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MATTER AND ENERGY TRANSFORMATION: AN INVESTIGATION INTO SECONDARY SCHOOL STUDENTS' ARGUMENTS

By

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ABSTRACT

MATTER AND ENERGY TRANSFORMATION: AN INVESTIGATION INTO SECONDARY SCHOOL STUDENTS' ARGUMENTS

By

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Arguments are important to the construction of scientific knowledge and practices including the development of skills and tools for assessing that knowledge. Whereas research on arguments continues to accumulate, there is little evidence that this work focuses on the development of both instructional and assessment tools to support students in using empirically verifiable data and make connections of data to claims about natural phenomena. In this dissertation study, I use a modified version of Toulmin's (1958) model of argument analysis to examine the kinds of Data and Warrants, and sometimes Backing (elements of argument) students use to support the Claims they make about matter and energy (e.g. see Jin & Anderson, in preparation) in their oral arguments about the Carbon Transforming Processes (CTPs) of Tree Growing (TG), Flame Burning (FB), and Car Running (CR).

Findings from this study suggest that students use different kinds of elements to support their Claims. In particular, more sophisticated responses tend to be characterized by those elements that appeal to scientific principles. However, less sophisticated responses tend to include elements that are, for example, analogical, and/or tautological, as well as personal beliefs to support the Claims made about these processes, and thus tend toward force-dynamic reasoning (Pinker, 2007). Implications for teaching, learning and research in science education are included.

Dedication

I dedicate this dissertation study to my loving family. First, to my understanding, patient, and lovely wife Stella, who has endured long years of conceiving and writing this study. Second, to my adorable children Bitutu, Nyanchera, and Onyancha who have born my long absence with a child's unbelievable humility-they are the joy of our family. Third, to my mother Josephine B. Onyancha for her motherly love from which I have always drawn full and unconditional support. Fourth, is a piece of dedication to my siblings for generously sharing their childhood dreams with me and urging me to reach for the skies. Finally, to my late father Benson Onyancha who instilled in me a sense of respect, hard work, truthfulness, and pursuit of knowledge.

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I would like to thank my graduate colleagues whose contributions made this Dissertation a reality today: Li Zhan who helped me with reliability checks, besides data collection; Hui Jin, Jing Chen, Jonathon Schramm, Hamin Baek, Jennifer Doherty, and Dante Cisterna who helped me with Data collection and organization.

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Note: **"Images in this dissertation are printed in color."**

Chapter 1: Introduction and Rationale

Important educational documents on reform-based science education (e.g. National Science Education Standards, 1996) have focused on and advocated for helping students to achieve scientific literacy. Research on science literacy, especially in learning progressions (e.g. Alonzo & Steedle, 2008: Mohan, Chen & Anderson, 2009), is expanding. In addition, school curricula have been developed partly in response to calls focused on helping students to achieve proficiency in science (NRC, 2007). This regards knowing, using, and interpreting scientific explanations of phenomena (NRC, 1996).

My study aligns with these goals for science teaching and learning. This study is part of our larger environmental science literacy project that focuses on the quality of students' accounts (Claims) of natural phenomena: in this case Carbon Transforming Processes (CTPs). In the project, we analyze claims they make relating to the role of matter and energy in individual processes, such as tree growing, baby girl growing, girl running, tree decaying, flame burning, car running, lamp lighting, and cross processes and how these connect to claims they make about larger environmental issues, for instance, global climate change.

The primary cause of global warming is the current worldwide imbalance among three classes of carbon transforming processes: (a) organic carbon generation (photosynthesis), (b) organic carbon transformation (biosynthesis, digestion), and (c) organic carbon oxidation (cellular respiration, combustion). Mohan et al. (2009) have analyzed students' accounts of these processes. This study is focused on the nature of arguments (Carlsen, 1997; Erduran et al., 2004; Gotwals et al., 2009; Newton et al., 1999) students construct in support of their claims. This is from a learning progression perspective which is described as sequenced and successively more complex ways of thinking about a topic that learners master and investigate over a broad span of time (Mohan, Chen, & Anderson, in press; NRC, 2007; Popham, 2007; Smith, Wiser, Anderson, & Krajcik, 2006).

Recent research on learning progressions (e.g. Alonzo & Steedle, 2008; Covitt et al., 2009; Jin & Anderson, 2008; Mohan, Chen, & Anderson, 2008) has shown that students have difficulties with the practice of tracing matter and energy in socio-ecological systems. We view socio-ecological systems as the intertwining of the social and ecological systems. Often, and as Mohan et al. report, students have matter and energy disappearing in their accounts of processes involving changes in states or forms. If research has to serve the goal of achieving science literacy for all students, then the practices relating to student reasoning about matter and energy should be explored in-depth as a way of informing both research and instruction. This way, it is possible to make sense of some of the challenges students face in learning science and use or design matching programs for supporting them in their efforts to overcome these challenges. This study is focused on making sense of students' arguments regarding matter and energy in socio-ecological processes such as Tree Growing, Flame Burning, and Car Running.

Purpose of the study

The purpose of this dissertation study is to seek to understand how students use evidence in constructing arguments. This involves analyzing elements of arguments (Toulmin, 1958) such as Data and Warrants, treated more fully under the analysis section, to support Claims regarding scientific processes about matter and energy transformation as a way of learning to talk science (Lemke, 1990). The view of learning to talk science encompasses "observing, describing, comparing, classifying, discussing, questioning, challenging, generalizing, and reporting among other ways of talking science" (p. 1).

The idea of learning to talk science in educational settings presupposes that, besides helping learners to learn how to use scientific practices in their specific forms, it is important too that their use does not impede such learning. This view tends to align with the Practices of Responsible Citizenship proposed by Covitt et al. 2009. I use this framework and argument as inquiry to contextualize my study within the larger environmental literacy project. That is, I bound my investigation within two scientific discourse community contexts: a) environmental literacy as described in the Practices of Responsible Citizenship framework which I briefly discuss next and b) the literature review relating to argument as inquiry.

Practices of Responsible Citizenship

I use Covitt et al.'s (2009) Practices of Responsible Citizenship framework, which lays emphasis on the practice of inquiry and argumentation, to help me bind this dissertation study within the larger environmental literacy project. In other words, this study is a slice of the larger environmental science literacy project. Covitt et al.'s theoretical framework relates to student involvement in intellectual work in the sense that it advocates for, to illustrate, students' engagement in socio-ecological issues in ways that likely lead to making environmentally responsible decisions. In their own words, Covitt et al. (2009) have argued that "when we judge that we don't know enough to make an informed decision, we investigate the problem, by inquiring directly into a situation or by relying on inquiry conducted by others" (p. 8).

