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Original Paper

Innovate to Mitigate: Learning as Activity in a Team of High School Students Addressing a Climate Mitigation Challenge

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Abstract

The Innovate to Mitigate project designed and conducted a competition for students aged 13-18 to propose and test strategies for mitigating rising levels of greenhouse gases. This paper explores the scientific inquiry and interdisciplinary learning of a 12th grade high school team over 6 months of participation. We used an activity-theoretic approach as a framework for capturing and analyzing the structure of the learning system in the team, situated within a science competition. This approach provided a lens both for finding and analyzing team learning at several levels—conceptual, procedural, metacognitive—and for revealing the processes by which learning was mediated by the activity system.

Keywords

environmental education, crowd-sourcing, activity theory

1. Introduction

Amateur scientists and volunteer enthusiasts recruited from the "crowd" online expend many person-hours of careful, engaged attention and creativity across a wide range of scientific and design projects. In such projects, they may engage in tasks such as solving protein structures or classifying galaxy types (Howe, 2008). Commercial enterprises are increasingly inviting such "solvers" in complex scientific problem-solving, with good results at very low cost (Howe, 2008; Surowiecki, 2005; InnoCentive, 2011). Some solvers are motivated to participate by monetary prizes; others wish to create something of value for the community and exercise a skill at which they excel. Others are just captivated by the problem itself (Lakhani et al., 2007). Young people are known to have participated in commercial scientific challenges posed by Inno Centive (Weisman, personal communication). Yet little is known about what, if anything, these young people have learned as a result of their participation.

We created a challenge that we called "Innovate to Mitigate", inviting teams of students, supported by mentors with scientific expertise, to propose and design projects to mitigate rising levels of greenhouse gases in the atmosphere. The challenge was designed to "foster knowledge through creative production" (Squire, 2008) in a context in which participants exert control over and ownership of the learning process, and retain or develop a strong sense of agency (Gee, 2011). One of the questions motivating this experiment was, can a crowd sourced experience in this context result in substantive STEM learning, both in terms of concepts and of practices?

We report elsewhere (Puttick et al., 2017) on measures of student learning about key aspects of science related to mitigation and climate change, and of student attitudes and dispositions towards science and their own capabilities. In this paper, we report on a case study that investigates the learning of many kinds enabled by the Innovate to Mitigate challenge, and reflect on the value of analyzing participation in such an experience from the point of view of activity theory.

1.1 The Problem: What Pre-and Post-Tests Don't Capture

Typically, studies of student learning will focus on a concept, skill, or body of knowledge that is taken as the learning focus. The study will then examine the efficacy of a curriculum, a pedagogical innovation, or a specific change in the learning environment (e.g., the use of a new technology) in improving student learning, using carefully designed assessment tools (NRC, 2001). During the recurring periods in educational history in which opinion favors student inquiry and the experience of "doing what scientists do", assessment methods include performance assessments, portfolios, or mixed-methods of various kinds. In such cases, however, the needs of the system for comparability and reliability of student "scores" (whether on fixed- or open-response measures) dictate that some control be established—of the task, the methods or processes to be used.

In a crowd sourced challenge like that of Innovate to Mitigate, however, the participant-learner has considerable freedom and (from the researcher's point of view) unpredictability with regard to what learning is possible and indeed necessary to the enterprise. The subject matter will be determined as the project unfolds, and the opportunity for learning will be shaped (and limited) by the resources discovered by the team or its advisors—and the usability (or not) of those resources. For example, some research articles may have relevant information or guidance for the team, but be couched in such technical terms or require prior knowledge, that the students cannot acquire in time, either because of their advanced nature, or the time limits of the competition.

Furthermore, the open nature of the challenge means that the purpose of the project, and therefore the means to accomplish that purpose, will require re-evaluation, debate, and revision on the part of the learner. Finally, participation in such a project is inherently a collaborative endeavor. In fact, the collaboration itself—the roles and contributions of the various participants, what they know and can do, and what they learn—will be subject to change and negotiation, and can have an impact on the content and quality of the work and its outcomes. All these elements, indeed, are characteristic of science, engineering, and design practice, and contribute to innovation in the face of ill-defined, or even "wicked" problems such as the mitigation of CO2 emissions, or the effects and size of climate change

(Dillon et al., 2016; Rittel & Webber, 1973).

1.2 Research Questions

In this study, we seek to understand (i) Who is learning in this open-ended STEM challenge? (ii) How do they learn? and (iii) What do they learn?

We conjecture that "activity theory", an approach with roots in both American Pragmatism and Vygotskyan psychology, can provide an analytical framework rich enough to address these questions.

2. Theoretical Framework

2.1 Science Learning through the Innovate to Mitigate Challenge

We hypothesized that the "previously unexploited collective intelligence" (Bull et al., 2008) of young people would be engaged, since the challenge was design to include many features of learning environments that have been found to be effective and engaging. These include: engagement with a real world problem (Falk et al., 2010), involvement in an engineering design process that makes authentic practices accessible to learners (Edelson & Reiser, 2006), learning in depth (Roth & Lee, 2003), communicating science findings (Passmore & Stewart, 2002), sustained engagement in "knowledge-building communities" (Scardamalia, 2003), project-based learning (e.g., Barron et al., 1998; Krajcik & Blumenfeld, 2006), and an emphasis on production that leads to higher-order thinking skills (Gee, 2011).

The project framework for scientific inquiry strongly overlaps with situated learning theories such as communities of practice (Lave & Wenger, 1991) and distributed cognition (Salomon, 1993). In such environments, participants' learning is emergent rather than prescribed (Jenkins, 2006). Yet much of the research on "project-based learning" is in the context of specific learning objectives, aligned with curriculum standards or other frameworks. Studies therefore often examine the learning in the context of scaffolded learning settings (e.g., Wirkala & Kuhn, 2011), in which there are several "voices" of agency at work—the students' being supported (and bounded) by those of the teacher and the curriculum, as well as the actual material of the project being conducted. This is understandable, since science educators for decades have seen project-based learning in terms of its effectiveness in achieving measurable aims (DeBoer, 1991), whether with regard to student motivation or metacognition, their understanding of science as practiced, or their understanding of specific content or skills.

