What, where, who?
Learning in an Innovate to Mitigate pilot team[1]

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Introduction

In an open innovation crowdsource-like competition, the Innovate to Mitigate project[3] invited students to propose innovations that would mitigate climate change. We hypothesized that the "previously unexploited collective intelligence" (Bull et al., 2008) of young people would be engaged, since many features of real world crowdsourcing align with 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., Krajcik & Blumenfeld, 2006; Wirkala & Kuhn, 2011), and an emphasis on production that leads to higher-order thinking skills (Gee, 2011).

Theoretical Framework

We have conjectured that a framework informed by activity theory may be useful for understanding how learning happens in a crowd-source-like process such as the Innovate to Mitigate competitions. At this point, roughly at the beginning of our analysis, we believe that this approach can usefully describe the learning systems represented by each team. Further analysis of student products will, we hope, offer evidence of specific science learning.

It may be useful to review briefly Wertsch's (1991) schematization of the three levels distinguished by classic activity theory for an activity system.

Activity — motive
Action — goal
Operation — conditions

To elaborate: An activity is a general set of motives and values, it is defined with respect to a particular problem space or objective, and with the purpose of achieving a specific goal, by creating an outcome or result. Activity corresponds to the "reasons I am doing this particular thing now" at a high-enough level that it relates coherently to the specific tasks you may be performing.

An action is a specific (complex) undertaking that is aimed at a goal, and has some specific outcome. You might say that an activity is implemented by one or more actions, or rather a

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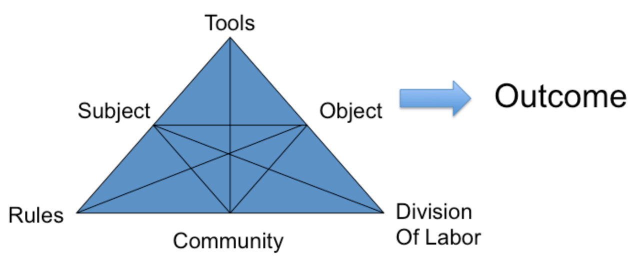
collection of (typical) actions, each with its own structure-- and the actions may articulate with each other either in sequence.

Finally, an operation is a specific practical process, which may be designed specifically to implement a particular action, or may be a generic process which one might use to implement many kinds of actions. An action is likely to be accomplished by many linked operations, but these operations are not limited to the carrying out of specific actions, as part of a specific activity. This also then allows us to explore additional dimensions of the "situation" of the specific action, as schematized in this Engstrøm chart expanding on the basic mediation triangle (Engstrøm and Middleton 1998):

Engstrom's expanded mediation triangle



Subjects engage in actions to address an object, their activity mediated (Wertsch 1985) by tools or other means, to perform or accomplish a goal or outcome. This process is shaped by its community context, which influences actions by means of rules and structures, and by the nature of roles 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 and is thus shaped or refined, depending on how it is understood by different participants in particular ways.

In what follows, we do not seek to cast our initial results into rigorous form, but use the model just sketched in developing a narrative relating the events and evidence that we have for one team. In particular, we seek in this essay to use this theoretical framework to test its value as a way to identify learning, and just as important, learning processes and events, in a project team. We will close with some methodological reflections.

I. Timeline and activity flow

The Intelligent Life-forms team: This team included 4 students, mentored by their chemistry teacher, Mr. Bowman. Their team was also advised by Mr. Schuyle, a research chemist. [4]

At this point in their project, a well-formed "innovation" had not been identified or conjectured. In activity-systemic terms: The goal of the Innovate project, for which the students were recruited, was for teams to develop innovative approaches to mitigation, and at least carry the investigation far enough that empirical data could be collected, or tests could be designed. This challenge was quite open-ended, by design, and it meant that the teams had to operationalize the idea by the following, which to a first approximation constitute actions, each

[4] All participants' names are pseudonyms.

with its own purpose or goal, resources, and systematic relations among the actors in the system (in this case students, mentor, advisor):

[1] learning enough about the general problem of mitigation to make some choice about possible strategies. [objects] In order to make choices at this stage, the team would need to gain at least an initial understanding of at least these topics: Carbon sources, some quantitative understanding of the carbon cycle, and human inputs to atmosphere, why interrupting that input is important — earth systems processes.