Covitt et al. thus conceive supporting students in engaging in evidence-based scientific investigation and argumentation as practices of responsible citizenship and use them to frame our understanding of students' work regarding socio-ecological issues. I present this conceptual framework in figure 1 below. This view presupposes that students do not necessarily make decisions about socio-ecological systems based primarily on scientific reasoning. Rather, that they do so based on "many other factors—students' family and personal values, their common family practices, their identities, economic and social considerations, etc…" (p. 5). This framework lays emphasis on four domains: *Investigating*, *Explaining, Predicting, and Deciding.*

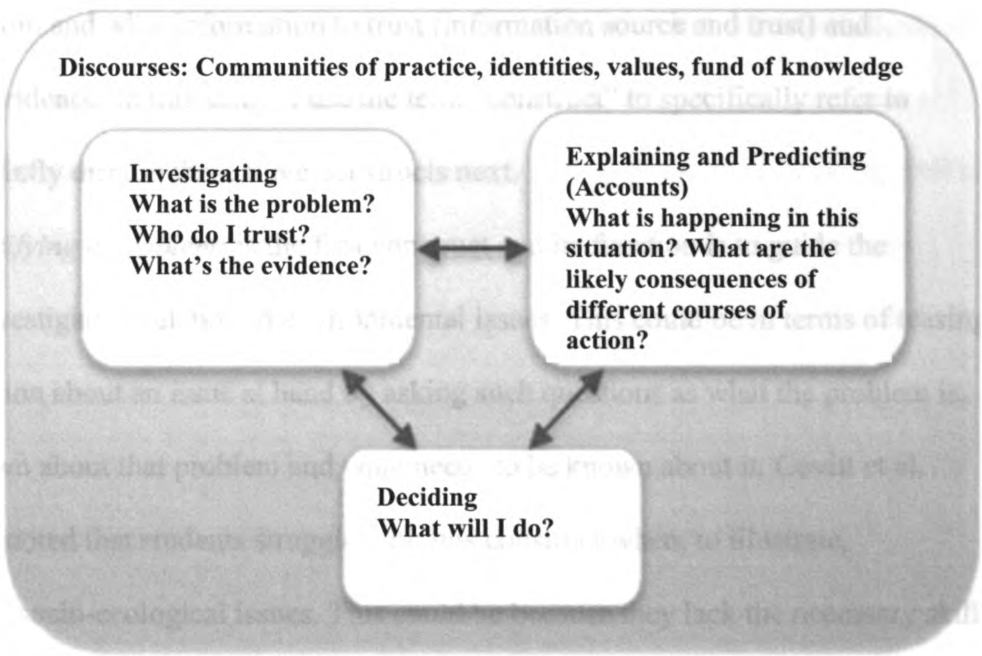

Figure 1: Practices of responsible citizenship

Although I make frequent reference to the accounts students make in their reasoning about Carbon Transforming Processes, this study mainly focuses on the domain of investigating. This is because our larger environmental literacy project work has covered the explaining and predicting domains as it relates to, for instance, water (e.g. Gunckel, Covitt & Anderson, 2009) and carbon (Mohan et al., 2009). Specifically, my focus is on how students use Data to defend the Claims they make in their oral work about transformations in matter and energy.

Research has shown that, although scientific practices are advocated in major science education documents [e.g. American Association for the Advancement of Science (AAAS), 1993 & NRC, 2007], students and other people as well, face challenges in carrying out this practice (Covitt et al., 2009; Lee & Songer, 2003). In this study, I use the inquiry domain of responsible citizenship to inform data analysis and interpretation. My hope here is to work toward contributing a possible solution to the challenges of practice that students face. This domain has three main constructs: Identifying a problem, deciding whom and what information to trust (information source and trust) and evaluating evidence. In this study, I use the term "construct" to specifically refer to concept. I briefly discuss these three constructs next.

Identifying a problem: is the first construct and its function is to guide the proposed investigation relating to environmental issues. This could be in terms of teasing out information about an issue at hand by asking such questions as what the problem is, what is known about that problem and what needs to be known about it. Covitt et al. (2009) have noted that students struggle with this construct when, to illustrate, investigating socio-ecological issues. This could be because they lack the necessary skills for using scientific information (Duschl et al., 2007) and therefore merely resort to, with little/no questioning, using social information sources and in effect treating these as authority.

Deciding whom and what information to trust: is the second construct and it regards reasoning about sources of information. This may be in terms of identifying, teasing out and selecting relevant sources of information needed for solving the identified problem. This amounts to making decisions about what sources of information to trust. Important education documents (e.g. NRC, 1996) recognize that encouraging students to be skeptical and engaging them in critically evaluating sources of information is important in making "personal and community decisions about issues in which scientific information plays an important role" (Duschl, et al., 2007 p. 7). However, pedagogy, curriculum and standards unlikely help students to achieve this goal because they tend to treat science as consisting "of solved problems and theories to be transmitted" (p. 3).

Evaluating evidence: is the third construct and it regards evaluating and using evidence in support of the claims made about the identified problem (Covitt et al., 2009): That is, in carrying out investigations about a clearly identified problem, this ought to be in concert with making decisions about what sources of data should be trusted, as well as how compelling the evidence is for use in solving the identified problem. My study focuses in particular on this aspect of investigating: using and evaluating evidence. In this study therefore, I examine students' reasoning in relation to argumentation as inquiry in their responses to questions about Carbon Transforming Processes. But before I specify the Research Questions that guide this study, I wish to note the link between argumentation and inquiry.

There is an association between Covitt et al.'s (2009) account of practices associated with decision-making in citizens' roles and argumentation as inquiry. As Covitt et al. inform us, people tend to ignore experts' perspectives on important issues such as global climate change because they either do not understand, for instance, the practices resulting in necessary decisions or simply tend to perceive the decisions as uncomfortable. Additionally, some individuals may base their decisions on sources of information they believe to be reliable with little/no regard for investigation. A consequence of this would be two or more individuals/groups with opposing viewpoints regarding environmental decisions with far reaching environmental implications.