The Innovate to Mitigate project sought in part to explore how the challenge could facilitate each of these kinds of learning. Indeed, as shown elsewhere (Puttick et al., 2017), students participating in the challenge reported significant increases in their knowledge about climate change and mitigation strategies. Almost three-quarters of the students (72%) reported that they understood more about the nature of science as a result of participation. They also were aware of other kinds of learning related to the practice of science in a project setting, such as collaboration, time management, and building on prior knowledge. Other areas of growth included constructing evidence-based arguments, reading primary scientific literature, and communicating research.

Beyond this, however, we were interested in the ways in which the process of participating as teams in a very open challenge, with access to mentoring upon request, and culminating in a prototype mitigation technique, could facilitate science learning.

2.2 Crowd Sourcing and Education

Crowd sourcing in its present form has grown up with the Internet, which has greatly facilitated the sharing of interesting problems, and the discussions and debates that can lead to solutions. Of course, the exploitation of distributed knowledge has been a part of scientific practice for centuries. International networks of amateurs and specialists have served many kinds of biology, earth science, and astronomy, and some scientists have been especially strategic in this regard—Darwin's practice being a celebrated case in point (Browne, 2002; Mahmoud et al., 2012).

Naturally, many different definitions of crowd sourcing have arisen. A careful study of many of these (Estellés-Arolasand & González-Ladrón-de-Guevara, 2012) has produced a "common denominator" definition which conveys several key elements that have promise for science education: "Crowdsourcing is a type of participative online activity in which an individual, an institution, a non-profit organization, or company proposes to a group of individuals of varying knowledge, heterogeneity, and number, via a flexible open call, the voluntary undertaking of a task. The undertaking of the task, of variable complexity and modularity, and in which the crowd should participate bringing their work, money, and knowledge and/or experience, always entails mutual benefit".

"Innovate" sought to take advantage of several of these characteristics. Each entry into the competition was by a team of high school students, and these were constituted by the students themselves, based on shared interest and friendship or at least mutual compatibility. Yet even these self-constituted teams were heterogeneous in terms of skills and interests. The heterogeneity of the teams was extended, again by design, with the inclusion of mentors and advisors with specific expertise in relevant science. The heterogeneous character of crowd sourcing comports well with Vygotsky's understanding of the social role in learning, in which a more adept or knowledgeable member of the group facilitates learning, especially the higher order learning in which semiotic tools such as theories, investigative processes, and so forth are developed and used to mediate purposeful action (Wertsch, 1985; Vygotsky, 1978).

The project's "flexible, open call" for voluntary participation elicited the design and implementation of a project from student teams. This required teams to formulate a research question, and develop a methodology and procedures for data analysis and critique with respect to the project outcome (Baron et al., 1998). Unlike project-based or (project-oriented) curriculum, the learning in this kind of an open challenge quite possibly requires iterative question-framing, methodology, data collection, and interpretation on the basis of experience. Indeed, this iterative process is part of the crowd sourcing process. As a result, learning may take place at many points in the process, and will require the whole team to be learning from its experience, as well as input/learning from individual members (or the mentors/advisors as well). We have used activity theory as a way to study learning in an Innovate to Mitigate team because of this dynamic, collective/distributed engagement with an open question for the purposes of accomplishing a partially defined outcome.

2.3 Activity Theory

Theories of learning can be distinguished by the units of analysis chosen by their adherents (Vygotsky, 1987; Wertsch, 1985; Zinchenko, 1985). For example, Vygotsky suggests that the ideal unit of analysis should preserve in a microcosm "as many dimensions of the general phenomenon under consideration as possible, thereby allowing one to move from one dimension to another without losing sight of how they fit together into a more complex whole" (1987, p. 211). As Rogoff notes: "In attempting to take account of the social setting in which learning takes place, the basic unit of analysis is no longer (the properties of) the individual but the (processes of the) sociocultural activity" (1990, p. 14). Since much of activity theory has been developed in rendering an account of work-place cognition (e.g., Engeström, 1999, 2001; Engeström & Middleton, 1998; Zinchenko, 1985; Scribner, 1997), it seems natural to frame team-executed projects such as those in Innovate to Mitigate in similar terms. What is not typical is to use that framing to address the challenge of studying student learning in such a project, as we attempt here.

In activity theory, the unit of analysis is the *activity* (Greeno, 2006; Greeno & Engeström, 2014; Weir & Drayton, unpubl. ms.; Nardi, 1991; Zinchenko, 1985), which can be elaborated as a system comprising (at a schematic level) just a few interacting elements, though analysis will elaborate this simple picture as necessary to describe elements and processes involved. An *activity system* consists, therefore, of a *subject* (the actor, which may be one or more persons), an *object*(ive), which is the ultimate purpose the system is to accomplish, and the *tools* (conceptual and material) which mediate the subject's work towards the objective.

In order to capture more of the elements of an activity system in, say, a workplace, Engeström elaborated on the basic "mediation triangle", consisting of "subject-mediating tools-objective", by making explicit the community setting of work as the context in which the subject engages in the activity (Engeström & Middleton, 1998) (Figure 1).

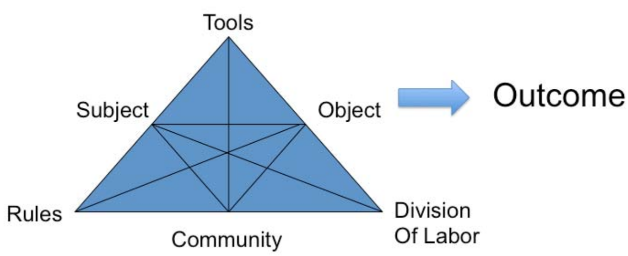

Figure 1. Mediation Triangle (Engeström, 1999)

The activity is shaped by its community context, which influences actions by means of rules and structures, and by the nature of roles and division of labor within the community. The nature of the community may shape, limit, or otherwise influence the kinds of mediational means used, and also the kinds of objects that can be conceived of or undertaken. Furthermore, the community itself is an object that subjects act upon. The community is thus shaped or refined, depending on how it is understood by different participants in particular ways.

Actions have clear points of beginning and termination and relatively short lives. *Activitysystems* evolve through long historical cycles in which clear beginnings and ends are difficult to determine. An activity system constantly generates actions through which the object of the activity is enacted and reconstructed in specific forms and contents—but being a horizon, the object is never fully reached or conquered (Engeström, 1999, p. 381).

Indeed, all elements in the system are in dynamic relationship, and even tension, so that, for example, as the members of the community change, or develop new tools for their work, the division of labor may change. This in turn makes possible (or requires) changes or additions to the repertoire of actions that constitute the continued activity. Even, or perhaps especially, the object(ive) itself may be reshaped as the subject and its community learn or change (Engeström, 2004).