[2] choosing a strategy (e.g. reducing fossil-fuel use, enhancing biological sequestration, etc. see Table 1)) — in this case, they chose carbon capture and sequestration. At this stage, they would need to have some understanding of at least these topics: knowledge of types of mitigation, and identification of technical strategies associated with each.

Table 1. Mitigation strategies suggested for Innovate teams

Major category	subcategories
Power Generation Techniques	Biochemical; Biomass; Hydro Power; Wind Power; Solar Power; Other
Power Storage Techniques	Potential; Kinetic; Chemical ; Electrochemical
Efficiency and Conservation	Agriculture; Manufacturing; Transit; Buildings
Carbon Capture and Sequestration	Agriculture; Direct; Geological
Programming	
Finance	
Social and Behavioral Change	

[3] choosing a specific experimental/engineering system with which to explore this strategy. To do this, they would need to work with their advisor and any resources they had acquired to date in order to identify a system that, at least at this stage, would be tractable within the constraints of the Innovate to Mitigate project: within their reach in terms of intellectual content, cost, time, and scale.

[4] making explicit the science they needed to learn to understand their choice. The base from which they are working is their high school chemistry course. In order to understand the distance between what they know, and what they need to know in order to follow their chosen mitigation strategy, they would need to rely on the greater expertise of their teacher and advisor, who know chemistry in the depth required to contextualize the ideas they are following, and the techniques and scientific theory that would be required. There are in this action or actions several kinds of learning needed, viz., [a] learning by the team (i.e. individuals who share their knowledge or make it available at relevant points), and [b] learning to collaborate with outsiders (that is, people not on the team proper, or who form with the students a "super-team") so that knowledge gaps are filled, as in all scientific enterprises.

[5] identifying materials, other resources, and expertise necessary to the task. This would take place in at least two stages: as part of steps [2] and [3] at the feasibility stage, and then, once a strategy has been chosen, moving from identification to acquisition, as part of the actual implementation of the project.

[6] designing tests or prototypes, predicted outcomes and metrics, etc.

In what follows, we elaborate on the actual events relating to these stages as enacted. In our theoretical framework, all represent actions -- and each of them has a structure (source of question, deciding on methodology, info gathering, deliberation/evaluation, decision on the basis of intention/model and evidence, implementation and evaluation.

Activity 1. Choosing a strategy. Their choice of a project focus establishes the subject domain, both as to possible content, and possible "practices" to be employed, and probably learned. To expand on the notes above: 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 CO_2 emissions are a critical factor, and that (iii) actions can be taken to reduce these emissions (either reducing emission rate or removing CO_2 from the atmosphere);
b. The students must learn what are 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.

As with much of the project activity, 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 Gilly Puttick, Mr. Bowman wrote that the team had settled on carbon-capture and sequestration as their project for "Innovate to Mitigate." Their teacher, Mr. Bowman, confirmed their interest in an email on June 19th, 2014, though not explaining how they'd come to that conclusion. :

> Hi Gilly-
> It was great speaking with you again today. We are very excited to apply to the competition and plan on investigating carbon capture and sequestration methods. Please find our preliminary application attached. I've copied Dr. Schuyle and Dr. Diane Perito on the email. Dr. Schuyle will be serving as our team mentor and Dr. Perito is the Malden Public Schools K-12 STEM director. Thank you again to you and TERC for providing this opportunity! -- Mr.

Activity 2. Choosing a method or system with which to implement their strategy.

As ILF defined their interest enough to join 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 CO_2 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 CO_2 capture by plants in some tractable natural system, with rates achieved by artificial means. One artificial method for CO_2 capture used in various experiments with biological systems is "scrubbing" with Ascarite®, a compound that adsorbs CO_2.

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 GoogleDocs, 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. Caspar, Kenzhi, Safran and I have not seen The Inconvenient Truth but plan to find a way.