On the one hand, if decisions about environmental issues are narrowly conceived, they are likely to lead to negative individual and citizenship choices. The likely narrow conception of important environmental issues points to possible challenges to science education. For instance, how might educators prepare all learners to work toward making environmentally responsible decisions now and in the future? For example, individuals, especially those in influential positions, may make or influence others to make little/no data-based decisions regarding, say Biofuel production (e.g. Gerbens-Leenes, et al., 2009) with a likely result of planting certain crops that are unlikely to deliver the results as claimed. To illustrate, these decisions may potentially lead to serious food shortages in the long run (e.g. see Wadhams, 2009). On the other hand, if well conceived, decisions are likely to lead to scientifically responsible citizenship choices, for example, why choosing energy efficient appliances over those that are energy inefficient as it relates to carbon footprint makes sense.

While it is important to focus on source of information and/or data as an aspect of making environmental decisions, it is equally important to see beyond source and consider quality of arguments based on those data. Thus, Covitt et al.'s (2009) study about the process of decision-making regarding socio-ecological issues suggests an in-depth analysis of students' claims about these processes and the quality of arguments they construct in support of those claims. An important step toward scientifically literate citizenry is to engage students in constructing arguments as they make sense of the world around them.

Argumentation as Inquiry and Research Questions

Literature on science education (e.g. Driver, Newton, & Osborn, 2000; McNeill, 2009) presents scientific argumentation, as it does explanations, as a practice of scientific inquiry. Indeed, the treatment of argument as a practice of inquiry is emphasized in current reform-based science (NRC, 1996): That is, with a focus on promoting scientific literacy among students, reform efforts point to the idea that in order to support inquiry, science instruction and learning should be anchored in argument and explanation. Moreover, researchers (e.g. Berland & Reiser, 2009; Clark & Sampson, 2007) view argumentation as being a central practice of science upon which inquiry and instructional goals are developed. Berland and Reiser, as well as other researchers (e.g. McNeill, 2009; Sandoval & Millwood, 2005) contend that argument and explanation are interrelated scientific practices of inquiry in that these not only emphasize building toward sense-making and articulation, but also toward persuasion regarding phenomena.

The view of argument as an aspect of *inquiry or investigation* (I use these terms interchangeably in this study) points to an age-old notion that substantial scientific knowledge is gained and developed through argumentation (Clark & Sampson, 2007). Indeed, Kilbourn (2006) contends that studies that aim to contribute to knowledge tend to "make claims…that are supported … by argument and evidence." And that these are "opposed to claims based on unwarranted opinion, ideology, dogma, power, and authority" (p 531). Again, this is suggestive: That argument is an integral part of inquiry.

The NRC (1996 & 2000) emphasizes the need to support students in the practice of developing deep understanding of scientific knowledge and skills. Zembal-Saul (2009) views this emphasis as supporting students in engaging in evidence-based scientific arguments, a shift from merely engaging them in a less effective exploration and experimentation focused on ascertaining scientific ideas which might be already known to students. Additionally, Zembal-Saul notes that this shift signals a "relationship between the goals of scientific inquiry and the practice of argumentation, constructing and evaluating scientific arguments as an aspect of engaging in school-based scientific inquiry" (p. 691). This is in line with other literature (e.g. Duschl, et al., 2007; Songer, Lee, & McDonald, 2003; White & Frederiksen, 1998) which indicates that students who engage in the practice of scientific inquiry of, say, identifying a problem, gathering data and evaluating it, as well as drawing data-driven conclusions demonstrate higher gains in science learning. These students too, according to literature (e.g. Mercer et al., 2004), are likely to engage in scientific arguments and in effect are likely to learn the practice of constructing data-driven arguments.

Furthermore, literature has indicated that learners who are engaged in the practices of scientific inquiry are likely to be motivated to learn science (Mercer et al., 2004; Mistler-Jackson & Songer, 2000; Okhee & Brophy, 1996; Tobin et al., 1999). To illustrate, Mercer et al.'s study about teacher scaffolding of student argumentation reported that those students who were engaged in argumentation contributed more to discussions and collaborated to reach consensus (based on scientific reasoning) than those who were not. Moreover, and as Bell and Linn (2000) inform us, students who engage in the practice of inquiry-based arguments are likely to promote knowledge integration. Additionally, these students' belief of science as dynamic would likely be related to the development of more complex arguments.

An equally important finding from the literature is that students who delve into the practice of scientific inquiry are not only likely to improve their metacognitive skills but also to experience conceptual change (e.g. Yore & Treagust, 2006; Duschl et al., 1999). Additionally, these students are likely to engage in intellectual development (Vygosky, 1986) based on, say, analytical (Toulmin, 1958) rather than rhetoric arguments (e.g. Driver, Newton, & Osborn, 2000). Consequently, these and other reasons arguably provide the impetus to use inquiry practices in both science learning and instruction.

For purposes of expanding on what is known about how students use arguments, I examined the quality of secondary students' arguments in their oral responses to questions about matter and energy transformation. To do this and to guide this study, I used the following research questions:

Research Questions

1. What is the nature of secondary school students' arguments about Carbon Transforming Processes (CTPs) such as photosynthesis (e.g. Tree Growing), and combustion (e.g. Flame Burning and Car Running)? How do these arguments align with the already established Claims (e.g. Mohan et al. 2009) about CTPs?
2. What is the nature of these arguments at two different points in time?

Before describing participants and data sources I include in this study (see Chapter 2), I would like to briefly explain the specific arguments I address in this study. Scientific studies present the nature of science knowledge as attempts to persuade others of the validity of their claims, rather than consensus based on democratic processes (e.g. Tippett, 2009). Indeed, other studies refer scientific argumentation to as the language of science in which claims are made in one way or another, and supported by data of some sort (Duschl, Ellenbogan & Eduran, 1999, in Tippett, 2009).

Whereas there are different forms of arguments, for instance, rhetorical/didactic arguments which present one point of view (Driver et al., 2000), and dialogical/dialectical arguments which explore different viewpoints during debate or discussion (Tippett, 2009), this study is focused on (I will return to this in the data analysis section) analytical argument as proposed by Toulmin (1958). This form of argument follows the rules of logic and is advocated for in reform-based science (e.g. Duschl & Osborn, 2002): That is, it is opposed to opinions and/or ideology. This study, therefore, lays emphasis on the quality of arguments students construct and diverges from the traditional rhetorical arguments characteristic of classrooms (Yore, 2003).

Dissertation Overview

This dissertation study consists of four chapters. In this chapter I identify and introduce the problem of the study by locating it within two contexts: First within our larger Environmental Science Literacy project relating to Practices of Responsible Citizens conceptual framework; and second within literature review relating to argumentation as inquiry. I also briefly discuss the purpose of the study and identify Research Questions that guide this study.

