Alternative Learning Trajectories Toward Understanding Matter and Energy in Socio-Ecological Systems: Principle-Oriented Level 3 (PL3) and Fact-Oriented Level 3 (FL3)[1]

Hannah Miller, Allison Webster, Jenny Dauer, Charles W. (Andy) Anderson
Michigan State University Department of Teacher Education
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Abstract

Research on learning progressions in socio-ecological systems indicates that students progress along various trajectories towards sophisticated reasoning, and often struggle to achieve scientific understandings of matter and energy in these contexts. This study interprets interviews from undergraduate pre-service elementary school teachers with the goal of characterizing how students who follow various trajectories (the "messy middle") progress towards sophisticated reasoning about scientific processes and principles in the course of one semester of instruction. We analyze accounts of carbon-transforming processes from two students who represent distinct Level 3 student profiles: Principle-oriented Level 3 (PL3), and Fact-oriented Level 3 (FL3). We hypothesize that PL3 students may be in a better position to move to Level 4 reasoning in a class that incorporates instructional strategies that use conservation laws as tools for analysis, whereas FL3 students may have a more difficult time progressing to Level 4 reasoning in the same class. Although we envision this paper as a starting place in a longer process of inquiry into the complex nature of the "messy middle," we begin this inquiry by 1) proposing two distinct Level 3 student profiles, 2) considering instructional strategies that might move students towards Principle-oriented Level 3, and 3) discussing implications for further examination of these hypotheses in different contexts.

Introduction

Developing explanations of matter and energy in socio-ecological systems has been identified as a productive practice for student progression towards environmental literacy (Mohan, Chen, & Anderson, 2009; *Next Generation Science Standards*, 2013). Using the laws of conservation of matter and energy to constrain accounts of carbon-transforming processes is a powerful tool for interpreting global processes (e.g., carbon cycling and climate change) as well as everyday events (e.g., decay, combustion, and growth and movement of plants and animals)

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(Hartley, Wilke, Schramm, D'Avanzo, & Anderson, 2011; Rice, Doherty, & Anderson, 2013, in press). However, many secondary and undergraduate students struggle to apply these laws in their explanations of carbon-transforming processes and other scientific phenomena.

The purpose of this paper is to examine possible alternate trajectories students take as they progress towards sophisticated reasoning about carbon-transforming processes in various contexts. We build on the levels of achievement developed in previous work in learning progressions for environmental reasoning (Table 1) as a way to characterize student accounts.

Table 1. Defining characteristics of four levels of achievement of the Learning Progression Framework

Level 4: Coherent Scientific Accounts. Students successfully apply fundamental principles such as conservation of matter and energy and genetic continuity to phenomena at multiple scales in space and time (generally consistent with Next Generation Science Standards).
Level 3: Incomplete or Confused Scientific Accounts. Students show awareness of important scientific principles and of models at smaller and larger scales, but they have difficulty connecting accounts at different scales and applying principles consistently.
Level 2: Elaborated Force-Dynamic Accounts. Students' accounts continue to focus on actors, enablers, and natural tendencies of inanimate materials, but they add detail and complexity, especially at larger and smaller scales force dynamic reasoning.
Level 1: Simple Force-Dynamic Accounts. Students' accounts focus on actors, enablers, and natural tendencies of inanimate materials, using relatively short time frames and macroscopic scale phenomena.

This learning progression framework divides learners into four levels: Level 1 students have naïve or beginning understandings of the subject matter at hand, while Level 4 students have progressed to a sophisticated understanding and are able to engage in discourse constrained by scientific principles. This paper focuses on student reasoning at Level 3: Incomplete or Confused Scientific Accounts.

Research focused on science learning has consistently shown that students come to the science classroom with intuitive ideas and notions that they have developed through everyday experiences (Smith, Wiser, Anderson, & Krajcik, 2006). These initial understandings often differ from scientists' views of how the world works. As students progress from initial understandings to scientific accounts of the world they retain some of their initial naïve understandings and mesh them with newly acquired scientific knowledge as they progress to scientific understandings, creating what Gotwals and Songer (2009) have called the "messy middle." Gotwals and Songer (2009) suggest "there are multiple 'messy middles' students may move through as they develop the ability to reason about complex scientific situations" (p. 259).

Assuming that student pathways to the upper anchor are non-linear and various, we might assume one goal for learning progression researchers is to characterize these multiple pathways so as to support educators in curriculum design, assessment, and instruction. This study interprets interviews from undergraduate pre-service elementary school teachers enrolled in a science course with the goal of characterizing how students in the messy middle progress towards sophisticated reasoning about scientific processes and principles in the course of one semester of instruction.

This paper aims to address *theoretical* and *pragmatic* goals. Our *theoretical* goal is to identify potentially "productive" learning trajectories students may follow in the construction of knowledge about matter and energy in socio-ecological systems. To address this goal, we analyze accounts of carbon-transforming processes from two students who represent distinct Level 3 student profiles: Principle-oriented Level 3 (PL3), and Fact-oriented Level 3 (FL3). These profiles represent alternative pathways students might take when developing scientific discourses about matter and energy in socio-ecological systems. By a "productive" learning trajectory, we mean a trajectory that will be beneficial as a student moves through the messy middle to achieve Level 4 reasoning.

Our *pragmatic* goal is to identify instructional and assessment strategies that will help educators guide their students along more productive pathways towards mastering these scientific discourses. To address this goal, we propose instructional and assessment strategies that may support educators, and suggest future research agendas that might further our understanding of these strategies.