With their advisor's assistance, the ILF got interested in the effects of CO_2 absorption in sea-water, a significant issue since the oceans act as a massive CO_2 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 CO_2 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 Schulz make clear that he was engaging them with challenging content, and that they were working on it:

SIS 6/29 folder's created. writes:
1. I will look into K_2CO_3 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 NH_4OH sequestration cycle, also industrial process; a good lab study as well.
3. We might consider doing a sea water loading experiment that models CO_2 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) CO_2 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.

SIS 7/8/2014 again:
The CO_2 acid base equilibrium problems that I sent along to you'all a few days ago is only part of the sequestration system. You ought to be asking yourselves how does the CO_2 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 CO_2 that becomes dissolved in a body of water based on the partial pressure (or concentration) of CO_2 in the atmosphere. The greater the partial pressure of CO_2, the more CO_2 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 CO_2 as key words, or Henry's Law constant for CO_2 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 urges the students to enlist their teacher's help as they work 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 on-line, as evidenced in this note:

SIS 7/18 Added
-Carbon Dioxide Capture pdf
-Sea Water C02 pdf

In a Progress Report, they write:

We spent the first few weeks discussing the research we have conducted and also brainstorming and sharing possible solutions to the CO_2 problem. We all had many ideas ranging from a machine in the atmosphere or ocean that could filter CO_2, to using algae to clean of CO_2 in the ocean. We settled on conducting research on how/why the ocean observes CO_2 and what conditions would cause it to take in more or less CO_2. We agreed on first getting a baseline to compare future experiments with so we began planning on ways to put CO_2 in water.

Team-member Calvin said:

> It was a good challenge. It forced me to really do some research. I have been studying a lot on my own. As far as making use of the information that I'm gathering, I found this to be worthwhile. I'm beginning an online course in nuclear physics, and I really wanted to apply what I was just barely learning into what we were doing with this machine.
>
> 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.

Dr. Schyule 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:

> SIS 8/2/2014... now have a gmail account owing to Mr Bownman's assistance. It is nine@gmail.com.
> 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 CO2 that would allow us to distinguish it against water. I will look into forms of extraction for CO2. In taking this approach, we recognized that the ramifications of reducing amounts of CO2 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

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

This turn of events did, however, distract significantly from the original objective of the team — thus creating a third competing activity, with its own appropriate resources, objectives, and activity structure. Upon reflection, one team-member registered the tension between the nascent activity systems as frustration:

> "The most frustrating part of the project definitely centered around our early trouble with setting a baseline for pH changes in water due to CO2. 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. Their experimentation had made clear to them that CO_2 sequestration in marine phytoplankton was mediated by CO_2 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 CO_2, and one that made their intended experimental system more complex. Every step they took unfolded more actions, e.g. to develop an understanding of acidification, of CO2 uptake by phytoplankton, of relevant ocean chemistry, and so forth.

> Initial Project Plan
> Team name: The Intelligent Lifeforms
> 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 CO2 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 CO_2 by using aquatic life such as plankton.
>
> 4. What are the first steps?
>
> We are first going to measure CO_2 in various bodies of water in different locations to see how much CO_2 they hold and what possible factors lead them to hold the amount that they do.
>
> 5. What are your burning questions at this stage? Other comments about your plan at this stage?

> When will we be introduced to our student teacher and what types of supplies can we get to use in our experimentation?

The quest continues. As part of the video competition in 2015, the students were asked to elaborate their description of their experimentation:

> [A judge, Gilly, asked:] You mention in your poster that you were able to calculate the acidification of seawater by CO_2. 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 C Co-Presenter, answered:
>
> February 26, 2015 | 07:54 a.m. Hey Gilly,
>
> We went to Revere beach and gathered ocean water samples with a few test tubes. In our lab at our high school, we introduced CO_2 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 CO_2 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 CO_2 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 CO_2 extraction and alkalinity detection system which is very similar to our design.