In Chapter 2, I present methods of data collection by first discussing research context, participants, and data sources. Then, I discuss data analysis for Research Question 1 in four steps: step 1 focuses on analyzing individual arguments by offering examples of analysis; step two focuses on developing coding rubric for Data and Warrants; step 3 discusses reliability checks; and step 4 focuses on finding patterns of association among Claims, Data, and Warrants. Additionally, I discuss data analysis for Research Question 2.

In Chapter 3, as an attempt to respond to Research Questions presented in Chapter 1, I present findings of this dissertation study culminating in a proposed Argument Levels of Achievement.

Finally in Chapter 4, I discuss limitations of the study as well as contribution of the study to the teaching and learning of science.

Chapter 2: Research Methods

Note: Images in this dissertation are presented in color.

In this chapter I describe the following aspects of my research methods:

- The context of the study
- The research participants
- The protocol for clinical interviews that were my data source, administered at two different points in time
- Role of interviewers
- Data analysis procedures for Research Questions 1 and 2

Context

This study is part of a larger multi-year Environmental Literacy Project work that draws from a learning progression perspective (Mohan, Chen, & Anderson, 2009; NRC, 2007; Popham, 2007; Smith, Wiser, Anderson, & Krajcik, 2006). The goal of the project has been to document students' reasoning about events in socio-ecological systems (Mohan et al. 2009). This includes their reasoning, at both the macroscopic levels (we can see with our eyes) and microscopic levels (we cannot see but can use a microscope to see), about carbon-transforming processes: Tree Growing, Flame Burning, Car Running (all 3 are the focus of this study), Decay and so on. The broader focus of this project therefore, is to develop a framework that describes students' reasoning as it specifically relates to Carbon Transforming Processes about the principles of matter and energy and broadly scientifically responsible citizenship.

Whereas the larger project includes such strands as water cycle, Biodiversity, and citizenship, this dissertation study is part of a carbon strand. For over five years now, work in this strand has focused on how students reason about Carbon Transforming Processes (CTPs) and developed a carbon cycle learning progression framework. This framework is characterized by 4 Levels of Achievement (For a more complete description, see Table 2, this section) as described by Mohan et al. (2009). Work on this framework suggests that each student's reasoning tends to fall into one of the four levels briefly described as follows:

- Level 1 students generate accounts that are characterized by force-dynamic reasoning (Pinker, 2007). These students view, to use Pinker's words, enablers (e.g. air, wood, gasoline, & sunlight) as needs that satisfy natural tendencies of actors (e.g. trees, flame, cars).
- Level 2 students similarly develop accounts that are characterized by force-dynamic reasoning but begin to recognize hidden mechanisms as driving carbon transforming processes. However, this recognition is limited to, for instance, viewing enablers as conditions for processes to happen rather than reactants in the same processes
- Level 3 students tend to generate accounts that begin to recognize transformations in matter and/or energy. However, they inconsistently apply the principles of matter and/or energy by, for example, reasoning that matter is converted to energy (and vice versa) during Carbon Transforming Processes
- Level 4 students generate accounts characterized by a recognition that Carbon Transforming Processes are driven by hidden mechanism: That transformations are constrained by scientifically established principles such as those of matter and energy conservation

In an attempt to make sense of students' reasoning about Carbon Transforming Processes, this study builds on this work by focusing on the kinds of data students present in developing their accounts and how these (data) align with the four levels of achievement just described.

Participants

In this study, I followed 16 secondary school students (6^{th} to 12^{th} grade) from four secondary schools in rural and suburban southwest Michigan. This included 4 males and 4 females for each grade level, a total of 8 males and 8 females. These students participated in a one-to two-month long learning progression intervention as they were taught using designed instructional tools about carbon transforming processes. The schools included two public middle schools, one public high school, and a math and science center for gifted high school students. All of the four teachers were science majors with at least a bachelor's degree. Using Michigan Science Curriculum Standards, these teachers tough units that that included Plants (e.g. needs of plants to grow and what is food for plants); Animals (e.g. what makes up food we eat and What happens to food in our bodies); Systems and Scale (e.g. Key Principles for reasoning about environmental processes-Scale, Matter and Energy) and Decomposers (e.g. What happens to dead plant and animal materials? and how decomposers work). Selected teachers and students came from school districts with a largely Caucasian student population (approximately 88%). In these schools, an average of 37% of the students received either free or reduced lunch.

Data Collection: Clinical Interview Protocol

I used data from clinical interviews regarding eight carbon-transforming processes including photosynthesis, biosynthesis, digestion, food chains, cellular respiration and combustion (Mohan, Chen, and Anderson, 2009; see also interview protocol below). This data was from student pre-post clinical interviews conducted during the 08-09 academic year. Student interviews lasted for approximately 40 minutes. My specific focus here was on students' use, if at all, of elements of arguments (Toulmin, 1958) described in detail in the analysis section, this chapter.

My analysis focused on the portions of the interviews that addressed three processes: Tree Growing (TG), Flame Burning (FB), and Car Running (CR). Although the interview protocol itself for these three processes is included in Appendix A, I offer its brief description here below. This is for purposes of illustrating the sort of questions we asked and how the interview progressed.

For both our large project on learning progression and this study, we developed an interview protocol to elicit students' understanding about eight focus environmental events: tree growing, baby girl growth, girl running, tree decaying, flame burning, car running, lamp lighting, and cross processes. All of these events involve organic carbon generation, transformation, or oxidation.

The interview protocol contains a set of semi-structured questions for each focus event. For each event, we started the interview with a set of *general questions*—questions that use everyday language to ask about the actor and its enablers. For example, the major general questions for Tree Growing are:

- What does a tree need in order to grow? How does sunlight help the tree to grow?
- Do you think that water will change into other materials inside the tree's body?

However, these general questions are not effective in eliciting higher-level accounts. Hence, we also ask follow-up higher-level questions which are more specific about matter, energy, and processes. One example is:

- You said that the tree needs Carbon dioxide and breathes out oxygen. Where do the carbon atoms of CO_2 go?

Teaching experiments (for details, see e.g. Jin & Anderson, in preparation): Before the intervention, the selected students responded to these kinds of questions. Depending on class schedules, the start of the intervention varied from school to school. During the intervention, teachers of these students used designed instructional tools (Tools for reasoning) to help them (students) work toward constructing scientific explanations of what happens to carbon during the aforementioned processes (Mohan et. al, 2009). An introduction to and an example of these tools is included in Appendix B.