The object of the activity which student teams undertook in initially accepting the Innovate to Mitigate challenge was the production and submission of a video and poster. Subjects (student teams+others) engaged in actions to address this object, their activity mediated by tools or other means, to accomplish their goal and outcome. The following account of one team's learning may constitute a "proof of concept" of this approach to identifying and analyzing the learning that takes place in an unconventional, collaborative learning configuration.

2.4 Research Questions Restated

With this theoretical background, we can restate our research questions more fully in terms of the key components of the "mediation triangle", as follows:

The subject: Who is learning in this open-ended STEM challenge?

The object/outcome: How does the team describe its research goals? How do they change? What do they learn?

Tools: How do they learn? What artifacts, tools, methods are used, how, and at what stages? What do they learn in this connection?

Rules: How do they learn? Who maintains timelines, and monitors progress? Who calls for evaluation of progress? Is this explicit? What do they learn in this connection?

Division of labor, community: How do they learn? What people constitute the team? What is their perceived expertise? Who accomplishes the work? What do they learn in this connection?

3. Methods and Data Sources

3.1 Participants

The Intelligent Life-Forms (ILF) team included 4 12th grade students, Ricardo, Safran, Casper, and Kenzhi at a public school near a large city in the Northeast. They were mentored by their chemistry teacher, Mr. Bowman, and advised by Mr. Schuyle, a research chemist. They participated in the competition from September 2014-March 2015, but began work on their project in summer 2014. Therefore, their work on the project extended over about 9 months. The documentation does not permit a definite estimate of actual time spent on this ambitious project by the ILF members, but from September 2014 through February 2015, after-school meetings were not more frequent than weekly, and probably less so, thus approx. 16-20 meetings of various lengths, but probably never longer than 2 hours. Participants and teachers are given pseudonyms to protect their identity.

3.2 Data Sources

We drew on several data sources for the study:

a. Competition documents (generated by the students). These included (i) an application form, (ii) a project abstract form, in which the team declared the mitigation strategy they intended to take, and their first formulation of their project; (iii) progress reports; (iv) abstract for their entry into the video hall competition; (v) survey responses, and (vi) the video they finally produced (http://innovatepilot.videohall.com/presentations/455).

b. Team process documents, including: (i) internal notes and other resources posted in a shared Google docs space, including exchanges with mentors, video footage from field experiments, team lab notes; (ii) emails from team members or the teacher sponsor with TERC staff; and (iii) team responses in the video hall to judge's queries.

c. Interview and focus groups and related researcher notes, including (i) an interview with the teacher sponsor, (ii) a focus group interview with students, and (iii) TERC researcher notes on observations and interactions with the team (e.g., in connection with a visit to the team's school to discuss progress).

3.3 Analysis

A chronological catalogue of all items of data was created, including research papers or other references used by the team. Two researchers examined all data sources, identifying an initial set of themes emerging from the data relating to the structure and development of the team's understanding of its purposes and resources. Initial categories were derived from the major elements in the system, e.g., types of resources available, people and roles, constraints provided by the task (Engeström & Middleton, 1998). Since moves to "higher" cognitive functioning are often triggered or facilitated by the introduction of new mediational means in a social learning process (Vygotsky, 1978; Wertsch, 1985), we paid particular attention to transitions in teams' work when they appropriated new tools, ways of talking, or other resources. At the same time, we looked for new patterns as they emerged (Creswell, 2009). We characterized changing patterns in the dynamics of the system over time so that we could track how emerging learning was shaped by interactions among individuals, group, tools and mediating interventions that others made. An initial narrative of the project's history was created, in terms of the elements in the activity system at each of several stages of project development, and then the researchers critically examined and revised the narrative in the light of each data item. Some points of uncertainty were resolved by queries to the ILF sponsoring teacher. Iterative confrontation of narrative with data continued until the narrative stabilized, with each assertion in the account warranted by the data.

4. Results

4.1 Learning As the Object of Activity is Identified and Transformed

The "object" of this team's work went through several transformations, discussed below:

Object 1. Choosing a strategy.

Object 2. Choosing a method with which to implement their strategy.

Object 3. Learning how to infuse CO2 into water, and measure it.

Object 4: Creating and presenting a video and report.

In consequence of each of these changes, the tools, rules, and division of labor were adjusted. The knowledge base from which the team worked was their high school chemistry course, but in order to move towards their goal, they became aware of what they did not know (both in regard to science content and to tools and techniques), and undertook a sequence of inquiries to address the questions raised. To get at what they needed to know, they relied on the expertise of their teacher and advisor to contextualize the ideas they were following, and the techniques and scientific theory they might need. In this work, therefore, as the objective changed, there were changes in domain knowledge, in the instruments/tools they found necessary, and in the division of labor amongst the team-members.

4.1.1 Object 1: Choosing a Strategy

The team's choice of a project focus established the possible content of their project, and the possible "practices" to be learned and employed. At this point in the development of the project, the product or learning outcome is the project topic itself. The knowledge required here is already rich:

a. The students must understand what mitigation is, which means understanding (i) that climate change is occurring, (ii) that anthropogenic CO2 emissions are a critical factor, and that (iii) actions can be taken to reduce these emissions (either reducing emission rate or removing CO2 from the atmosphere);

b. The students must learn the main strategies for carbon mitigation, to the extent that they can make a choice about which strategy they will adopt for their project;

c. They need to learn what tactics or methods for implementing their strategy are, and then

d. Learn enough about these methods to identify which are (to a first approximation) possible for them to attempt, and then to decide amongst them.

Many details of the team's learning activities at this point were not captured. One note from a team member (Ricardo) to the rest of the team suggests that a lot of Web searching was going on, to find resources to place the project into context:

If anyone would like to get a bit more out of the project and see some of the science that goes into tackling climate change I would recommend signing up for an account on this website coursera.org (totally free) and watching some video lectures (totally free) from this class: https://class.coursera.org/globalwarming-002. Week 8 in particular covers mitigation. None of the work is mandatory, and paying is optional. There are many other courses on the site worth taking a look at.CO2 and water: http://aquaticconcepts.thekrib.com/CO2/CO2_faq.htm

CO2 Injection: http://www.aquariumadvice.com/beginners-guide-to-CO2-injection-in-the-planted-tank/

In an email to a project researcher, Mr. Bowman wrote that the team had settled on carbon-capture and sequestration as their project for Innovate to Mitigate. The learning associated with this "object" was as expected: the students were learning about mitigation strategies, and the kinds of science that each might require. During this time, they were also increasing their understanding of climate change, the role of CO2 emissions, and specific predictions of consequences or feedbacks between biotic and abiotic components of the climate system. As a result, the team identified a mitigation strategy (carbon capture and sequestration) and thus the object of their work was altered.