The evidence from this exchange (and others) suggests (aside from other documentary evidence available in their database) that the students had acquired considerable usable knowledge about the research question and methods. Their 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 biocomplex 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, at this stage. By now, however, the ILFs had learned considerable amounts of science content, and skill with science practices, and 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:

> JH's reply to a judge's query during the pilot video competition, 3/1/15

> 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 activity systems 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 CO_2 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 CO_2 into the water, it turns out it's more sensitive than we initially anticipated.

This then led to additional experimentation, which at the time seemed hopeful, but were still under way:

> So we've been, we ran several experiments on how we could control the CO_2 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.

II. What can we say about learning in this team system?

Introductory note

The design of student activities in this project makes the challenge of documenting learning difficult, since

1. The project is engaged in inquiry. The content to be learned mostly cannot be specified ahead of time, but has to emerge from the choice of the project, the one exception being §1 below. Therefore the standard "pre-post" measures cannot be applied. This requires then a qualitative approach, using multiple types of data.
2. Knowledge and cognition is distributed. The project is a group effort, so individual attribution, except in the case of teams which choose to divide labor rigorously, will largely be difficult or impossible to establish. Even in cases where there is a clear and consistent division of labor, however, the collaborative nature of team inquiry and design means that all members potentially will have a share in the products, techniques, and learning of all.
3. The learning/knowing team includes diverse levels of expertise. The learning in these projects takes place within a system that also includes mentors and advisors, adults with a range of knowledge and skill relevant to the project, including both content knowledge and process knowledge (e.g. keeping track of data, organizing documents, managing deadlines, as well as techniques related to instruments and data collection, etc. Again, in an inherently collaborative process, an active advisor will have an impact that is hard to measure or even identify, but may be quite large.

Methodological reflections

We embarked on this case study in order to grapple with a challenging question identified in our proposal to NSF: What warrant can we give that participation in a crowd-sourcing project like Innovate to Mitigate can be a a way to learn substantial science content and scientific processes? in the proposal, we characterized the challenge we set for ourselves this way:

> In order to understand the dynamics of collaborative thinking and doing among participants, we will do a first pass through the data by categorizing the major "ingredients" in the distributed-cognition system, such as types of resources available in the system (technology, mentors, library resources, etc.), people and their roles, constraints provided by the task, an approach developed by Engström and Middleton (1998)... Since we expect that 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 will pay particular attention during our analysis to transitions in teams' work when they appropriate new tools, ways of talking, or other resources. At the same time, we will be on the lookout for new patterns as they emerge (Creswell, 2009). We will characterize changing patterns in the dynamics of the problem solving system over time so that we can track how emerging learning is shaped by interactions among individuals, group, tools and mediating interventions that mentors, TERC staff, or others make.

In addition, we might ask whether there is something in the structure of these events which makes such learning likely? That is, it is probably safe to say that anyone who participates in a hands-on science project which involves actual inquiry, and the use of ideas and techniques not familiar to them, to investigate a question not identified and answered by the curriculum, will result in some identifiable learning. On the other hand, this truism about human activity is hard to reconcile with the commitments or intentions of a school system to produce some learning reliably for all of its participating students. Therefore, it is worth inquiring whether the structure of this team constitutes some guarantee that learning is likely to take place, and in the educational sense, is it worth all of the effort?

Operationalizing research on participant learning. In order to collect relevant data about the project, we developed several instruments which we hoped would both support the teams' work, and give us information about that work, and the learning that ensued. "progress report" forms to help us track the knowledge resources (human and other) and tools being used by each team. A standardized reporting schedule, beginning with a full project prospectus due in late 9/14 will enable us to create a narrative framework for each project, by which to relate process, tools, and artifacts/representations (including documentation of current/persistent challenges and problems for the project). This narrative structure for the documentation will provide the basis for hypotheses about science content and practices learned, and used, in the course of the teams' work, which can then be tested by data collected subsequently.

For this case: All this is transformed for the purposes of this report into these two questions: First, What is the evidence that they learned something, and what specific learning does the evidence point to? Second, how did this come about? This means accounting for the roles of actors in the system and their contributions to the documented learning. The narrative above has already addressed the second point, to a certain extent.