Drawing on data from undergraduate teaching candidates' written assessments and interviews, we hypothesize that Allen (our PL3 student) may be in a better position to move to Level 4 reasoning in a class that incorporates instructional strategies that use conservation laws as *tools for analysis,* whereas Jake (our FL3 student) may have a more difficult time progressing to Level 4 reasoning in the same class. Although we envision this paper as a starting place in a longer process of inquiry into the complex nature of the "messy middle," we begin this inquiry by 1) proposing two distinct Level 3 student profiles, 2) considering instructional strategies that might move students towards Principle-oriented Level 3, and 3) discussing implications for further examination of these hypotheses in different contexts.

Methods

This study represents early steps in the process of validating a learning progression framework for matter and energy in socio-ecological systems that includes multiple trajectories to Level 4 reasoning. This study, like other learning progression research, follows an iterative process including many tests and levels of revision (Gotwals & Alonzo, 2012; Jin & Anderson, 2012a).

In these first steps, we began with learning progression frameworks previously developed for energy (Jin & Anderson, 2012) and environmental literacy (Gunckel, Mohan, Covitt, & Anderson, 2012). Employing this framework as a model for student progression from lower to upper anchor accounts of scientific phenomena, we conducted an analysis of student interviews to look for characteristics of student reasoning in the messy middle (Level 3 students). Pre interviews were transcribed and analyzed, paying special attention to how students at Level 3 discussed:

1) matter (i.e., how do students talk about matter, materials, atoms, and molecules?)
2) energy (i.e., how do students talk about forms of energy, transformations of energy, and energy degradation?), and
3) context-specific knowledge (i.e., how do students use knowledge of local processes and systems, particularly carbon-transforming processes?).

Examples of Level 3 reasoning were taken from a total of 20 pre and post interviews collected in 2012-2013. The sample consisted of undergraduate pre-service elementary teachers enrolled in a science course at a large midwestern university. Students enrolled in this course were selected because the instruction is designed specifically to help students employ the laws of conservation of matter and energy as a reasoning framework for understanding natural phenomena (Rice et al., 2013, in press).

Pre-interviews were conducted before the semester of instruction, and post-interviews were conducted at the end of the semester. Students completed a written assessment with a total of four items designed to elicit their ideas about matter and energy in natural systems (Appendix A). Students were then asked to explain their selections during clinical interviews that followed the written assessment. The interview protocol (Appendix B) includes additional items designed to elicit student reasoning about matter and energy in natural systems.

After reading the pre-interview transcripts, a coding scheme was developed based on the patterns identified in the transcripts and was then applied to the transcripts. We identified patterns in student ideas as they progressed over the course of the semester, and transcripts were placed in one of four categories (Level 2, Principle-Oriented Level 3, Fact-Oriented Level 3, and Level 4) based on the student responses across all items (Appendix A). Implications of these multiple trajectories identified during this process are discussed in the results section.

Results

The interviews in our sample included Level 2, Level 3, and Level 4 accounts. In our analysis, we focused on the Level 3 accounts—the "messy middle." All Level 3 students were alike in two ways:

1. *Attempting to trace matter and energy:* In contrast with Level 2 students, Level 3 students understood that we were asking them to trace matter and energy through carbon-transforming processes and attempted to do so.
2. *Missing important details:* In contrast with Level 4 accounts, the Level 3 students lacked detailed knowledge of the particular systems or processes that they needed to trace matter and energy through the processes we asked about.

These patterns are consistent with our prior work and explained in more detail in previous publications (Jin & Anderson, 2012b; Mohan et al., 2009). In this study, though, we focused in particular on differences we saw among the Level 3 accounts. In particular, we saw two important kinds of differences:

1. *Conservation laws as principles rather than facts:* All Level 3 students were aware of conservation of matter and energy. For some students, though, the conservation laws seemed to be "facts" they could choose to include or leave out of a particular account. Other students showed a *sense of necessity* in applying conservation laws: They recognized the laws as "rules" that constrained every account of a chemical or physical change.
2. *Precision and consistency in using matter and energy words.* We also noticed differences in the ways that students used some key words describing matter and energy: *matter, materials, atoms, molecules,* and *energy.* Some Level 3 students consistently used these words with clear and distinct meanings; other Level 3 students were "fuzzier" in their word usage and implicit definitions.

In this section we first illustrate those differences using two students, Jake and Allen, as examples. We then discuss how Jake and Allen exemplified more general patterns in the Level 3 accounts that we analyzed.

Pre-Interview Results

The following interview excerpts are taken from the pre-interview transcripts with two of the participating undergraduate pre-service elementary school teachers, Allen and Jake (pseudonyms). Although Allen and Jake were both identified as Level 3 students at the beginning of the semester, the following section highlights some of the differences in their responses that emerged from the transcripts. The following excerpts are responses to an item called ECOSHPERE, which consists of a written explanation, a prompt, and a picture (Appendix B).