4.1.2 Object 2: Choosing a Method with Which to Implement Their Strategy

As ILF defined their interest enough to join the competition part of the project, their choice of capture-and-sequestration then narrowed their focus to the point that they could ask the next round of questions, and decide which systems to explore, for which solutions to the challenge. Starting in Sept. 2014, they identified marine algae as a tractable system to work with experimentally: there was the possibility of working with it in the lab, there were ways to estimate biomass or other parameters from water samples, and it appears from their videos of field trips that the setting (seashore) was attractive.

At this point, the human resources represented on their team drove the next phase of their work: Their chemist-advisor challenged them to think about the whole process of carbon-capture and sequestration by understanding some basic science relevant to the problem. It could be said that Schuyle, the practicing scientist, guided the students to an approach which both engaged them with the basic science, and also introduced the problem or topic of measurement: How to tell how much CO2 has been taken up, what units of measure are relevant, what methods are possible for them, and what chemical procedures are involved in these measurements.

They decided to create some experiments to compare rates of CO2 capture by plants in some tractable natural system, with rates achieved by artificial means. One artificial method for CO2 capture used in various experiments with biological systems is "scrubbing" with Ascarite®, a compound that adsorbs CO2. This decision in turn facilitated the collection of more specific resources in the form of research papers and other references.

As they began assembling resources to understand the chemistry relevant to their project, they organized a work area for themselves on-line, using Google Docs, and one of the team designed a plan for tracking workflow, so as to coordinate efforts:

Summary 1 (Meeting 6/26)-Ricardo

We were able to meet each other and discuss our intentions for the future regarding how work would get done. We talked about and outlined the goals for the competition and identified probable approaches at modelling a solution to the carbon dioxide sequestration challenge. Schuyle suggested we take a look at the chemical Ascarite and its abilities to absorb carbon dioxide gas. He presented the idea that we compare the effects of natural carbon dioxide capture by use of plants with that of the Ascarite. We agreed that after having read through a packet on the various possible forms of carbon dioxide capture, each individual will choose one of the methods and provide a summary of the method for us to learn about and see here on the google docs. Casper, Kenzhi, Safran and I have not seen The Inconvenient Truth but plan to find a way.

With their advisor's assistance, the ILF became interested in the effects of CO2 absorption in sea-water, a significant issue since the oceans act as a massive CO2 sink, but this in turn drives down the pH, with several potential negative consequences for marine organisms (and thus the rest of us). This topic lent itself to understanding a lot more about CO2 chemistry, and the process of taking measurements in very complex systems; their engagement with this area of new knowledge began to shift the "activity space" once again.

The science was sophisticated, and the students worked at it diligently. Two messages from Schuyle make clear that he was engaging them with challenging content, and that they were working on it:

Sign-in-Sheet 6/29, Schuyle writes:

1) I will look into K2CO3 sequestration reaction. This is an up and coming sequestration process in industry and would make a good lab study for us.

2) I will look into NH4OH sequestration cycle, also industrial process; a good lab study as well.

3) We might consider doing a sea water loading experiment that models CO2 absorption in the oceans. Sea water pH change is a really important problem, kills aquatic life including coral reefs. This involve understanding carbonic acid equilibria and perhaps running a KOH titration. See enclosed presentation.

4) We can run Ascarite (NaOH) CO2 absorption experiment as well. This is another well known sequestering agent.

5) Figure 1 in review is interesting. We should all take a look at it and discuss, when we get together or through email.

Sign-in-Sheet7/8/2014 Schuyle writes again:

The CO2 acid base equilibrium problems that I sent along to you'all (sic) a few days ago is only part of the sequestration system. You ought to be asking yourselves how does the CO2 in the atmosphere get into the oceans or lakes.

In order to solve this problem, please read up on Henry's Law. Perhaps you've already discussed this with Mr. in class. Henry's Law is a mathematical formulation that can determine the amount of CO2 that becomes dissolved in a body of water based on the partial pressure (or concentration) of CO2 in the atmosphere. The greater the partial pressure of CO2, the more CO2 will be dissolved in the ocean. The Henry's Law constant will be temperature dependent as well.

You can get your feet wet by going online using Henry's Law and CO2 as key words, or Henry's Law constant for CO2 as a function of temperature as key words.

Next try to design an experiment, and pass around to the group that will demonstrate the workings of Henry's Law in carbon sequestration.

The chemistry here was not part of the students' chemistry curriculum, but the scientist judged it to be within their understanding. He urged the students to enlist their teacher's help as they worked through the new concepts, something they were inclined to do in any case. The students read resources provided to them, and continued to curate their project space online by archiving the pdfs provided. In a Progress Report, they wrote:

We spent the first few weeks discussing the research we have conducted and also brainstorming and sharing possible solutions to the CO2 problem. We all had many ideas ranging from a machine in the atmosphere or ocean that could filter CO2, to using algae to clean of CO2 in the ocean. We settled on conducting research on how/why the ocean observes CO2 and what conditions would cause it to take in more or less CO2. We agreed on first getting a baseline to compare future experiments with so we began planning on ways to put CO2 in water.

Mr. Schuyle was attentive to the students' efforts, and shared some of his own motivation and view of science in response to their energetic response to the developing project:

Sign-in-Sheet8/2/2014

My thanks to Safran for putting this information/communication site together. Any original effort is an adventure, and this is what we are embarking on regarding sequestration. What I like about Science is that it allows one to discover for oneself the truth. We do not rely on another's interpretation of the truth, which is second hand. Anything we learn from others, in Science, ought to be verified, and I propose we set about the sequestration question/issue with open minds. I can assure you, if we are earnest, whatever we learn through our efforts, regarding an honest reading of the literature, or through direct empirical study, will affect us directly - intellectually, emotionally, or physically.

This message is notable for the way it conveys a working scientist's voice. It gives several kinds of permission: to test ideas, and not take things for granted, even well-established things; to not pre-determine what "success" means, and indeed to be prepared to recognize several kinds of success; to put the focus on learning, and learning both by empirical investigation, and by reading the literature; to be aware of, and welcoming to, impacts on the whole person—"intellectually, emotionally, or physically".