In a memo dated Oct. 2014, we proposed determined that our model for a case would be explored using a specific framework based on 6 themes, which can be related also to the data sources used to address them. The 6 themes are:

1. Problem statement/research design.
2. Resources: Information gathered.
3. Resources: People.
4. Resources: Tools and methods.
5. Division of labor, and processes relating to collaboration
6. Thinking processes.

How does this apply to the Intelligent Life Forms team? I note here that for this project, this discussion entails also an exercise in identifying lacunae in the data. These gaps affect what can be said with confidence in analysis, but they also represent areas in which we will have to innovate methodologically in future studies of this kind.

1. Problem statement/research design. How does the team describe its research goals? How will it change? Perhaps: a. Change in core concept or strategy (e.g. from biomimicry to biochar); b. Strategy remains the same, but becomes more explicit (elaboration of theory of action) with respect to resources, techniques, methods of building/testing, outcome measures, etc.

    The project supported teams' development of a problem statement and research design principally through several documents: the initial statement of interest, the project plan, and the progress reports. The project plan and the progress reports pay attention to some core elements of project activity:

- theoretical framing: types of mitigation, strategies, and the mechanisms by which these strategies are expected to have an impact
- implementation methods
- project design

After working through the summer on a fairly unfocused idea (basically "How does the ocean remove CO_2 from the atmosphere, and how do we measure CO_2 content in seawater?), the team arrived at Sept 20th with a more elaborated research topic: "Isolating/controlling CO_2 by using aquatic life such as plankton."

In response to the "initial project plan" request to identify "first steps," the team's response identified quantitative methods that they felt they needed, though still in fairly summary or abstracted form: "measure CO_2 in various bodies of water in different locations to see how much CO_2 they hold and what possible factors lead them to hold the concentration that they do."

By the end of the project, they characterized their work in the abstract for their video as follows:

> Phytoplankton Behavior Through The Meticulous Introduction of Iron
> To address the problem that the growing concentration of CO_2 poses on the atmosphere, and more specifically, the water of our planet, we conducted research and experimentation that have allowed us to quantitatively calculate the acidification of ocean water by induction of CO_2 and, furthermore, hypothesize mechanical solutions. We propose a subaquatic vessel capable of manipulating phytoplankton behavior through the meticulous introduction of iron: a vital nutrient for diatom proliferation. The role of this group of algae aligns with current mitigation strategies because it is one in which natural photosynthetic reactions follow, providing a method of carbon breakdown and a method for alternative energy. Given current technology, this machine would be a submersible equipped to absorb algae and determine dissolved concentrations of CO_2 when resurfaced. Algae biofuel extraction could prove profitable in the near future. It is worth noting that companies have embarked upon similar solutions—manifesting validity in our machine.

By this time, which was the final iteration of their project, the idea had been elaborated in several ways.

1. The rationale was more completely articulated
2. The project had been elaborated into several discrete steps, including measurement, testing of mechanism, systematic implications of their proposed solution, and some validation of the idea by comparison with others' work. The team was aware of the ways in which these stages of their inquiry built on each other.
3. There was still a strong element of fantasy or imagination in their design, but one might suggest that this helped encourage them to reflect on additional dimensions/implications for the project, and in a sense the imaginative, "play" element was an important motivation for their persistence through to the end of the project (persistence that only 4 other teams managed).
4. The implications that they had identified were quite wide-ranging, including profit, alternative fuel generation, carbon sequestration, countering ocean acidification, and bioengineering (iron fertilization).

This suggests that, in addition to specific methods of measurement and idea-testing[5], the ILF had learned, or at least enacted, a more general inquiry, which Dewey (1933) labelled "intellectualization": the process of reflection by which implications and connections — meaning — are identified as part of the system and problem being investigated.