Table 2. Level 2, 3, and 4 partial responses to the ECOSPHERE item (pre-interview)

<table>
<tr><th colspan="2">ECOSPHERE</th></tr>
<tr><th colspan="2">Level 4</th></tr>
<tr><td colspan="2">INTERVIEWER: Let's see, so do you think that matter changes from one form to another in the ecosphere?
LEVEL 4 STUDENT: Matter as in…I think molecules—the atoms won't change, but they'll recombine with other molecules—with other atoms forming different molecules in whole system. But the atoms themselves are all the same.</td></tr>
<tr><th>Jake (Level 3)</th><th>Allen (Level 3)</th></tr>
<tr><td>INTERVIEWER: So, when the matter is changing forms, like you said, and making new molecules does any of the matter ever get used up?
JAKE: Yeah.
INTERVIEWER: Okay. How does that happen?
JAKE: Well, it's getting used up by the algae and the shrimp because they are consuming it to stay alive inside the orb. And it is being used up through them and being worked off through the physical energy that they're creating.</td><td>INTERVIEWER: Do you think that matter changes from one form to another in the ecosphere?
ALLEN: Since there's no exchange out—so yeah, probably. If it got really hot in there, the water would do like—evaporate into the space and then when it cooled, it would go back to its liquid form. So, definitely within the water.
INTERVIEWER: Okay. Does matter get used up when it changes form in the ecosphere?
ALLEN: No. There's always the same amount whether of what state it's in.</td></tr>
<tr><th colspan="2">Level 2</th></tr>
<tr><td colspan="2">INTERVIEWER: Do you think that matter changed from one form to another in the ecosphere? Why not or how does that happen?</td></tr>
</table>

LEVEL 2 STUDENT: Matter changing from one thing to another…I wouldn't really think so just because there's really no source to make it change. Everything in there is pretty natural.

We note three patterns in comparing Jake's and Allen's responses to one another and to the Level 2 and Level 4 accounts:

1. *Distinguishing levels of accounts:* The Level 4 student responded to the deliberately vague question by switching to the atomic-molecular scale and making conceptual distinctions among three key words—*matter, molecules,* and *atoms*—then explaining how the conservation laws apply to atoms but not molecules. Both Jake and Allen understood the question, but they struggled to answer in a way that was clear and concise with respect to all the processes taking place inside the ecosphere, focusing instead on particular examples and claims that were not fully responsive to the question. The Level 2 student, in contrast, doesn't really "get" the question, failing to see *anything* that happens inside the ecosphere as an example of matter changing from one form to another.
2. *Use of conservation laws as principles rather than facts:* Although in other parts of the interview (see Table 3 below) Jake used conservation reasoning, he failed do so here, using a series of phrases implying that matter or energy can be created or destroyed: "consuming it," "used up," and "worked off through physical energy [the algae and shrimp] are creating." Although Allen could not explain how matter is conserved in all the processes taking place inside the ecosphere, he chose an example—evaporation and condensation—where he was confident and explained how conservation laws applied to that example.
3. *Precision and consistency in word use:* Neither Jake nor Allen matched the Level 4 student's move of switching to the atomic-molecular scale, then making quick and precise distinction among *matter, atoms,* and *molecules.* There are important differences in the way they used matter and energy words, however. Jake used the vague pronoun "it"

in response to a question about matter, and by the end of his response, "it" seemed to be associated with the "physical energy that they are creating." In contrast, Allen chose a specific type of matter—water—and traced it quantitatively through changes of state.

It might appear from the excerpt above that Jake is simply like the Level 2 student with respect to conservation principles—he simply fails to understand that matter must be conserved. Looking at Jake's responses to other questions, though, we can see that this is not quite the case. When we examined their entire interviews across all items, another important difference in Jake and Allen's reasoning emerged. In Table 3, below, we see both Jake and Allen following the rules in their responses to the GLUBEX item (Appendix A). The GLUBEX item was designed to elicit student reasoning about atoms and molecules in the context of a mystery organism. Allen adhered to principles of matter conservation in suggesting that the atoms of the glubex cannot gain weight, saying: "atoms cannot gain mass." Similarly, Jake declared that it would be impossible for glubex to make new atoms because "you can't exactly create new atoms from atoms that have already been created." If we were to read only the excerpts below, we might assume that Jake and Allen are both able to apply the principles of matter and energy to their understanding of natural systems.

Table 3. Jake and Allen both "follow the rules" in these sections of their responses to GLUBEX in their pre-interviews.

GLUBEX	
Jake	Allen
JAKE: 'Glubex used chemical energy stored in its fat to make new atoms.' I put possible, but I'm not sure about that anymore. **INTERVIEWER**: Well why did you put possible then? And you could change it, it's okay. But what was your reasoning behind that? **JAKE**: As soon as I saw, 'Chemical energy stored in its fat,' I just thought of hibernation. So I was just like, 'Oh yeah. That's possible.'	**INTERVIEWER**: And so, if you could just go down through each one and explain your answers? **ALLEN**: Okay. So, for the scientist could've made a mistake would be possible because he could've just recorded it wrong. I put that atoms could not have possibly gotten heavier due to the fact that atoms cannot gain mass… **INTERVIEWER**: Okay. **ALLEN**: Then, the last two I put impossible

But I didn't read the rest saying, 'new atoms' and I'm like, 'It wouldn't exactly create new atoms inside the fat.' So I'm going to say impossible on that one. I could be wrong, what do I know. And divided to make new cells that made new atoms too? Wouldn't that just make new molecules? Wouldn't the atoms still be the same, even if it divides? So you can't exactly create new atoms from atoms that have already been created.	because atoms cannot be created or destroyed. So, those two options of creating them or like getting rid of them wouldn't be possible.

When we read these excerpts from Jake and Allen's pre-interviews (Table 3), we do not identify any problems in the reasoning provided by either student. They both "follow the rules:" They use the terms *matter, material, atom,* and *molecule* in concordance with scientific uses of these terms, they do not suggest that matter or energy are created or destroyed, and they do not suggest that energy can turn into matter or matter can turn into energy. However, if we revisit Table 2, we will recall that Jake contradicted these principles of matter in part of his response to the ECOSPHERE item. He suggested in that excerpt that matter was "used up" and turned into energy that was "created." This exposes an inconsistency in the reasoning Jake used to explain phenomena in the world: In some responses he adhered to these principles, but then he contradicted himself later by suggesting that matter gets "used up" and turned into energy.

