grazia

This was an 8th-grade team comprising 4 girls and 2 boys. Some of the team had participated in the previous year's competition. Their team project in both years was a prototype solar oven.

<u>First abstract.</u> Their abstract argued that reducing fossil-fuel use for cooking would reduce CO_2 emissions, with this *causal* argument: "Solar cooker can help with this problem because it doesn't use fossil fuels but uses the suns heat for energy." They briefly described the greenhouse effect (*science*). They suggested that solar cookers would be cheaper than conventional ovens, be compact, portable, and scalable; their one *empirical* statement mentioned the price of conventional ovens, in contrast to their prototypes which were made with recyclable materials. No authorities were cited, and no other data were adduced. Other *rationale* statements were consequently coded as *factual* (3 occurrences); there was one rhetorical statement noted, which invited the reader to imagine themselves weighing whether to try their innovation, as opposed to staying with conventional systems: "Instead of using an oven, which costs about 300-1,000 dollars (extremely expensive) you can choose to create a cheaper one that can heat up food through radiation."

<u>Dialogue with other students.</u> Student comments focused on design features — Did the team see their invention as a convenience for, e.g., camping trips, or as a replacement for conventional ovens? What about when sunshine was not available? Two mentioned batteries as supplemental power, not mentioned by the La Grazia team (and not compatible with their design). La Grazia did not respond to any of the student feedback.

<u>Scientist input.</u> One scientist commented, asking how the proposed design differed from their design from the previous year, and how their innovation might increase the impact on CO_2 emissions (*causal*). The scientist comments therefore addressed innovation, design, and the rationale for the project. In contrast to the team's non-response to student feedback, La Grazia did ask for clarification from the scientist about one comment about the innovative nature of that addressed innovation.

<u>Second Abstract.</u> In revising their abstract, LaGrazia did not address students' design questions. In response to the scientist's question about their innovation, they noted that they had to conduct their project from home (owing to pandemic restrictions) but did not note any changes in design. However, this change in method was not relevant to the question. They did add a new *rhetorical* element to their rationale, which was that presenting their project to the community could raise

awareness about climate change**.** Otherwise, all causal statements were *factual* (10 coded occurrences). The increased number of *factual* arguments (3 coded instances in the first abstract, 10 in the revised version), and a marked increase in the number of statements asserting advantages of their proposed system (5 in the first abstract, 9 in the revision) constituted a heigthened attention to the need to persuade. In this case, one may say that the team employed the rhetorical technique known as "accumulation."

Final paper and discussion. In their final paper, LaGrazia enriched their rationale by increasing the use of statements coded as *causal* (from 2 to 4) or *authority* (from 0 to 10), that is, adding backing to their claims from (a very few) published sources. They and also represented their rationale as drawing on a causal theory of the phenomena. Moreover, they reported data from a series of *empirical* trials of two different instantiations of their solar cooker design (6 coded occurrences). In this case, the required separation of the students from each other had the benefit of making replication and comparison possible. Because there were several uncontrolled variables in their comparisons, their data were inconclusive. Nevertheless, all data were reported, and discrepancies were identifiable from their account. Thus, the proportion of rationale elements coded as *empirical*, *causal,* and *authority* increased dramatically. Moreover, the number of data items coded as *rhetorical* also increased slightly (3 instances).

The team's attention to *empirical* and *causal* rationale elements continued through the discussion on-line of final products The changes were noted by the judges. For example, one judge commented "I liked that you cited several references and provided the bibliography, and that you stated hypotheses for your proposed innovation of the solar cooker design." Judges and other participants continued to note open questions or unsolved problems, and the team responded directly and appropriately. They introduced another thematic strand at one point when they discussed the possible uses at scale of solar cookers (not necessarily involving their own particular design).

3. Pranav No-Till

This "team" comprised a solo high school student in his senior year. He proposed a design for working with farmers to reduce emissions through a dual strategy of education about no-till agriculture coupled with a shift to renewable energy, and payment with carbon credits for the resultant carbon sequestrations and reductions in emissions.

First abstract. The initial abstract described a goal ("to motivate farmers to practice sustainable farming practices" by "incentivizing no-till agriculture and on-farm renewable energy sources with carbon credits"). The student proposed a mechanism ("farmers that practice no-till agriculture and shift their energy sources from fossil fuels to renewables can earn money for storing carbon and reducing emissions") and provided a rationale that was *causal* (e.g., "Paying farmers to deliberately shift to renewable energy sources, along with no-till agriculture (a concept that has been used in the past), can lower greenhouse gas emissions"). By stating that no-till agriculture has been used in the past, it is implied that his idea is a novel adaptation of an existing mitigation strategy. The rationale in this abstract was logically tight, with 3 *causal* statements, 4 *factual* statements, and 1 *empirical* statement, and 4 *advantages* postulated.

Dialogue with other students. One student from other teams posted a response to No-Till's first abstract (but see Second Abstract, below). The proposal focused on Florida only, and the student queried why this was the case. No-Till did not respond to this query.