The students had a meeting with their advisor, and agreed to the shift in focus, as noted in this meeting summary:

Summary 2 (Meeting 8/28)-Ricardo

We met in person and took time to figure out what direction we wanted the project to go in terms of what we would study and what goals we would pursue. We agreed on the idea of CO2 removal from seawater. By doing this we would have the ability to measure the change in CO2 by means of pH change in the sample of water. Kenzhi and Safran agreed to look into the properties of CO_2 that would allow us to distinguish it against water. I will look into forms of extraction for CO_2. In taking this approach, we recognized that the ramifications of reducing amounts of CO_2 in seawater could potentially preserve ocean biodiversity and coral reefs facing acid erosion. We put together the team name and became aware that we may have access to a lab for experimentation purposes as well as a graduate student for possible help in research

4.1.3 Object 3: Learning How to Infuse CO_2 into Water, and Measure It

This turn of events led to the emergence of a third competing activity, with its own appropriate resources, objectives, and activity structure. We say "competing", because work oriented to the earlier object continued for a time, in parallel with the new line of investigation. While this made sense, in that the ILF saw them both as necessary to achieving their project outcome, it did impose additional management challenges—managing time, attention, and other resources. Upon reflection, one team-member registered frustration at the tension between the shifting object systems:

The most frustrating part of the project definitely centered around our early trouble with setting a baseline for pH changes in water due to CO_2. Even with the help of our Chemistry teacher and one of his colleagues who works in a lab in the area, we were unable to get accurate results for much of the early part of this school year. In the end we succeeded, but the experimentation route was seeming less viable as the deadline approached (from JH, reply to a judge's query during the pilot video competition, 3/1/15).

However, this was the plan that they continued with for the rest of the fall. Their next meeting summary indicates their progress:

Summary 3 (Meeting 9/13)-Ricardo

We ran a baseline test today, gathering pH results from unheated and heated distilled water as well as unheated and heated tap water. We figured it would give us perspective on pH values of water at different temperatures, considering the indirect correlation between water's temperature and rate of absorption of gas is what will guide our research.

Their "Initial Project Plan" indicates a further direction, the use of phytoplankton as the sequestration agent:

Initial Project Plan

Team name: The Intelligent Life forms

Date: 09/20/2014

1) What area of mitigation is your project about? (e.g., sequestration, energy efficiency, alternative energy generation, social change). Sequestration by means of isolating CO_2 from seawater.

2) How does this reduce carbon emissions?

This approach would allow us to gain an understanding of how the ocean and sea hold CO_2 and how we can possibly reduce it through a process that separates it from the water. We would also recognize how aquatic life interacts with the CO_2 and if they can help us control it.

3) What will your approach be? (e.g., biochar, solar concentration, public education...) Isolating/controlling CO2 by using aquatic life such as plankton.

4) What are the first steps?

We are first going to measure CO2 in various bodies of water in different locations to see how much CO2 they hold and what possible factors lead them to hold the amount that they do.

Their experimentation had made clear to them that CO2 sequestration in marine phytoplankton was mediated by CO2 absorption by the seawater, so measurement continued to be a key theme in their reading and experimentation. They early on became aware that acidification also is an important consequence of the increases in atmospheric CO2, and one that made their intended experimental system more complex. Every step they took unfolded more actions, for example, to develop an understanding of acidification, of CO2 uptake by phytoplankton, and of relevant ocean chemistry.

4.1.4 Object 4: Creating and Presenting a Video and Report

The complex and shifting history of the project's objects shaped the final result of the video presentation in the final competition. During that competition in 2015, Ricardo responded to a question from a judge asking the team to elaborate their description of their procedures:

Judge: You mention in your poster that you were able to calculate the acidification of seawater by CO2. Can you briefly describe some of your methods and findings for these calculations? Also, I am curious to know how algae deploy CO2 … Do they draw on gaseous CO2 in the water just like land plants?

Ricardo: We went to Revere beach and gathered ocean water samples with a few test tubes. In our lab at our high school, we introduced CO2 into multiple samples in a controlled system by means of baking soda and vinegar reactions. We were able to measure the pH of our modified samples to find that with a pH probe detector the acidity increased (h + ions were created), which was made evident by the lower pH value (below 7) read by the pH detector. Algae absorb dissolved CO2 in a process much like that of normal plants and create glucose and O_2 through photosynthesis, however, in order to receive such energy from the sun, algae must be situated in areas where the sunlight can reach which make them populous in the photic zone of waters. If we manipulate the number of algae in the ocean then we can control the amount of harmful CO2 the ocean has obtained through the atmosphere and prevent damaging effects such as coral reef erosion. In terms of innovating a method of determining pH with an autonomous structure like the machine we proposed, we had ideas for creating a portable titration system whose functionality would be governed by computer software. With a little research, we found an organization known as Marianda (Marine Analytics and Data) who specializes in developing instrumentation in the field of chemical analysis and has prepared the VINDTA 3D, a CO2 extraction and alkalinity detection system which is very similar to our design.

The evidence from this exchange (and others) suggests that the students had acquired considerable usable knowledge about the research question and methods. The team continued to include both their chemistry teacher and their science mentor.

They had been able to identify a series of actions each of which would yield information [a] about the bio complex system they were studying, [b] about the chemistry at work in the phenomena they were focusing on, and [c] about possible mitigation mechanisms they could consider. They had assembled a library of reference papers, but had also identified tools in their school lab, as well as other tools obtained through their advisor, and had learned to use them and do at least initial analyses of the data.

The choice of a specific mitigation methodology (iron fertilization to stimulate algal growth, and the design of a robotic delivery device) led them into areas beyond their capacities. By now, however, the ILFs had learned considerable amounts of science content, and skill with science practices. Despite the lack of completion of their project, it had left them with a sense of engagement and excitement about science, and about their ability to do it, as shown by Casper's reply to a judge's query:

I can't speak for my whole team, but personally I was drawn to the opportunity to actually do something tangible with what I had been learning in school. I love academics, but I am also interested in applying what I learn (which is why I am drawn so strongly to computer science) ... I know that personally I would love to test what we came up and to see the results for myself. While my passion doesn't strictly lie in this field now (as I mentioned, it lies in computer science), I would love to see where our work could take us in the future. As of right now I am planning on getting some experience in computer science/programming over the summer through internships or research programs in the Boston area.