This is in contrast to Allen's responses *across* items in the written assessment and interview, in which he consistently adhered to the principles of matter and energy. Allen never "broke the rules" in his explanations of scientific phenomena. Even in times in which his context-specific knowledge was insufficient to provide an entirely precise account of a phenomenon (e.g., cellular respiration, photosynthesis), he did not transgress the principles of matter and energy in times of uncertainty about the details of the phenomena in question. Thus Allen showed a *sense of necessity* about following the rules that Jake did not.

Post-Interview Results

Considering the differences observed in Jake and Allen's pre-interviews, their progress over the course of the semester is not surprising. Coding of Allen's post-interview transcript revealed that Allen successfully achieved Level 4 reasoning across items after the semester of instruction. However, after the same semester of instruction, Jake was still a Level 3 student. The excerpts from their post-interviews below (Table 4) show that although Jake had pieces of the story, he was still unable to trace matter through the ensuing processes when a shrimp eats it, and he suggested in response to the ECOSPHERE prompt that it gets "used up" and is "gone." Allen, in contrast, was able to move into an atomic-molecular scale (which he was unable to do in the pre-interview) and described what happens to the matter with sophistication typical of Level 4 students.

Table 4. Excerpts from Jake and Allen's post-interviews after the same semester of instruction. Both Jake and Allen began the semester as Level 3 students. After the same semester of instruction, Allen progressed to Level 4 reasoning, whereas Jake remained a Level 3 student.

ECOSPHERE	
Jake (Post Interview)	**Allen (Post Interview)**
INTERVIEWER: Okay, Do you think that matter changes from one form to another inside the ecosphere? **JAKE**: I [am] trying to remember this. I don't think matter does change. It does, but it's like it…it's weird, it's like it moves to the next…It's like 90 percent of it is burned off and 10 percent of it is stored into its next host as you will. So, yeah, I guess the matter does…no matter still stays the same because the CO_2 goes out of the shrimp and back in, so it's still like it's CO_2. It the carbon that goes from to another to another, so. **INTERVIEWER**: Okay. Does matter get used up in the ecosphere? **JAKE**: Yes. **INTERVIEWER**: Okay, how does that happen? **JAKE**: It's at the final stage on decomposers. Once everything is gone the decomposers have nothing else to feed upon, so that's how it's	**INTERVIEWER**: So, do you think matter changes from one form to the other in the ecosphere? **ALLEN**: Yeah. **INTERVIEWER**: How would that happen? **ALLEN**: I guess because molecules are being rearranged and a bunch of different processes throughout like the algae make their own food and then like the shrimp using the matter in different ways, breaking down the molecules and then also the bacteria breaking it down so there's always change of atom groups. But then all the atoms still exist overall. **INTERVIEWER**: So, does the matter get used up when it changes form? **ALLEN**: No, it's constant.

used up.	

Discussion

Differences in Tracing Matter and Energy

Jake and Allen exemplified two different patterns that we saw in students' Level 3 accounts. As we noted at the beginning of the Results section, the Level 3 accounts all shared some similarities. In contrast with Level 2 students, Level 3 students responded to the interviewers' question by attempting to trace matter and energy through carbon-transforming processes without being completely successful. In contrast with Level 4 accounts the Level 3 students lacked the detailed knowledge of the particular systems or processes we asked about that they needed to trace matter and energy through the processes.

Differences in Context-specific Knowledge.

Level 3 accounts differed from Level 4 accounts in use of *context-specific knowledge.* By context-specific knowledge, we mean content knowledge needed to explain specific scientific phenomena. For example, context-specific knowledge needed to explain how a plant gains mass might include details about 1) photosynthesis, biosynthesis, or cellular respiration, and 2) the molecular structure of the tree, the soil, and the air. A Level 4 student has the context-specific knowledge needed to explain how the tree's mass comes mainly from carbon and oxygen atoms taken from the carbon dioxide in the air; a Level 3 student who has less context-specific knowledge would believe that the mass must come from *somewhere,* and might be able to explain some details of photosynthesis (at varying scales), but might have trouble using information about photosynthesis to explain the plant's mass gain, and might suggest that the mass comes from water, soil, nutrients, sunlight, or air. Some of this knowledge is specific to the context of a plant gaining mass, and entirely different from the knowledge needed to answer an item about, for example, what happens to the mass in ethanol when it burns.

In the case of ethanol burning, the context-specific knowledge needed to answer this question might include details about 1) combustion, and 2) the molecular structure of the ethanol and the air. A Level 4 student will have the context-specific knowledge to identify that the carbon atoms from the ethanol are released as carbon dioxide into the air; a Level 3 student who has less context-specific knowledge knows that the mass must go *somewhere,* and might be able to provide some details about combustion (at various scales), but might suggest that the mass, turns into heat or goes into the air.

Analysis of our interviews suggests that Level 3 students in "the messy middle" are able to draw on relatively similar stores of context-specific knowledge for most carbon-transforming processes and natural phenomena about which they were prompted. In this way, they are similar.

Differences in Ways of Using Conservation Principles.

We should note that using context-specific knowledge to interpret natural phenomena draws on a different funds of knowledge than following the rules when interpreting natural phenomena. It is in this way that Jake and Allen exemplify different kinds of incomplete accounts. Context-specific knowledge can be used to explain a particular phenomenon in specific contexts (fact-oriented) whereas the "rules" are reasoning principles we can apply across all contexts (principle-oriented).