In terms of "missing data" which would be necessary for a full accounting of the development (and the learning) in a team like this: The team provided episodic documentation of their thinking about the object of their work and their designs for accomplishing it. They did not provide us the biweekly documentation that we requested, which would have helped us trace the changes in their thinking over time, but in any case, such a documentation would still need to be supplemented by some narrative account of the problems encountered which motivated a shift or development in their thinking. We suspect that these debates happened sometimes electronically, and some times in their regular meetings; in any case, a more intensive data collection effort, perhaps using new methods for capturing strategic moments (e.g. video memos, voice memos) would be necessary.

2. Resources: Information gathered. How do they identify the knowledge they need to have, and how do they find it? Does this continue as their experiment continues, or do they have an initial phase of info-gathering and then stop? Who holds this knowledge (i.e. do they all learn it and create a shared knowledge base, or are there specialists who are the "ready reference" for one or more areas of knowledge.

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 Schulz: "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 geoengineering technique to increase algal primary productivity.

The evidence is not complete over the course of the project, but what we do have suggests that the information they gathered — for methods and for theoretical background — 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 TERC 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:

[5] The team never got to a formal "hypothesis testing" process using statistical methods. Even their quantitative investigations were evaluated impressionistically, as might be appropriate for a prototyping project like this one.

a) 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
→ While 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.

3. Resources: People. Who are the people on the team, and surrounding the team? What is each one's perceived expertise (from the students' point of view)? How do Innovate staff see these same people? Are new human resources added during the project? Why, and how does it happen?

This team included 4 students, mentored by their chemistry teacher, Mr. Bownman. Their team was also advised by Schuyle, a research chemist. Finally, TERC's project team was a part of their activity system as well. Both the adult associates were active participants, and we have some documentation of their roles. Bownman provided space, equipment, some monitoring of activity (e.g. encouraging regular meetings), communication with TERC, and general chemical advice.

Schulz provided encouragement (his tone was uniformly positive), but represented also good science practice, 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 Schulz to their work:

> 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. Brierman 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?

Calvin: 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. Brierman 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 00:17:17] is important.

TERC was present in several ways.

i. The TERC 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, Schulz.
iv. TERC found and supported a mentor, Sara Waldo. though she was not an active participant with this team, after initial introductions.
v. TERC provided templates and timelines 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. TERC provided the videohall 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, as well as 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 Malden 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 w/ our programming background

There was also a (college) student mentor, whose impact, the team felt, was not as great as it should have been:

> Calvin: " Not only the snow days limited us but the fact that we got our mentoring late, our student mentoring...That and meeting up with a little later than planned. But otherwise, we used our time effectively if we just got these resources a little sooner.

With regard to accounting for the "community" and division of labor in which the ILF was embedded, we note that we lack information on at least two dimensions which would need to be addressed in future research if we really want to account in detail for the team's learning, and for the ways in which it developed. First, we would need "thicker" data — more detail, tied to the timeline of the project, for almost every aspect of the interactions between ILF, who are of course the core of this system, and their partners. Second, and related to this, it would be very desirable for a full account to include some more evidence about internal discussions, at least with regard to key decisions, division of labor, and "division of knowledge" - the extent to which the team members specialize on different aspects of the content or process.

4. Resources: Tools and methods. What artifacts, tools, methods are used? Is a set identified from the beginning, or are tools &c added at several points during the project? Do these come into use as a result of an analysis or growth of understanding, or is there experimentation with a tool which results in increased understanding of the problem or proposed solution?

There is evidence that, over the course of its roughly 6 months of research, the team learned to conduct (or increased their skill with) several core chemical methods, from titration and the use (and interpretation_ of various meters (e.g. for pH), to the design of short- and long-term experimental investigations. This also included the experience of mishaps and mistakes. As mentioned above, while data were taken, the data were mostly single-reading measures of a specific event. From one of their internal memos (11/18/14):

> <u>Experiment</u>: Take a sample of water, in our case it was Sample 1 from Revere, and produce and introduce CO_2 into the container that's holding the water sample. A trap was implemented to capture any unwanted particles that would obscure our results. Later, a balloon was filled with a student's breath which was then strapped and secured to a Erlenmeyer flask. This was done to introduce CO_2 to the surface of the water.
>
> <u>Actual experiment and procedure:</u> We took 3 flasks that would be used for; a container for the sample of water, a trap, a container for a reaction to be held. We connected each flask using a series of rubber plugs and tubes. We secured the flasks with clamps to ensure the flasks couldn't tip over. We used 40 mL of vinegar and 30g? of baking soda to create the