After the intervention, the selected students responded to the same pre-interview questions. The purpose here was to seek students' reasoning about the same processes before and after more targeted instruction. The pre-posts provided students with two opportunities to explain their reasoning about Carbon Transforming Processes. This also allowed for what I view as a wide enough range of responses from which I could examine students' arguments. I analyzed pre-post interview data from 16 students (a total of approximately 32 interviews) for the Carbon Transforming Processes of Tree Growing, Flame Burning, and Car Running (a total of 83 arguments-some students did not complete all the events in their interviews).

Choices about elementary students' work and level 1 accounts: The fact that I was specifically interested in how students justified Claims about matter and/or energy, I did not include elementary students' work in the analysis. This was because most of these students' accounts did not include specific Claims about matter and/or energy. For the same reason, I did not consider Level 1 accounts from the selected secondary school students in this study. That is, my focus was on acquisition of scientific forms of argument or socialization into scientific practice, and not on analysis of a full range of arguments developed by students at all levels. On the basis of these decisions, my analysis will be limited to middle and high school students' arguments. This is with a likely consequence that I will be unable to establish a more complete picture of the nature of arguments across grade levels.

Role of interviewers

Before I briefly discuss the intended role of the interviewers during data collection, I would like to briefly provide a background in terms of planning for interviews. This likely sets the stage for the development of and use of the interview protocol, described in detail under Data Collection: Clinical Interview Protocol (see the preceding sub-section). To move toward interviewing identified respondents, the research team (PI, Co-PIs, and research assistants) planned for the interview. I should note here that I was one of the research assistants working on the project. Our focus was to first establish a common goal: To seek students' ideas about such processes as Tree growing, Flame Burning, Car Running, Lamp Lighting, and so on. Our overall goal was to use these ideas to design classroom tools/materials for use in teaching and learning science (see also introductory part of the interview protocol, Appendix A).

Second, we focused on constructing items around our overall goal, guided by the idea that each question was designed in such a way that it clearly sought as much information from the interviewees as possible. The constructed items were semi-structured and rank ordered from general (e.g. needs of each event) to specific (high level order) regarding matter and/or energy.

Throughout the planning sessions, we tried to make clear the intended role of the interviewers as including establishing a working relationship with the respondents through, for example, introducing her/himself to the respondent, explaining the general purpose of our study, and explaining that there were no "right" or "wrong" answers and that the respondent was free to ask any questions during the interview. Additionally, interviewers were to ask questions in the interview protocol (see Appendix A) and record data as verbatim as possible by videotaping the interview sessions.

Despite the identified efforts to assure consistency in interview approaches, interviewers were not entirely consistent during the interviews. To illustrate, some interviewers asked unintended leading questions. Although it may be true that the questions these interviewers asked were those on the interview protocol, some of the questions might have been worded in a way to suggest a likely sought for response: That is, for the most part, some interviewers paraphrased respondent's answers to the extent that this reflected the interviewer's views. Together, such questions and paraphrasing yielded responses characterized by either "Yes", "No" or both.

To minimize errors in my analysis therefore, I was not interested in "Yes" or "No" responses. Rather, I specifically focused on analyzing students' responses that had little suggested interviewer responses—I focused on what I viewed as respondents' verbal answers only but not those of the interviewer. The reason for focusing on students' responses was to make sure that the Data and Warrants I was coding came from students rather than from interviewers.

Data analysis for Research Question 1

My analysis for Research Question 1---What is the nature of secondary school students' arguments about Carbon Transforming Processes (CTPs) such as photosynthesis (e.g. Tree Growing), and combustion (e.g. Flame Burning and Car Running)? How do these arguments align with the already established Claims about CTPs (e.g. those by Mohan et al. 2009?) included four main steps. First, I used color codes to identify the key elements of Toulmin's framework in each student's arguments about Carbon Transforming Processes. Second, I developed coding rubrics to classify students' Data and Warrants according to their nature and level of sophistication. Third, I worked with a colleague to establish reliability for the codes. Fourth, I looked for patterns of association among Claims, Data, and Warrants. These steps are described below.

Step 1: Analyzing individual arguments

In this study, I used student interview texts (transcribed verbatim), to examine how they used data to defend their claims about how matter and energy are involved in Carbon Transforming Processes (CTPs). To help me to follow students' reasoning, I used Excel to organize data based on each CTP. Then I color-coded students' utterances for elements of Toulmin's analytical framework (e.g. see Examples 1 & 2, this Chapter).

Research Question 1 and Toulmin's analytical framework: For purposes of this analysis I used a modified version of Toulmin's (1958) model of argument to help me code transcripts in terms of students' arguments. The interviews were designed to elicit students' accounts or *Claims (C).* In particular, I was interested in the claims that students made about transformations of matter and energy during CTPs. I therefore sought to understand how students supported their *Claims* with *Data (D)* and usually *Warrants (W)*. These three elements constitute what Toulmin calls a *basic argument*.

I also examined how students used *Backing (B)* if at all, to construct arguments relating to Carbon Transforming Processes. But the interview protocols rarely elicited what Toulmin refers to as *complete arguments* (constituting Claims, Data, Warrants and Backing). I provide descriptions of these elements in Table 1 below, which I first generated from preliminary data analysis. A possible reason why the interview protocol rarely elicited complete arguments could be the nature of questions we asked---we rarely challenged students to justify their Claims in detail. Although my analysis focuses on basic arguments, I include analysis based on the element of *Backing*.

Table 1 has three columns: the first column shows the type of element present in an argument as identified by Toulmin (1958). The second column indicates Toulmin's descriptions of those elements. The third column shows a modified version of Toulmin's descriptions of the same elements. I included this modification to align with data for this study. In this study, I did not consider the elements of Qualifier and Rebuttal. This is because these did not emerge from data analysis.

Most students' accounts of Carbon Transforming Processes included the elements of Toulmin's basic argument. For example, through the questioning process, we began by asking students to provide what Chi (1997) calls "messy" data in the sense that it is in the form of verbal observations. In this study, I operationalize (Feest, 2005) Data to refer to information relating to, for instance, visible observations (inputs and outputs) about given Carbon Transforming Processes.