Identifying students who employ the rules of matter and energy as *reasoning principles* (Table 5) helps us distinguish between students like Jake, who inconsistently follow the rules, and students like Allen, who consistently follows the rules. Students like Allen apply the rules to interpret scientific phenomena across contexts, using the rules as reasoning principles. For example, when explaining how a plant gains mass, student might know that "matter is not created or destroyed," and recognize that the matter that makes up the plant has to come from somewhere. A Level 4 student who uses the conservation of mass as a reasoning principle to explain this phenomenon might say that a plant takes carbon out of the air and uses it to make glucose molecules, which are then rearranged during biosynthesis to create the biomass of the plant.

A Level 3 student who uses the conservation of mass as a reasoning principle to explain this phenomena might say that a plant must get the matter from somewhere, but isn't sure where (and may suggest that the matter comes from air, water, or soil, but NOT from sunlight). Thus Level 4 reasoning and principle-oriented Level 3 reasoning were alike in that both Level's responses used the principles of conservation of matter and energy as described in Table 5.

Table 5: Reasoning principles in principle-oriented Level 3 accounts. The second pattern that emerged when coding the interview transcripts was the students' use of the "rules" of matter and energy as reasoning principles.

	The "Rules"	**What to look for**
Reasoning Principle 1: Conservation of Matter	Matter cannot be created or destroyed in physical and chemical changes. Matter can be traced through carbon-transforming processes. Matter cannot be converted to energy or created from energy.	Do students suggest that matter is created or destroyed? Do students try to trace matter through carbon-transforming processes? Do students suggest that matter can be turned into energy or created from energy?
Reasoning Principle 2: Conservation of Energy	Energy cannot be created or destroyed in physical and chemical changes. Energy can be traced through carbon-transforming processes. Energy cannot be turned into matter or created from matter.	Do students suggest that energy is created, destroyed, or "used up?" Do students try to trace energy through carbon-transforming processes? Do students suggest that energy can be turned into matter or created from matter?
Reasoning Principle 3: Precise and Consistent Use of Matter and Energy Words	<u>Matter</u> and <u>energy</u> are separate entities that can be traced through carbon-transforming processes. <u>Matter</u> cannot be created or destroyed, but <u>materials</u> can be deconstructed and cease to exist. <u>Atoms</u> cannot be created or destroyed or gain mass, but	Are students able to trace matter and energy separately through carbon-transforming processes? Do students use precise language to distinguish between matter and materials?

	molecules can be deconstructed and cease to exist. Energy cannot be created or destroyed, but forms of energy such as heat, light, and chemical energy can be created from other forms of energy or cease to exist.	Do students use precise language to distinguish between atoms and molecules? Do students use precise language to distinguish between energy in general and specific forms of energy?

Fact-Oriented and Principle-Oriented Level 3

The differences between Jake and Allen above suggest that Allen uses the reasoning principles above (Table 5) of conservation and energy as a reasoning framework to interpret scientific phenomena in all contexts, whereas Jake considers these principles of matter and energy "facts" in a long list of other facts memorized in a science class. We think this difference between Jake and Allen represents two Level 3 profiles: Fact-Oriented Level 3 (Jake), and Principle-Oriented Level 3 (Allen). These two profiles, then, represent two distinct trajectories to Level 4 reasoning.

Principle-Oriented Level 3 (PL3) students consistently use the laws of matter and energy as organizing principles to explain natural phenomena. For example, a PL3 student might use her understanding of the rule "atoms cannot be created or destroyed" to trace carbon atoms from CO_2 in the atmosphere to glucose in a leaf (as a result of photosynthesis). Because a PL3 student knows that the rule "atoms cannot be created or destroyed" is always true, she will use this to constrain all of her accounts of natural phenomena, recognizing that the material of a leaf could not have been created from nothing or from energy. Although the PL3 student is not familiar with all of the context-specific knowledge needed for Level 4 reasoning, she will not break the rules in the construction of these accounts. For example, when asked where the glucose in a leaf comes from, a PL3 student might not know that carbon atoms in the glucose come from carbon atoms in CO_2. However, the PL3 student in this situation will not suggest that the atoms were created by the plant or that they came from sun energy.

Fact-Oriented Level 3 (FL3) students see the laws of matter and energy not as a reasoning framework or as "rules" to apply, but instead as another "fact" in a long list of facts they have to memorize in order to learn school science. An FL3 student might state, "atoms cannot be created or destroyed" in response to one item, but then in another item break this rule in an attempt to describe a natural phenomenon. For example, the FL3 student might suggest that the carbon atoms were either created by the plant or that they came from energy. In this sense, FL3 and PL3 students are similar in the amount of context-specific knowledge they have about natural phenomena, but they differ in that FL3 students will sometimes break the rules in their accounts of these phenomena, whereas PL3 students will adhere to the rules across all accounts.

Based on our analysis and results, we hypothesize that Principle-Oriented Level 3 students (like Allen) are in a better position than Fact-Oriented Level 3 students (like Jake) to move to Level 4 reasoning. We think this is the case for a few reasons. To explain our reasoning for this hypothesis, we should examine the similarities and differences we have identified between Principle-Oriented Level 3 and Fact-Oriented Level 3 students.

Challenges For Future Research and Practice.