Scientist input. One scientist asked, "What is the innovation in your plan?" thus requesting a response to an explicit requirement described in the rubric (Table 1). Another question focused on a detail of design while the third asked how no-till methods reduce emissions. In effect, this question asked the student to make the mechanism in his idea explicit and thus provide a *causa*l rationale for his proposal.

Second Abstract. In the revised abstract, the main improvement the student made was to describe how he thought his idea was innovative: Although carbon credits and no-till agriculture are not new ideas for carbon mitigation, combining them is. He also incorporated a more specific statement than in the first abstract about the particular crops that could be targeted. Finally, in response to the scientist's question, he stated that no-till farming "works because it leads to carbon being stored underground, not emitted," offering a partial *causa*l element for this rationale. He also added a few more *empirical* statements (1 in the first abstract, 4 in the second). In all other respects his abstract was unchanged. The rest of his rationale included the same number of *factual* claims (4).

At this point, another peer commented on the second abstract, asking two questions crucial to the potential impact of his proposal: "How will you release your information to farmers, and will it cost anything to them?" Pranav responded with a strategy for dissemination, acknowledged the initial cost to farmers, and included a *factual* claim that his strategy would benefit farmers later. As with the other two cases in this study, analysis of the sequence and structure of the discourse shows a small collaborative improvement in the specificity of the ideas in his proposal at this stage of the competition.

Final paper and discussion. Pranav No-till's final paper reflected the discourse about his abstract. In elaborating on points raised in the discussion, as well as reporting on the completed project, the author deployed a coherent rhetorical strategy in the composition. The elements in this strategy include:

a. Rationale elements. The paper shows a consistent deployment of authority (coded in every paragraph), along with causal or empirical elements. Every paragraph includes rationale elements of various kinds: 5 instances of factual assertions, 4 empirical statements, 5 causal statements, and 18 citations of authorities.
b. Goal or design elements. The overall aim of the design is reiterated frequently in conjunction with elements of rationale (the code was used in 6 of the 9 paragraphs)
c. Innovation, advantage, scaling. The potential contribution in CO_2 mitigation of a widespread adoption of no-till agriculture are reiterated in every paragraph, either explicitly connected with rationale or goal/design elements, or juxtaposed.
d. Rhetorical. Rhetorical elements (4 instances in 9 paragraphs) introduced affective notes (e.g., "no-till agriculture is "environmentally friendly, and economical for farmers, too."), or motivational/moral notes (e.g., "We still have a long way to go") that introduced the final paragraph of the "conclusions" section. Moreover, the argument iterates the "goal/design/rationale/benefits/rhetorical" elements. This repetitive, one might say rhythmical, use was itself an effective rhetorical performance in posing a problem and

advocating for a potential, innovative solution. This had an affective impact, increasing the sense of cogency bolstered by empirical evidence.

Conclusions

(i) What evidence is there that crowdsourcing led to changes in students' designs and rationales, generated during an I2M challenge? What kinds of changes are seen?

The three cases described above show several shifts in students' designs and rationales. In each case, there were increases in *rationale* statements. *Empirical*, *causal*, and *authority* statements are more salient in the final papers, and in the case of the Pedalpushers and Pranav No-Till, they became more important in the second abstract, even before the paper was written.

As we laid out in the theoretical framework, students' use of ideas generated in dialogue has been shown to support students' reasoning, understanding of concepts and practices (Ketonen et al. 2020, Samarasekara et al. 2020, Cheng & Tsai 2012), growth in quality and depth of student argumentation, and students' capacity to evaluate their own reasoning (Anker-Hansen & Andrée 2019). However, La Grazia showed little change in regard to *empirical*, *causal*, and *authority* statements in their second abstract, but in fact they dramatically increased their use of factual rationales at that point. They increased their use of *authority* rationales in their final paper, but their sources were relatively few. The Pedalpushers increased the use of empirical rationale statements in both their second abstract and their final paper, but many of these were statements of what kinds of data would be collected in a full development project.

All teams also showed increases in their uses of *advantages* and a small increase in *rhetorical* elements. While these do not fit into the *claim-evidence* version of scientific argumentation favored in the NGSS, such statements are in fact very much a part of scientific writing and argumentation. Such argumentation often includes attention to methods of persuasion (Wander & Jaehne 2002) and "informal argumentation" (Cecarelli 2001) to build a case, since they frame the researcher's results in a way to increase the likelihood of impact (while still maintaining integrity).

In this small data set, therefore, we see evidence that tends to support our conjecture that the teams' need to make their presentations as persuasive as possible (in the context of the I2M competition) motivated the refinement of "everyday arguments" (McCarron 2021) with attention to appeals to logic (especially *empirical, causal,* and *factual* statements), to authority (*authority*), to imagination (*advantages),* and to esthetic/moral/affective ideas and images. Thus the "rhetorical triad" of *logos*, *ethos,* and *pathos* are deployed in the construction of the teams' arguments. It is important to note, however, that in all cases the students did not only rely upon more impassioned or imaginative appeals to their audience but saw the need to adduce improvements in empirical or theoretical arguments, as is foundational to scientific argumentation.