Yet the competing objectives were both still alive, even to the end of the project. In December of 2015, during a focus group conversation (12/8/15), one ILF member said, we were going to create a baseline with distilled water and like put in CO2 and see how it absorbed it, which we did. And it's in our notes ...

They then sought to apply their method to a sample of sea-water, collected from the nearby seaside, and found fresh complications:

But after that ... We went to the Beach [in] Revere and we collected seawater from several areas and we put them in containers. And then the next day we started running some experiments on them. And that's when we started to get into some, hit a brick wall a little bit, which is where we are at right now. We are trying to persevere through where what we are trying to manipulate the CO2 into the water, it turns out it's more sensitive than we initially anticipated.

This then led to additional experimentation, which at the time of reporting seemed hopeful, but were still inconclusive:

So we've been, we ran several experiments on how we could control the CO2 to make sure nothing leaks in or leaks out and doesn't contaminate our samples. And we just recently, finally, got something where we are managing to control it in an effective way without having like drastically odd or similar results. So here's some shots of our notebooks that we took. These are ... some recent ones.

As they came to this final form of their work, the students were also able to articulate the longer-term implications of this project for themselves—which in turn re-defined their understanding of the objectives and implications of their process.

You know, it was a problem in terms of the deadline for the project because you need—you know, you're looking at something this month. But I guess we're thinking at the same time you're also interested in process and that's kind of what—it looked like you weren't necessarily fixed on a product. Like we didn't need to necessarily deliver a product by mid-December. But that we definitely needed some kind of process. And we're in it for the competition. But it's more important I guess for the group that we're exploring something that they want to continue even past the project.

4.2 Learning by Acquiring and Using Tools

From the point of view of activity theory, the tools of particular interest are *semiotic* tools—concepts or methods that mediate the subject's actions in pursuit of their object. Tools can include physical or digital tools as well. The tools of particular importance for ILF included:

4.2.1 Chemical Methods

These principally included digital (probe) and physical (pH paper) methods for testing pH. These were known to the students from their chemistry class, naturally, but they were a key part of the vocabulary for their investigation, as they understood that pH was a "proxy" for CO2 concentrations in water (and hence indirectly in the atmosphere). As ILF continued following their objects, so to speak, much more effort was focused on pH than on other elements in their climate model. For example, there was little or no documented discussion about rates of exchange of CO2 between atmosphere and water (in this case, ocean); there was no work done on the rates of uptake of CO2 by algae in the ocean (an important point, since eventually their proposed intervention centered on fertilization of algae, so that increased algal biomass would rapidly sequester carbon); nor any examination of the biology of algae, targeted species, methods of measuring biomass, etc. This is evidently because once the team arrived at the sea (and its pH), they encountered a large number of very difficult issues that were insoluble within their time frame and expertise. On the other hand, with respect to these issues, the students learned or gained increased facility with:

4.2.2 The Role of Information in Science Practice

The students, in dialogue with their mentors and advisor, learned how theory, methods, data, and the work of other researchers form a key dynamic in scientific research. One of the authentic features of this project work was the way that learning happened instrumentally, that is, the content or methods that the students had to learn emerged from the questions before them, quite in contrast to most school science learning, which is largely sequenced by the curriculum. The quotations above give examples of this emergent property of the learning, and show also how the structure of the "community", including both mentors and TERC staff, played a key role in this process, both articulating and in some cases modeling the process itself, as well as scaffolding the students' learning and search for information.

Many of their documents mention specific information that they wanted to find out (some of these have been quoted above). Their files include several articles, and the technical ones were suggested by Schuyle: "Ocean acidification prompts study", "Seawater CO2 parameter—measurement methods", "Carbon Dioxide capture: Prospects for new materials", "Comment on: Modern age buildup of CO2 and its effects on seawater acidity and salinity", and what appears to be a handout (perhaps for HS Chemistry, perhaps college): "Dissolved oxygen and carbon dioxide (Henry's Law)". In addition, there is evidence of web searches on algae and photosynthetic rates, and on iron fertilization of sea-water as a reengineering technique to increase algal primary productivity.

While the evidence is not complete over the whole time-course, what we do have suggests that the information they gathered was sought in answer to questions that arose as their conversation and thinking continued. As seen in examples above, they used the Web as a first go-to source, but also took advice from their teacher, their mentor, and from others who offered suggestions (as when project researchers visited in December of 2014).

An excerpt from a working document which reflects the intra-team conversation in preparation for their final video suggests, in condensed form, what appears to have happened over the course of the whole project:

We can cram a lot ton of Algae into the subs to absorb CO2—then when the algae absorb enough or we need to regulate the CO2 in the area the subs surface and we collect the algae and use it as fuel

→ Let me research how the algae work;

→ hile you do your research I'll start the intro, that works for me;

The standard size is the size of a submarine →derp.

OK, option i for now, we'll worry about the logistics in a minute, lets just get everything down.

OK, with that said, on to 2, In all seriousness I like option A for distributing the machines.

But which method, algae or something else?→ I need to understand how this works.

4.2.3 Failure As a Meditational Means

The team, supported by their mentors, did not see failure as defeat, but rather as an opportunity for learning, and this understanding supported their decision-making and design of next project phases. In one exchange, a student recounts a road-block they were currently struggling with, and the teacher comments on the creative impact of such "failures":

We were getting readings that just didn't make any sense. And so we're thinking that what's happening is, in terms of the kinetics it's so slow, what's going on what we're not seeing any change. We know that something must be happening, just based on our prior knowledge. But we're just not seeing it in the experiment. So what these guys decided to do was, again, let's try to establish some kind of base line where we introduce a known quantity of CO2 into the water and get a known change in the ph. And then once we have that, we can go and collect seawater from different sites. And then based on those results then we can start to ...

Teacher: That's kind of where we're at. We've had a lot of failure in terms of actually establishing a baseline experiment that's going to allow us to, you know, allow us to … or the kind of cool, creative stuff they want to do.

4.3 Learning through Division of Labor and Developing the Community

Who were the people on the team, and surrounding the team? What was each one's perceived expertise (from the students' point of view)? How did Innovate staff see these same people? Were new human resources added during the project? Why, and how did it happen?

In addition to the 4 students, their chemistry teacher, Mr. Bowman, and their advisor, Mr. Schuyle, the TERC's project team was a part of their activity system as well. Both Bowman and Schuyle were active participants, as already documented. Bowman provided space, equipment, some monitoring of activity (e.g., encouraging regular meetings), communication with TERC, and general chemical advice.