Table 1: Rubric for coding for elements of an argument

Element	Toulmin's Description	My Description
Claim (C)	The conclusion whose merits the proponent of the claim seeks to establish	Statement(s) students make about how matter and/or energy are involved in CTPs: Relate to hidden mechanisms
Data (D)	Evidence that the proponent of the argument clearly appeals to as a basis for the identified claim	Visible observation(s) about CTPs, regarding a claim that students may make: May include verbal observations-- - typically statements about needs of organisms or conditions for processes to occur and statements about visible results of processes.
Warrant (W)	General, hypothetical statements, which can act as bridges, and authorize the sort of step to which our particular argument commits us	Universal premises students make that link either one type of data and/or different types of data to the claim regarding specified CTPs.
Backing (B)	The credentials which are designed to certify the beliefs of the warrant	Universal premises students make that link warrants to theoretical frameworks which explain hidden mechanisms of CTPs

Then, we probed students to explain how that Data linked to the Claim they made (Warrants). Whereas I was particularly interested in Warrants that mention principles such as conservation of matter and energy or hidden mechanisms, I was also interested in analyzing other types of Warrants that students generated. Following this, we asked them to provide further information that supported the connection they made between Data and Claim (Backing). Here are two examples to illustrate the sort of analysis I did.

Examples of analysis

Example 1 illustrates a student's work (transcript) that uses Data and Warrants to support the Claims made in ways consistent with scientific standards of argument. By contrast, example 2 illustrates a student's work (transcript) that uses Data and Warrants in a more analogical sense to support the Claims made. Both transcripts focus on the process of Flame Burning (FB). In this process, we provided students with two pictures: one represented a match burning, and another represented a candle burning. For other examples of color coded Data and Warrants, see Appendix C, Tables C1 and C2 respectively.

Example 1: More sophisticated response. In the following interview transcript about match burning, I demonstrate how the dialogue between an interviewer (I) and a student (ANW) proceeded. In addition, I show how this dialogue likely aligns with Toulmin's analytical framework and how data analysis likely proceeded. The color codes, in the two examples below, represent specific elements as shown in the analysis after each transcript:

1. I: What does a flame need in order to keep burning?
2. ANW: It needs oxygen, wood, wax and wick in order to keep burning
3. I: What is in wood that makes it burn?
4. ANW: Wood has chemical energy and that's what makes it burn. You have to
5. have stored up energy to make it burn.
6. I: So, talk about chemical energy of the wood. So, when wood is burning,
7. where does that chemical energy to go?
8. ANW: It's what's being burned.
9. I: So, do you think the chemical energy still exists or somewhere or changing
10. to some other types of energy, or just burn up?
11. ANW: It changes into heat and light energy.
12. I: Oh, so chemical energy changing to heat and light energy. Very good. So,
13. how about wood?
14. ANW: When wood burns the, it gives off the same things from the candle

15. burn, carbon dioxide and water (inaudible).

Data: From this dialogue, ANW offers, what she considers to be needs or inputs of the process of Flame Burning that it "needs oxygen, wood …in order to keep burning" (line 2, blue highlight). Given the descriptions in Table 1 above, this chapter, I consider this to be **Data**. Noticeably, in this interview, the interviewer influences the direction of the dialogue in, for instance, focusing it on wood only with no mention of other needs for Flame Burning (FB) that ANW identifies. For this reason, the interviewer probes about the specific premise of the need for wood for the flame to keep burning. Wood, as a need for flame burning, is therefore presented both as a source of chemical energy and as a raw material for matter transformation. Indeed, when further probed about the material of wood, ANW proceeds to account for it saying that it is given off in the form of carbon dioxide and water (lines14-15). I regard these two products as Data in the sense that they are visible results of FB which ANW uses to make claims about energy and matter.

Claim: When the interviewer further probes about energy, ANW provides information about the energy of wood, that it "changes into heat and light energy" (line 11, green highlight). That is, ANW seems to suggest that when a match burns, the chemical potential energy of the wood is transformed into other forms of energy, in this case, heat and light. Based on the descriptions in Table 1 above, I consider this to be a Claim about how energy is involved in Flame Burning (FB).

In addition, she points to the idea that wood, on burning, chemically transforms, implicitly though, into water and carbon dioxide (lines 14-15, green highlight) in the argument she makes: That is, ANW suggests that some hidden mechanism happens to wood with the resultant observable water and carbon dioxide. I consider these two statements as **Claims**, one about energy (from the preceding paragraph), and another about matter, in the sense that the argument develops around both energy and matter: That is, these are the main parts of the argument around which the interview is developed.

Warrants and Backing: After being probed by the interviewer about how wood helps the flame to burn, ANW points to the idea that wood has chemical energy (line 4, Pink highlight). This statement suggests the notion that wood is a source of fuel necessary for the process of Flame Burning. This way, the statement would serve as a universal premise to link wood to the process of FB. Thus, this statement would be part of the **Warrant** she provides to support the need for wood in this process. Moreover, she seems to more fully offer a universal premise in support of the idea that wood is needed for the flame to keep burning saying, "You have to have stored up energy to make it burn" (lines 4-5). This seems to be what Toulmin calls personal knowledge that wood has indeed energy necessary for the flame to keep burning. ANW therefore successfully links Data to the claim she makes regarding both energy and matter transformations. ANW's work contrasts with JMJ's work which I present in example 2 below.

Moreover, ANW correctly suggests the idea that both energy and matter are neither created nor destroyed during flame burning (lines 11, 13-15). Rather, though implicitly, that these are conserved during this process. That is, ANW seems to point to the idea that the energy and matter of wood are constrained by the laws of conservation of energy and matter which explains the hidden mechanisms, in this case, relating to Flame Burning (FB). I interpret this implicit understanding and use of universal (scientific) laws in support of the identified warrant (see Transcript above) as implicit

Backing. This is on the basis that it supplies more information about not only warrants but also the claims ANW provides and in the process, validating them.