(ii) How are these changes related to students' use of ideas generated in dialogue? (iii) To what extent does the composition of the community of practice contribute to the dialogue contents or to students' uptake of these inputs?

As the analysis in the previous paragraphs shows, one can be reasonably confident that the community's comments stimulated the teams' attention to details of their design, and especially to their rationales. Students asked questions primarily about details of design, implementation, and impact, and about proposed or suggested advantages. In response, the teams produced answers acknowledging the question or suggestion, and evaluating, accepting, or refuting the points made. The revised abstracts reflected these exchanges, and in most cases material from the dialogues appears in the final papers as well.

The scientists asked questions that were complementary to student questions. Scientists sought clarification in *causal* rationale, both about the elements of the design, and its connection to the mitigation of carbon emissions. Scientists also probed for empirical evidence about the designs and arguments for innovativeness. Again, the teams acknowledged the points made, and adjusted their arguments and reports, and this is reflected in the increase of *empirical*, *authority*, *causal*, and *factual* statements. In several cases, responding to these questions required additional research or re-design.

Taken together, the community input had a significant impact on the way the teams thought about most aspects of their designs and rationales in Vygotskian fashion (Wertsch 1985), and the diversity of the community composition made an important contribution. The scientists' emphasis on causal and empirical rationale elements, in contrast to students' main focus on design, is evident. But other differences came into play— most striking, when a student raised the possibility that the Pedalpushers' design might benefit kids with ADHD. Diversity in a community benefits science and engineering because it brings richness of experience and attention as well as richness in expertise or other kinds of knowledge.

It may be of interest to note here that in post-competition conversations, student participants noted that the responsibility to ask questions and critique other teams' proposals stimulated them to learn about the other proposals (content, design, and methodologies), but reflexively affected their critique of their own proposal. This reflexive dynamic has been noted in studies of communities of practice of other kinds (Newman et al. 1989, Wenger 1998, Palincsar and Brown 1984).

(iv) Finally, to what extent do the data allow investigation of microgenesis of students' design and rationales?

This question is in a way a paraphrase of a methological one: Can an environment such as I2M be used as a tool for microgenetic studies of students' learning of such higher-order skills as argumentation?

The narratives presented show successive stages in the development of the designs and rationales, but at the same time, they represent evidence of growth in students' understanding of the processes of design and argumentation. Stimulation by the community of practice to elaborate different kinds of rationale, for example, appeared to result in arguments that were more coherent, and logically and conceptually consistent. Moreover, the student teams strengthened their rhetoric by incorporating affective and aspirational elements, and by arranging their arguments to keep the goals and potential advantages of their approach before their audience (including peers as well as judges for the competition).

Given the small corpus of data, we can claim no more than suggestive evidence about the usefulness of such a medium for microgenetic studies of student understanding of argumentation and design. However, the environment has some important advantages in this regard. First, the overall goal is clear since it is set by the competition structure. Within the general aim of mitigation, the students choose for themselves a particular way of responding to the challenge, and from the beginning are required to articulate and negotiate their ideas in a social setting. Second, the conceptual field is rich — there's a lot to talk about, a lot of information to make use of, a lot of scope for experimentation and for the adducing of new questions or new mediational means to move the investigations and discussions forward. Third, the medium makes visible much of the social environment — the discourse community— within which the students' thinking takes place and develops, and because it is in written form it is available both to the participants and to researchers for a period of weeks or months, thus facilitating reflection and research. These advantages can be seen in the cases we have presented.

The I2M environment, however, does have some drawbacks as a medium for microgenetic studies. Most important, perhaps, is the density of communication, essential for the tracing of ephemeral intermediate formulations of concepts (Siegler and Crowley 1991). The schedule of the competition requires students to share and discuss their work only a few times over the course of the 8 months of the competition. Between these defined events, there is naturally a large volume of communications, especially within teams, which is not recorded in the I2M environment. Students use face to face meetings, telephone calls, and text messages day to day, and even when some of these streams are captured for analysis, they tend to be fragmentary. The project also requires several kinds of interim reports, and also requests permission to use student notebooks or other documentation, as well as conversations and occasional classroom observation. Such material can be rich enough to allow investigation into student learning from various points of view (e.g., Drayton and Puttick 2018), but do not provide good data for microgenetic studies.

We suggest, however, that it will be possible in future to co-design a study with one or two teams to address the issues of density and inaccessible data, both by carefully specifying the learning to be tracked, and by establishing clear protocols (and encouragement) to ensure reporting that is frequent enough, and simple enough from the user's point of view that compliance will be as little burdensome as possible.

Such an effort would be valuable if successful, since it would enable researchers to track the interplay of student thinking (externalized in documents and designs), peer interaction, and development of understanding in the context of a student-chosen task requiring factual, conceptual, and instrumental learning, and its representation in narrative and in argument. A further benefit would then be the use of such media for microgenetic studies of other learning communities, for learners and practitioners of all ages, in the many subject domains now using Internet tools for their collaborations.

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