Schuyle provided encouragement (his tone was uniformly positive), but represented good science practice also, and was not reluctant to challenge the team with advanced ideas or techniques. While he suggested readings and methods, he also gave thought to what the students might need to learn to be able to make use of these suggestions. In this he was supported by Bowman, who was able to interpret or explain unfamiliar concepts to the students. Indeed, the team was eloquent on the importance of Bowman and Schuyle to their work, and their support of their own agency in the project:

Ricardo: Another helpful thing is maybe not every team has not the capability of doing, so but having some form of mentor or guide who's well-known in the field like we had our teacher, Mr. Bowman and he helped guide us to come up with our ideas of innovation. That can be a very useful thing in terms of organizing the team and controlling expectations, and showing us ideas on what's possible and what's not. We have a better idea what to do. That can be very valuable to a new team entering a competition such as this. Anything else?

Casper: I want to say the value of adult mentor is really important because I know for a fact that if we never really felt like doing the project, Mr. Bowman would always be on top of us and tell us like, "Oh, guys, we got to meet up soon". We're like, "Oh, when are we going to do this or that?" That was really important to have, someone who could hold us accountable besides the four of us because I know we're all really similar. If one of us doesn't feel like doing it, we're all feeling that way. I feel like he's the mentor [inaudible] is important.

The students on the team divided the work among themselves, Kenzhi and Safran agreeing to look into the properties of dissolved CO2, while Casper looked into forms of extraction for CO2 (meeting notes 8/28).

The Innovate to Mitigate project was also part of their activity system, in several ways: (i) The Innovate to Mitigate project website provided suggestions and "inspirations", resources, a place for communication, and a place for record-keeping about experiments undertaken, and about meetings. (ii) TERC provided timelines and reminders about milestones and tasks for the accomplishment of the project. (iii) TERC staff were accessible by email and by phone to team members (though communication was often mediated by the teacher). In the case of this team, TERC had little communication with the outside expert, Schuyle. (iv) TERC found and supported a graduate student mentor, though she was not an active participant with this team, after initial introductions. (v) TERC provided templates for reports, designed to record progress (as data), but also with the intent to help support the team in their process, helping them connect specific tasks they might undertake with their project goal and the overall team objective, and remind them to relate choices they made to their research plan. (vi) TER Cprovided the Video hall space, with associated rubrics and support, which again was a tool to support the team's reflection on, and in a sense completion of, their learning from the project. It was also a venue within which to present their work (another core science practice) and receive feedback from peers and experts. (vii) TERC staff met with the team in early December, 2014. The team gave a presentation on their process to date, including some video of team field trips to collect sea-water samples, and a "presi" presentation about the project. There was some brainstorming about some current questions or issues they were facing, and the team took notes on some suggestions that arose, creating a memo to themselves (and TERC) about key ideas, which they entitled "Improvements from TERC meeting":

• Stir-rod to continuously mix the solution;
• Introduce the CO2 below the surface of the solution (straw below the surface, etc.);
• Use dry ice to introduce fixed amounts of CO2;
• Theoretical framework for why and how our innovation would work. Evidence required for validation;
• Extension of final deadline to the end of January.

Machine:

• Atomically Precise Manufacturing (APM) research at DARPA;
• Low cost for maximum effectiveness on large scale;
• Passive vs. Active;
• Software focus we/our programming background.

4.4 Learning by Developing Rules

Project management was both team-initiated and project-initiated. As discussed above, in a general sense Innovate to Mitigate set the timeline and main milestones, though throughout much of the time, Innovate to Mitigate's schedule was mediated through the teacher. A management framework was "reified" by documents and templates which were intended to have at least three functions: team self-management, modeling/teaching of good process, and data collection for Innovate to Mitigate.

The students did make some effort to organize their project and materials, but as Ricardo acknowledged above, this was inconsistent at best. Early on, Safran created a file called READ ME, which provided detailed instructions for keeping the project organized, including reporting documents, ways to organize information (e.g., links to web documents), and places for notes and meeting summaries. For example, the instructions for keeping organized included:

This is just a document on how I set things up. Read everything and email me if you have any questions or feedback or comment/adjustment to the setup.

Sign in Sheet: The purpose of the sign in sheet is for notifying the rest of the team of

• any documents/information you have added to the folder.

- any adjustments/edits you've made to an existing document.
- any comments, questions, or feedback you may have.
- the current status on your research.

--- When you put something in the Sign in sheet make sure the information you put down is on your assigned color (feel free to change it if you don't like it) and that each entry is dated. You're not obligated to have something in on a regular basis so feel free to work at a pace you're comfortable with.

--- If you're responding to someone's question, email them or place your response in their box with the words in your color.

---The sign in sheet should be the first thing you look at when you enter the folder so you know what everyone is up to.

--- After you're done adding to the folder make sure to update the sign in sheet so everyone knows what you've added so there is no confusion. Do this every time you make an addition. ex) under Safran: 6/29/14 Added new info in my info sheet.

5. Discussion

5.1 Learning Seen through the Lens of Activity

Our analysis has gone deeply into several aspects of the ILF activity system. It has provided, within the limits of the available documentation, answers to our research questions:

The subject: Who is learning in this open-ended STEM challenge?

The object/outcome: How does the team describe its research goals? How do they change? What do they learn?

Tools: How do they learn? What artifacts, tools, methods are used, how, and at what stages? What do they learn in this connection?

Rules: How do they learn? Who maintains timelines, and monitors progress? Who calls for evaluation of progress? Is this explicit? What do they learn in this connection?

Division of labor, community: How do they learn? What people constitute the team? What is their perceived expertise? Who accomplishes the work? What do they learn in this connection?

5.1.1 Subject

The students' documentation provides evidence of a range of types of learning that would be difficult to capture otherwise—to capture, and to understand as mutually reinforcing elements of a whole learning experience. As discussed above, these learning types included:

• Concepts in chemistry, in scientific methodology, in climate change, in mitigation, and in science communication.

• Skills and practices associated with the development and evaluation of concepts and methodologies necessary for this research project. These included both data collection and analysis, as well as the kinds of data management and documentation that are required to make sense of a research program that extends over several months, with a clear aim but many indeterminate elements, and with multiple participants whose roles need to be re-negotiated as the inquiry unfolds. In addition, there were "composite" skills and practices intrinsic to the development, refinement, and conduct of inquiry, such as modeling, collaboration, and the defining and redefining goals.