> CO_2. However this proved to be too much for the flask and some of the reaction travelled through a tube. After waiting for a period of time, we removed the container with the sample to take the pH value. We saw that the pH still increased.
> After cleaning our materials and acquiring another sample however, we chose to fill a balloon with CO_2 and wrap it around the flask. We decided to leave a flask with the filled balloon overnight to see if there was a change.

5. Division of labor, and processes relating to collaboration. How does the work get accomplished (what are the tasks/roles, and how are they apportioned)? Do these roles/tasks get assigned informally/implicitly, or are there sometimes (always) explicit discussions and decisions about who does what? What consultative processes are put in place, and are there tools or resources used to make these happen (memos, meeting rhythms, email lists....)? Are there members of the system that are not included, or whose activity waxes and wanes over the course of the project?

The division of labor seems to have evolved naturally, in that the team allowed each other to work from their areas of strength. Ricardo commented:

> It was more like it evolved depending on the situation or who just had time. We shifted ideas and stuff like that. There wasn't really much of a designated role. In some occasions, one person would do what we were doing one day and one person would work with the communication or whatnot, and make sure everybody is on task. For the most part, it wasn't the most organized group. We still did a fairly good job in getting the job done.

Ethan said:

> One thing that I have to say about this team as a whole is that one thing that I like is that, for me, I'm more of a theoretical person. I like coming up with ideas or like to see how far you could take something or something like that. When this competition started, I was like, "Oh, we could do this and we could do this." I have all these ideas of what could possibly happen.
>
> For the most part, they were really theoretical. I like that fact that I was in this team with Caspar and Ricardo and Calvin [inaudible 00:10:13] down a bit into reality so we can make something a bit more tangible.
>
> We respected how Ricardo went really hard when it came around his research. That carried a lot of ideas forward with his extracurricular studying. That actually helped us come up with the idea of the machine, and how we would make it to a submarine or something like that.

Calvin added:

> Everyone else on this team is more like computer science based, and I'm more definitely like the biochemistry person in this group besides Ricardo. Ricardo is like everything. It was really interesting working with other people who might be fun, and who's definitely very innovative and comes up with more theoretical ideas, as versus me and Caspar who think some more in reality I would say.

Again, there is not a lot of evidence on this point, though episodic notes suggest some process:

> After our last report…
> -We assigned each group member a topic to study so that the next time we all came together we each might have some ideas/knowledge on the types of issues we could tackle and apartments we could conduct.
>
> - We also planned to meet every Tuesday and Thursday to work on the project in Mr. Bowman's (our advisor) room because he is well versed in chemistry and his room had many tools we could use to run potential experiments. (This didn't always go as planned as some of us would be busy at times)

As it turned out, time pressures limited their ability to collaborate and share information in the way that they would have liked to do:

> Calvin: We had a downfall in coming together with that knowledge and really making sure that the team was aware of what I was picking up, and what we could actually do with these new ideas that I have. We would have been more empowered in developing a machine that could be tested quantitatively if we could meet together, and discuss more what we were finding on our own. I find that we were limited simply by the snow days, and our schedules like we've talked about.

Over the course of their work, Schuyle did some independent work to find information and make suggestions about concepts or methods that might be of use. See for example the message cited above:

> The CO2 acid base equilibrium problems that I sent along to you'all 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....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.

6. Thinking processes.
    a. Metacognition/project management. Who maintains the timelines? Who monitors progress towards the goal? Who calls for evaluation of progress? Who monitors the health of the team? Is this a matter of explicit attention (design), or is it informal?

As discussed above, in a general sense TERC set the timeline and main milestones, though throughout much of the time, TERC's schedule was mediated through the teacher. A management framework, including cycles of reflection and reporting, were "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 TERC. Moreover, as narrated above, the external expert, Schulz, provided a welcome person to be accountable to.