Example 2: Less sophisticated response. In this example, I provide and analyze an interview dialogue between an interviewer (I) and a student JMJ for the same process as in example 1above ---FB. This analysis pertains to how JMJ attempts to both use Data and link it to the Claims, about matter and energy, she attempts to make in the interview. Here is the interview dialogue:

16. I: What does a flame need in order to burn? ...
17. JMJ: It needs the gas that they put on it. Like…
18. I: What gas?
19. JMJ: The gas that burns … like for the candle or the match …like the wood on the match
20. I: Ok. So what happens to the air when the flame uses it to keep burning?
21. JMJ: The *air like gets taken over by all the gases* in the flame. And then it uses the air.
22. I: Now what do you mean by take over?
23. JMJ: It like … I mean *it already is a gas but it makes it like a burning gas.*
24. I: Ok. …Why does the flame need wax and wood …? What happens to them?
25. JMJ: *It will disappear* because …*wax and wood are kind of like flames' food... without it,*
26. *they'll just die off.*
27. I: Oh. Ok. …And then do you think the wax and the wood are kind of used up?
28. JMJ: *Yes.*
29. I: Ok. So do you think this burning is kind of related to energy?
30. JMJ: Yes.
31. I: Could you give me more explanation about that?
32. JMJ: burning using energy just to stay alive…*without …energy, it's going … die*
33. I: So do you think the energy is created… [or] comes from like a wax or a wood or air?

34. JMJ: I think it comes from – *it's created*. So *it's kind of chemistry*. So like when two

35. things come together, there's that energy to burn.

36. I: Ok. So energy is created.

37. JMJ: Yes.

Data: As in example 1 above, JMJ was provided with two pictures: one represented a match burning, and another represented a candle burning. The dialogue above is therefore based on questions about Flame Burning in the two pictures. From this dialogue, and like ANW, JMJ provides what she considers to be an observation (**Data**) that the flame needs "gas" (line 17, blue highlight) which she likens to the candle, match, and wood (line 19, blue highlight) to keep burning. From this interchange, the interviewer takes it that JMJ is talking about air, candle, and wood (line 19) as needs, and therefore, in this case, constituting Data for the flame to keep burning. Moreover, after being probed about what happens to wax and wood (line 24), the student seems to think that they disappear. Thus, although JMJ's idea of wax and wood disappearing reveals her thinking, it suggests that this reasoning does little to conserve matter. With the assumption that JMJ is treating air, candle, and wood, as needs, the interviewer shifts his questioning from seeking ideas for more needs to focus on more information regarding these three needs.

Although the interviewer later uses wax in place of candle (line 24), he probes for JMJ's understanding regarding how (see Dialogue above) the three needs relate to flame burning. Thus, air, wax, and wood are seemingly treated as raw materials in the sense that without, for example, wood and air (Oxygen), the process of flame burning will not proceed. The shift in focus seems to be about seeking to understand JMJ's thinking about how matter and energy are involved.

Claim: To further understand how JMJ reasons about Flame Burning (FB), the interviewer explicitly focuses the student's attention on both matter (lines 27 & 28) and energy (lines 29 & 30). When JMJ responds to the interviewer's questions, she suggests, implicitly, two points. First, that the matter of wax and wood are used up in flame burning, and in effect implying that that is how it should be, a view that is force-dynamic (e.g. Mohan et al. 2009) in nature. Unlike ANW who perceives FB as constrained by transformations of matter and energy, JMJ perceives the flame as needing wax and wood (matter) to keep it alive (lines 25-26). Compared to ANW's perception, I consider JMJ's perception as constituting a different kind of Claim: That matter undergoes some mechanism with the result that, rather than change of form, it ceases to exist.

Second, JMJ acknowledges that burning is somehow related to energy (line 30). Nonetheless, when asked for further information regarding this relationship (line 31), rather than focus on energy transformation, she contends that burning uses energy "to stay alive" without which the flame will "die" (line 32). In contrast to ANW who treats energy as one of the constraints of FB, JMJ perceives energy as causing this process to happen and helping the flame to stay "alive." In addition, JMJ maintains, as she similarly did regarding wax and wood (line 25), that energy is "created" (line 34), rather than a manifestation of energy transformation.

Furthermore, JMJ points to the idea that some hidden mechanism, which she refers to as "chemistry," (lines 34 – 35) happens to result into the energy of burning. I interpret this, implicitly, as constituting the Claim about energy. Again, this Claim is of a different nature from ANW's in the sense that it presents hidden mechanism in a mysterious way (line 34, green highlight). In addition to specifically probing JMJ about matter and energy, the interviewer also seeks to understand how JMJ thinks the data (inputs and outputs) link to the claim made.

Warrants: When JMJ is asked by the interviewer about how air (lines 20 & 22), wax, and wood (line 24) help the flame to burn, she reasserts her original Data (lines 21 & 23, Pink highlights). In fact, rather than provide a scientific bridge (Toulmin, 1958) between these three needs and the Claim about matter and energy, JMJ provides human analogy that connects claims to data in an entirely different way (see pink italicized texts). This is unlike ANW who points to the idea that wood has chemical energy (line 4, pink highlight). JMJ uses a Warrant that is analogical in nature to link the identified Data to the Claims—fuel for the fire is like food for a person. Arguably, using Warrants that are analogical in nature, in contrast to ANW's responses, is less sophisticated.

Step 2: Developing coding rubrics for Data and Warrants

These two examples just presented raise important questions that relate to my research questions. For instance, what is the nature of all other individual students' arguments? How do individual arguments relate to those of other students? These are among the questions I used in both guiding further data analysis relating to Claims, Data, Warrants, and/or Backing as well as identifying patterns that arose from all the 16 students. But before I followed examples 1 and 2 to code all of the 16 respondents' data, I made a decision about the unit of analysis.

I designated an individual argument as all responses by a student in a single process. For example, if a student did both pre and post-interviews in relation to the process of Tree Growing, then her/his responses will constitute two arguments (one for pre, and the other for post). In this study, I decided to use a single argument, for instance, pre-interview for a specific process such as Tree Growing, as my unit of analysis---post-interview for the same process will constitute another argument. The reason for this decision is that this study was not about case studies of the interviewees. Rather, it was about the nature of their arguments about Carbon Transforming Processes. A consequence of this choice is likely to be that I will not be able to specify why a students' argument changed, if at all, in particular ways. The overall focus here therefore was to identify characteristics associated with elements of argument (Claim, Data, Warrants, and/or Backing) rather than how each student's arguments changed. It is for this reason that I used Mohan, et al.'s (2009) Levels of Achievement to classify the Claims in each argument. Then, I developed rubrics for classifying Data and Warrants, as described below.

Identifying levels of Claims: Mohan et al. define "*Levels of Achievement* as patterns in learners' knowledge and practice that [extend] across processes" (p 8). In this study, I focused my description of levels of achievement on students' knowledge and therefore use of elements of arguments as described in Table 1 above to construct their arguments regarding Carbon Transforming Processes: That is, for each level, I tried to describe how each of the identified element is factored into the students' arguments.