• Metacognitive processes and tool development necessary to define the inquiry in terms of questions, theoretical issues at play, and methodologies, and to manage and represent schedules, procedures, findings, and methods.

• The deployment of imagination, and the productive uses of failure. These elements are not usually included in the evaluation of science learning, yet have long been understood in the philosophy of science as essential elements in successful inquiry.

Understanding learning in the context of a science competition can help us understand the consequences of including such learning contexts in the ecosystem of school-based science learning. The summary of evidence presented here suggests that the students acquired considerable knowledge about the research question and methods, learned considerable amounts of science content, and skill with science practices. While the specific mitigation method they chose led them into areas beyond their capacities, the project left them with a sense of excitement about science, and their ability to do it.

5.1.2 Object

The transformation of the Object of the activity system was driven by the learning the students and their adult collaborators did, as they moved from the very general "outcome" target, that is, the development of a video describing an innovative mitigation strategy, to successive operationalizations of this original aim. In the major phases of their project (Object1-3 above), the students gathered resources, solicited advice, and to a certain extent developed empirical experience with core concepts. These steps occurred iteratively, as brainstorm led to proposed specific actions which were then critiqued by the expert "shell" of the team, by the students' own logic and reflections, and by trial, experiment, and error.

5.1.3 Tools

The project incorporated a range of tools, whose choice emerged as the Objects evolved. The students and their adult colleagues had from the start a comfortable collaboration, which predisposed the students to accept guidance about tools, including methods, theoretical frameworks, and useful concepts, as well as management/metacognitive processes which could keep the project moving towards a definite outcome. Meanwhile, the adults (including the scientist advisor) found themselves engaged in research on a topic new to them.

5.1.4 Rules, Division of Labor, Community

The Innovate to Mitigate challenge framed a certain set of rules—initial objective and design of final outcome, as well as a time-table for the whole event in which the team was participating, and interim reporting. This framework was not sufficient to structure the activity of an individual participating team. As depicted above, the students themselves recognized that they needed to "get organized", and structures emerged—schedules and habits, but also inscriptions: reports, lists, meeting notes, lab notebooks, photographs and videos. These emergent tools mediated their work, both by making some elements of their activity explicit, thereby reifying them as resources for further inquiry, and as distributed memory which enabled directionality in the work: Where have we got to? Where are we starting from?

It is striking that in this collaboration, the students retained the function of imagination and conjecture, while the adults served to regulate these to serve the objective, by means of guidance about tools, and also of mentoring/modeling: showing how to think about the implications of a question, suggesting possible limits, biases, or issues with methods, reaching for literature that might ground the work theoretically—all the "moves" that a mature investigator has learned to make, to turn curiosity into disciplined inquiry.

The whole project occupied approximately 32-40 hours over 7 months, and the team members themselves noted the sense of constraint that they felt—constraint both because of the timeline of the Innovate to Mitigate competition, and because of the other demands on their time, for school and out-of-school activities. It can be conjectured, however, that the episodic/iterative nature of their work together was in fact a benefit, in that it gave time for reflection and further research for information or ideas. This rhythm could perhaps have been even more productive if the students had been more aware of the importance of documentation and review and it may be that some sort of orientation to research habits of this kind would have value both for student participants, and for teachers or mentors.

In the course of our analysis, we were struck by the dynamism of this team's trajectory, the way that ideas came and went, and objectives were re-framed or reformed, or initiated. Indeed, for an inquiry of this kind, the "mediation triangle" has the drawback that it represents a static system—static in the sense that the various elements in the system, including the objective(s), the resources, and the division of labor, are defined, that is, given definite articulation in the model. There are certainly dynamics and interactions within that frame, of course, but the "roles" and "players" are constant to some degree.

In attempting to account for the "community" and division of labor in which the ILF was embedded, we lacked information on at least two dimensions that would need to be addressed in future research. First, we would need more detailed data tied to the timeline of the project, for almost every aspect of the interactions between ILF and their partners. Second, and related to this, a full account would need to include more evidence about internal team discussions with regard to key decisions, division of labor, and "division of knowledge"—the extent to which the team members specialized on different aspects of the content or process.

5.1.5 Coda: Object as Horizon

During the development of the ILF system, however, everything was in motion, and in a sense the whole system moved directionally, morphing into additional or even competing activities related to shifting Objects, each with its own "local" purposes and structure, role definition, etc. The whole could not be said to be merely a subdivision or differentiation of potentials within the original system, as might be the case of (say) the functioning of an office or workshop which has a long-term, more or less fixed objective (cf. Engeström, 1999). By the time the ILF were fully engaged, the project's initial definition of their object and goals was beginning to recede in their minds, and they all began to think beyond this episode in their lives, to future investigations for which this was preparation or prototype. In a progress report from December 2014, they were able to talk about how their technical strengths could lead them to engage with the material using computational thinking which had not been part of their project hitherto, and this related in ways not clearly documented to the emergence of their final design, of marine microrobots that would be used to stimulate algae growth by the targeted dispersal of nutrients.

5.2 Conclusion

An activity-theoretic approach seems promising as a framework for capturing and analyzing such a learning system, since it provides a lens both for characterizing and analyzing team learning of many kinds, and the processes by which this learning is mediated by the activity system. One comment from a student interview summarizes many of the strands emerging from our reflection on the case of the Intelligent Life Forms:

I did enjoy the competition. It was a good challenge. It forced me to really do some research … The things that interested me a lot in science, I wanted to make use of just to see how extravagant or how broadly we could make this design, and see if we could actually work in some way if I actually take the time to research the specifics. On my own, I felt as though there was a lot of information to deal with. It was more so a matter of how creative you could be with the information, and how practical it could be.

5.2.1 Limitations

Because this is a study of a single team, engaged in a single event, results about the nature and kinds of student learning resulting from participation in a crowd-source challenge cannot be generalized. Further work on fresh cases would enable us to better formulate theory on elements shaping individual and group contributions to the learning environment, and students' (and other participants') ability to take advantage of the affordances of that environment. With regard to the methodological aims of the study, the results provide some warrant that an activity-theoretic framing can provide rich insight into the diverse kinds of learning taking place in such a project. However, for this insight to be applied further, an enriched design for data capture will be required. This would provide better control of inferences about participants' roles and use of mediational means such as scientific references and tools, process tracking, and metacognition about subject-matter content, rules for collaboration, and participation patterns, including division of labor among the participants.

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