Testing this hypothesis presents distinct challenges. For one, to assess a student as FL3 or PL3, a researcher or teacher must be able to examine a student's responses in multiple contexts. Both FL3 and PL3 students may state that "energy cannot be turned into matter" in one context, but the PL3 student will consistently adhere to this principle across contexts, whereas the FL3 student will be inconsistent in the application of this rule. For this reason, classifying students into PL3 or FL3 profiles using written assessments requires assessment of a student's responses across multiple assessment items. This presents a challenge for future research, as we often develop coding rubrics to characterize student reasoning for *individual* items that elicit student reasoning about specific carbon-transforming processes or phenomena, rather than a rubric that characterizes consistency across *multiple* items.

A second challenge is in using this information for formative assessment practice in science classrooms. Considering the applicability of the findings of this research for formative assessment, we are developing instructional supports to scaffold teachers in their use of this information to assess their students' learning. However, in order for a teacher to identify a student as PL3 or FL3, s/he will need to assess a student's performance across contexts, which would likely occur over a span of time. This means that this information might not be available to a teacher early in instruction for formative assessment. Teachers will need professional support to help develop the skills to recognize the difference between PL3 and FL3 students, which is an ongoing process.

A third challenge is that we are able to identify PL3 and FL3 characteristics in interview items better than in written response items. In an interview setting, we are able to probe student thinking with follow up questions, which is not possible with written assessments alone. We are currently working on scoring rubrics for individual written items, but so far we are limited in our ability to code these items. For example, in a typical MS/HS Carbon written assessment item, we are able to categorize student responses into three levels: *2, 3,* and *4*. We predict that we will be able to divide student responses from these items using our new coding scheme into four groups: *Level 2*, *FL3*, *PL3,* and *Level 4*. However, this is not the case with new items like GLUBEX, which was designed to isolate student reasoning of principles of matter and energy. This item provides no context (natural phenomena) to give us clues about the students' context-specific knowledge, requisite for Level 4 answers. So, instead of *Level 2, PL3, FL3,* and *Level 4,* we are instead able only to divide into *L2, FL3*, and *PL3/L4*.

The coding scheme developed for interviews with the undergraduate students will be applied to the interviews with MS/HS students. Both the undergraduate and the MS/HS subjects are enrolled in classes that use the laws of matter and energy as organizing principles. We wonder if our coding rubric will identify similar or different patterns in the MS/HS students' thinking and reasoning about matter and energy in socio-ecological systems.

Results of our pre/post assessments show that most students enter both grades 6-12 and undergraduate science classrooms at Level 2. Few students are able to use Level 4 reasoning at the end of the year. Helping Level 2 students move towards PL3 might be a valuable place to focus our efforts in the development of curricular materials for teachers and students.

Other Questions.

We wonder how theories of motivation might shed light on our understanding of this pattern. For example, what motivates a PL3 student to exhibit a *sense of necessity* (Jin & Anderson, 2012b) to adhere to principles of matter and energy? How are students motivated extrinsically and intrinsically to "follow the rules?" Does the type of motivation make a difference in outcomes of student learning? And finally, what does it take for students to start seeing the "facts" in relation to the "rules?"

Finally, we wonder how the use of metacognitive learning tools might scaffold students in their progression from Level 2 to PL3 and Level 4 reasoning. The Carbon TIME curriculum uses a "Three Questions" strategy (Appendix C) to help students check their own accounts of matter and energy in natural systems. For example, after students record their initial ideas about carbon-transforming processes (e.g., photosynthesis, digestion, biosynthesis, cellular respiration, combustion, and fermentation) they are asked to evaluate their own responses to see if their responses "follow the rules." Do atoms endure? Do you trace matter separately from energy? Does energy last forever? We wonder how asking students to use metacognitive processing tools might serve as a scaffold to help move them to PL3 and L4 reasoning.

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Appendix A (written test)

MOUSEGROW

A student was studying how mice grow. He collected these data:
Mass of mouse at the beginning of the experiment: 50 g
Mass of mouse one week later: 60 g
Mass of water that the mouse drank: 30 g
Mass of food that the mouse ate: 30 g

The student said, "The food and the water weighed the same amount, so growing mice get half of their weight from food and half from water."

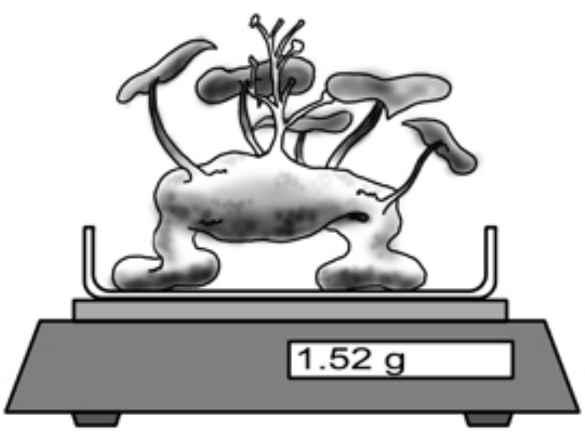
Do you think that the student's conclusion is correct? *Circle one:* Yes No

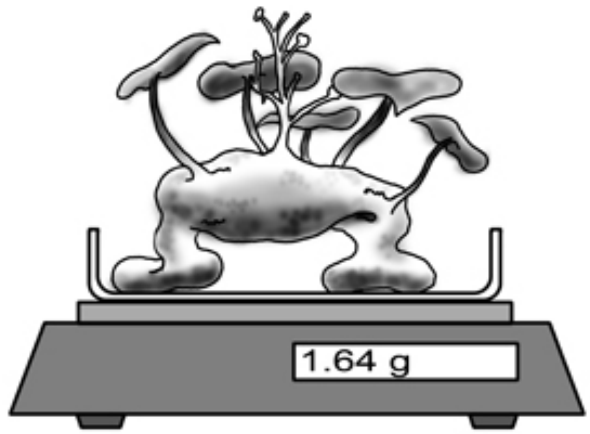
Explain your reasoning. Why is the student's conclusion correct or incorrect?