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.

> This is just a document on how I set things up. Read everything and email me (Safranhimel25@gmail.com) 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. Updated link sheet. Added a new document called Hi I'm Safran. Also when is the next meeting?
> IMPORTANT: Please be sure to put in what topic you're doing in the Sign in sheet so that everyone knows.
>
> Link Sheet: The link sheet is a document where you can place any links you found interesting or useful. The page is not just limited to websites as you can also put recommended books or other types of media there. Make sure your additions are under your color.
>
> Info Sheet: Your info sheet is a document where you can jot down any valuable notes and information on your topic. This is also the place you can place any ideas you have.
>
> Summary Sheet: The summary sheet is the document where the person whose turn it is summarizes any meetings we have had (Don't forget to date it).

Feel free add any extra documents that you might find helpful. Email me (Safranhimel25@gmail.com) if you have anything to say or add or if you don't like or want to change the setup.

Three meeting reports were made.

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. Caspar, Kenzhi, Safran and I have not seen The Inconvenient Truth but plan to find a way.

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 CO2 that would allow us to distinguish it against water. I will look into forms of extraction for CO2. In taking this approach, we recognized that the ramifications of reducing amounts of CO2 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.

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.

The "Sign-in" spreadsheet contains several entries from the summer of 2014 (the majority from Schuyle), but the document is not used after August.

<u>Failure as a tool</u>. The team, supported by their mentors, did not see failure as defeat, but rather as an opportunity for learning. 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 CO_2 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 [00:12:51] for the kind of cool, creative stuff they want to do

This was the genesis of Activity 3, which took the students all the way back to basic pH chemistry, cabbage juice indicators and qualitative exploration of a process they knew very well had eventually to be quantitative as well.

b. How are knowledge resources used — in initial design, or as a point of reference at various points, or in some other way? If there are "experts," either adult or on the team, do they take leadership at times by directing attention to knowledge that seems strategically important? Or are there "executives" or other team players among the students who initiate contact with experts?

This question has largely been answered in prior pages. As mentioned just above, Safran is the most evident "organizer" of the team, but most of the language is couched in collective terms: "We need to..." The three meeting summaries that we have were written by Ricardo, but he was not the principle communicator with TERC or Schuyle, as far as we can tell.

c. With regard to the design/test/evaluation/revision cycle, do different people take leading roles in different of these phases, or does the team work collectively all the way through?

There is no evidence on this point.

d. At what points does the team make their thinking and processes explicit? Does the frequency of this statement change over time? Does the vocabulary change over time, or the language become more precise or technical?

Discussion and reflection

The documentation of the ILF's process is also documentation of their learning. In the major phases of their project, labelled Activity 1 (choice of general mitigation strategy), Activity 2 (development of specific implementation), and Activity 3 (measuring and controlling dissolved CO2) 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.

The whole project occupied relatively little elapsed time, and the team members themselves noted the sense of constraint that they felt — constraint both because of the timeline of the Innovate t0 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 sometimes further research for information or ideas — and the team members used this "down time" in that way. 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.

As we worked through our retrospective analysis, we were struck by the dynamism of this team's trajectory, the way that ideas came and went, and Activities 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. What we saw in the development of the Intelligent Life Forms system, however, was that everything was in motion, and in a sense the whole system moved directionally, morphing into additional or even competing activities, each with its own "local" purposes and structure, role definition, etc. As we see it, the whole could not be said to be merely a subdivision/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. By the time the ILF were fully engaged in late summer of 2014, the project's definition of their objective 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 indeed preparation or prototype. In December, 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:

> We're trying to think of maybe modeling it after the way the trees take part in photosynthesis. So with that idea we want to see how we can manipulate the environment with some sort of manmade machine. And seeing that we all have a background in computer programming and algorithms and working with data in that way, we're pretty to see if we can actually develop some sort of application that would allow us to implement it in this machine and actually have some real-world effect.

They also were able at this point 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.

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