What questions about the mouse growing remain unanswered after collecting this set of evidence?

GLUBEX

A scientist has discovered a new living organism: the **glubex**. He put a glubex on the scale, weighed it, and left it alone for one day. Here is what he found:
Original mass of the glubex: 1.52 grams
Mass of the glubex after one day: 1.64 grams





Decide whether each of the following explanations is possible or not. ***Circle your choices***:

The scientist made a mistake when he weighed the glubex	Possible	Impossible
The atoms of the glubex got heavier when the glubex gained weight.	Possible	Impossible
Atoms that were outside the glubex moved into the glubex.	Possible	Impossible
The glubex used chemical energy stored in its fat to make new atoms.	Possible	Impossible
When the cells of the glubex divided to make new cells, it made new atoms, too.	Possible	Impossible

If you decided that any of the explanations were ***impossible***, explain why you decided that.

PLANTDATA

A student has 6 plants growing in pots. A student predicted that the weight of the plants in the pots would increase while the plants are growing.

The student collected the following data:

Weight of the container with the plant **Before (g)**	Weight of the container with the plant **After (g)**	**Change** in weight of the container with the plant (g)
5.23	5.45	+0.22
5.03	4.82	-0.21
4.77	5.96	+1.19
5.16	5.29	+0.13
4.87	4.77	-0.10
5.12	5.08	-0.04
Average: 5.03 g	**Average: 5.23 g**	**Average: + 0.20 g**

Do the data support OR not support the prediction of the student?

Why or why not?

Appendix B – Interview Protocol

PL3 & INQUIRY INTERVIEW PROTOCOL

Think-Alouds: give the student about 15 minutes to read and write down answers to these questions. Then ask them to explain why they wrote what they wrote. Additional follow-up probes below.
Mousegrow
Glubex
Plant Data

Regular interview-style question, using picture cards as prompts:
Karen & Mike
Meadow

Think Alouds follow-up probes:

1) Mousegrow:
Explain each of your responses.

What does this experiment and evidence tell you about where mice get their weight?
What do you think about the quality of this student's claim based on this evidence?
If you were going to explain to another student WHY this is a bad claim based on this evidence, what would you say?

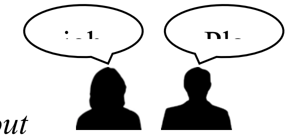
2) Glubex:
Explain each of your responses.
[Have them explain ***all*** choices, both the "possibles" and "impossibles." The "correct" answers are "possible, impossible, possible, impossible, impossible."]

3) Plant data:
Explain your response.
Then:

- Are their certain lines of data that support the claim, and others that do not?
- What are possible sources of error in the experiment?
- Do you have any comments on the quality of the data from this experiment? What is good or bad about these data?

KARENMIKE

[Show the image of Mike and Karen silhouettes.]

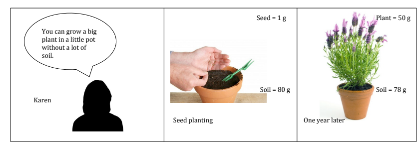


"We are interested in how people use evidence to support their ideas. We're going to talk about two students who disagree with each other about how plants gain weight when they grow. One student Karen said: "The plant gains most of its weight from materials that came from the air.'

"Another student, Mike said: 'The plant gains most of its weight from materials that came from nutrients in the soil.'

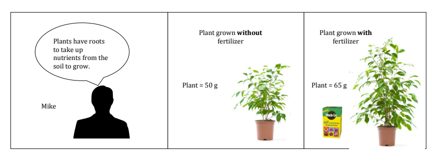
1. *"Who do you think is right?"*

"Now let's talk about the quality of their arguments that support their idea." [**Start with the argument that the student agrees with; either Karen or Mike could be first. Show the card associated with Karen or Mike one at a time.**]



Karen who you _____ [agree/disagree] with, explains, 'You can grow a big plant in a little pot without a lot of soil.' Karen adds some evidence to her argument and explains 'A seed weighing 1 g was planted in 80 g of soil. After two years the plant was removed from the soil and both were dried and weighed. The plant weighted 50 g and the soil weighed 78 g.'

1. *"Can you explain Karen's argument?"*
2. *"How does Karen's argument support her idea that the plant gains weight from materials that came from the air?"*
3. *"Are their some weaknesses in Karen's argument? Explain what they are."*
4. *What evidence would strengthen Karen's argument? How would it strengthen the argument?*
5. *Are there any other explanations for Karen's evidence that Karen hasn't considered?*



Mike who you ____[agree/disagree] with explains, 'Plants have roots to take up nutrients from the soil to grow.' Mike adds some evidence to his argument and explains 'A plant grown with no fertilizer weighed 50 g, and a plant grown with 3 g of fertilizer weighed 65 g.'"

6. "*Can you explain Mike's argument*?"
7. *"How does Mike's argument support his idea that plant gains weight from materials that came from the soil?"*
8. *"Are their some weaknesses in Mike's argument? Explain what they are."*
9. *What evidence would strengthen Mike's argument? How would it strengthen the argument?*
10. *Are there any other explanations for Mike's evidence that Mike hasn't considered?*

ECOSPHERE

[Use the card for ecosphere question]

[Tell the Student:] *"NASA scientists invented the EcoSphere – inside a completely sealed glass container, (there is no opening at the top of the jar!) there are air, water, gravel, (the branch-like thing is just for show) and three living things – algae, shrimp, and bacteria. (Identify the shrimp and algae as the **green parts like a plant**, you can't see the bacteria.) Usually, these three living things can stay alive in the container for two or three years until the shrimp become too old to live. The picture above shows an EcoSphere and it's inside parts. The EcoSphere is a closed ecosystem and has no exchange of matter with the outside environment."* **Note:** be sure to mention that the algae are like a plant.

1. *"How can the algae/shrimp/bacteria **[ask about one organism at a time]** stay alive? Do you think algae/shrimp/bacteria can get everything it needs? What are those things? Where do they come from?"*

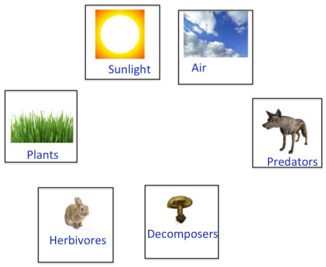
2. *"Do you think that matter changes from one form to another in the ecosphere? Why not? or How does that happen?" "Does matter get used up when it changes form in the ecosphere?"*

3. *"Does any energy go into this ecosphere? How does that happen?"*

4. *"Do you think that energy changes from one form to another in this ecosphere? Why not? or How does that happen?" "Does energy get used up when it changes form in the ecosphere?"*

5. *"Does any energy go out of this ecosphere? How does that happen?"* [If student says energy is coming in but not going out ask: "*Energy goes in but not out of the ecosphere, do you think that is a problem?*"]

ECOSYSTEM



[Show the image of the ecosystem.]
"Here is a model of an ecosystem. Each box represents something in the ecosystem."

"What do the boxes mean to you?"
"Is there any difference between how the model looks here and what it represents in real life?"
"Which of these things in the boxes have matter?"
[Start with the rabbit box, if they mention the rabbit box having matter]
"Where did that matter come from?"
"Does any matter go in or out of the boxes? Does any matter go between the boxes? What kind of matter goes between the boxes?"
"Can you trace where matter might move between the boxes, and tell me what kind of matter is moving?" [Student should say out loud, and may also draw on the picture with arrows.]

Ask a series of follow-up questions if they need help:
"Could matter that is in the rabbit box end up in the air box?"
"If so, how?" (possible follow up to these)
Could matter that is in the air box end up in the rabbit box?
"Could matter that is in the rabbit box end up in the grass box?"

Ask some follow-ups on interesting connections, for example: *"You say matter moves from [decomposers] to [air] how does that happen?"*
"Do you feel like your drawing is complete?"

"Let's consider the whole ecosystem that this model represents. If we look at the same ecosystem a year later, will the same matter be in it? How might it have changed?"

"Which of these things in the boxes have available energy? What kind of energy?"
"Where did the energy come from?"
"Does any energy go in or out of the boxes? Does any energy go between the boxes? What kind of energy?"
"Can you trace where energy might move between the boxes, and tell me what kind of energy?"
[Student should say out loud, and may also draw on the picture with arrows. Use a different color for energy!]

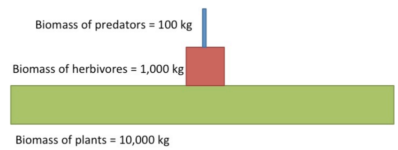
Ask a series of follow-up questions if they need help:
"Do you need other boxes to show where the energy comes from and goes to? Add them to the picture and draw arrows to show how energy moves from them or to them."
"Could energy that is in the rabbit box end up in the air box?"
"If so, how?" (possible follow up to these)
Could energy that is in the air box end up in the rabbit box?

"Could energy that is in the rabbit box end up in the grass box?"
Ask some follow-ups on interesting connections, for example: *"You say energy moves from [herbivores] to [air] how does that happen?"*
"Do you feel like your drawing is complete?"

"Let's consider the whole ecosystem that this model represents. If we look at the same ecosystem a year later, will the same energy be in it? How might it have changed?"

Only if needed: "*You said that energy is coming in, but not going out. Is that a problem?*" OR "*You said that energy is going out, but not coming in. Is that a problem*?"

BIOMASS PYRAMID



Here is another model of an ecosystem. The pyramid shows the distribution of biomass in a typical terrestrial ecosystem. The pattern is the same in almost all ecosystems: The biomass (living matter) of plants is much more than the biomass herbivores, and the biomass of herbivores is much more than the biomass of carnivores. Why do you think that this is true?

Do you think it would be possible for the predator biomass to be as large as the herbivore biomass?

Appendix C – Three Questions Table

Question	Rules to Follow	Evidence to Look For
The Movement Question: Where are atoms moving? Where are atoms moving from? Where are atoms going to?	**Atoms last forever** in combustion and living systems All materials (solids, liquids, and gases) are made of atoms	When materials change mass, atoms are moving When materials move, atoms are moving
The Carbon Question: What is happening to carbon atoms? What molecules are carbon atoms in before the process? How are the atoms rearranged into new molecules?	Carbon atoms are bound to other atoms in molecules **Atoms can be rearranged to make new molecules**	The air has carbon atoms in CO_2 Organic materials are made of molecules with carbon atoms • Foods • Fuels • Living and dead plants and animals
The Energy Question: What is happening to chemical energy? What forms of energy are involved? How is energy changing from one form to another?	**Energy lasts forever** in combustion and living systems C-C and C-H bonds have more stored chemical energy than C-O and H-O bonds	We can observe indicators of different forms of energy • Organic materials with chemical energy • Light • Heat energy • Motion