Mohan, et al. (2009) and other papers from the environmental literacy project provide rubrics for sorting claims into levels of achievement. For example, Table 2 illustrates the rubric we are currently using to designate levels of explanations in students' claims (from Jin, Zhan, & Anderson, in preparation).

Table 2: Levels of Claims

Level 4. Linking processes with matter and energy as constraints	Linking carbon-transforming processes at atomic-molecular, macroscopic, and global scales with matter and energy as constraints
Level 3. Changes of Molecules and Energy Forms with Unsuccessful Constraints	Link macro-processes with change of molecules and/or energy forms at atomic-molecular or global scale, but cannot successfully conserve matter/energy.
Level 2. Force-dynamic accounts with hidden mechanisms	Link macro-processes with unobservable mechanisms or hidden actors (e.g., decomposer), but the focus is on enablers, actors, abilities, and results rather than transformation of matter and energy.
Level 1. Macroscopic force-dynamic accounts	Describe macro-processes in terms of the action-result chain: the actor use enablers to accomplish its goals; the interactions between the actor and its enablers are like macroscopic physical push-and-pull that does not involve any change of matter/energy.

My study sought to find similar patterns in Data, Warrants and/or Backing. That is, what is the nature of each of these elements at each level of Claim? In particular, I report results based on analysis of arguments from all the 16 students. However, I should note here that some students did not complete all the interviews---some completed pre only, others post only, yet others partially completed pre-post interviews. I coded arguments for the processes of Tree growing, Flame burning, and Car Running from pre- and post-interviews for each student—a total of 83 arguments.

I was specifically interested in how students justified Claims about matter and/or energy. I looked for patterns of association between the Levels of Achievement in students' accounts and the nature of the Data and Warrants (and sometimes Backing) they used to support their claims.

Some of these characteristics are suggestive in the two examples (this Chapter):

- For instance, ANW'S idea that ***"Wood has chemical energy…"*** [Warrant] and that this energy is transformed ***"…into heat and light energy…"*** implicitly suggests an understanding of the law of conservation of energy-that energy is neither created nor destroyed during flame burning [Backing]. This kind of Warrant and Backing appeal to scientific principles regarding energy.
- In addition, ANW's idea that the flame needs "…wood …" (input) to burn and that "When wood burns it gives off… carbon dioxide and water…" (output) [Data] demonstrates her understanding that matter inputs (e.g. wood) undergo chemical processes resulting in different kinds of matter outputs. This kind of Data, like the Warrant and Backing in bullet 1 above, appeal to scientific principles regarding matter.
- In contrast to ANW, JMJ's idea that ***"wax and wood are kind of like flames' food…"*** [Warrant] and that, ***"without it, they'll just die off"*** points to the idea that this student understands the process of Flame Burning in terms of actors and enablers. This suggests a different kind of Warrant that is analogical in nature.
- Moreover, JMJ's idea that when wood burns, ***"It will disappear"*** [Data] demonstrates reasoning based on enablers and actors. This suggests a different kind of Data that is readily noticeable in nature.

Second, after color coding responses from all the 16 students, I used Excel to sort the transcript into Data and Warrants. I copied these into worksheets labeled All Data and All Warrants respectfully. I have included examples of color coding for the two elements of argument in Appendix C, Tables C1 and C2. This coding helped me to indentify, from general codes, the specific codes present in an argument.

Rubrics for classifying types of Data in students' arguments: Table 3a represents a snapshot of the coding for specific Data that emerged from data for all the 16 students. It shows a number of codes and their labels (in parenthesis) as identified from the data. I conceptually organized these codes based on how they relate to the principles of mater and/or energy. This was in the order of codes with little or no reference to either one of or both of these principles (least sophistication) to those that relate to one or both of the same Principles (most sophistication). For specific examples and a more detailed description of each of these codes, Tables 4a and 4b (Data) and 5 (Warrants), Chapter 3.

Before I get into the details regarding the kinds of codes I use to show patterns that emerged, I wish to try to present the distinctions among the identified three categories of the codes. Codes with least sophistication are compatible with force dynamic reasoning: the needs and results that they identify are more like causes and effects in a story than like matter and energy that are being transformed. They show little commitment to conservation of matter and/or energy. Codes with intermediate sophistication are characterized by some force dynamic reasoning and at the same time, show some commitments to conservation of matter and/or energy---these codes suggest unsuccessful conservation of the principles of matter and/or energy. Codes with most sophistication are compatible with the principles of matter and/or energy: the needs and results that they identify align with matter and/or energy transformation in the sense that the inputs and outputs are consistently accounted for in a specified process. Here below, I briefly discuss by offering examples of each category of these codes.

Codes with Least Sophistication: these include;

- Needs Other (NO) which refers to the needs that suggest conditions-they do not relate to either matter or energy
- Results Energy Other (REO)-results that suggest specific forms of energy for other processes and/or treats inputs as results and/or physical observations and/or matter inputs as energy results
- In this category too was the code Results Matter Other (RMO). These are Results that suggest specific forms of matter for other processes and/or specific matter resource for other processes and/or treats inputs as results and/or visible observations and/or energy/matter inputs as matter results.

Codes with moderate sophistication: these include;

- Needs Energy General (NEG)-suggest non-specific forms of energy/or energy source
- Needs Matter General (NMG)-Needs that suggest non-specific forms of matter and/or treats results as input
- Results Energy General (REG)-suggest non-specific forms of energy for a process
- Results Matter General (RMG). These results suggest non-specific forms of matter and/or treats results as input.

Codes with most sophistication: Among these are;

- Needs Energy Specific (NES). These suggest specific forms of energy and/or location of energy for a specific process
- Needs Matter Specific (NMS) which point to specific forms of matter and/or specific matter resource for that (specific) process
- Results Energy Specific (RES) show specific forms of energy for a specific process

- Results Matter Specific (RMS)-point to specific forms of matter and/or specific matter resource for that (specific) process.

I should point out here that whereas Needs refer to inputs of Carbon Transforming Processes, Results refer to outputs of the same processes-these are of different types as indicated in Tables 4a and 4b, Chapter 3. For example, whereas gasoline and oxygen may be inputs or needs for the process of Flame Burning, the Results or outputs would be carbon dioxide, light energy and heat for the same process.

For each student's argument, I used the code one (1) to indicate that a specific Data type is present, and code zero (0) to indicate that a specific code is absent. For example, from Table 3a, whereas both codes NMS and RMS are suggested (Blue highlight) and therefore present (coded 1 each), all other codes are absent (all coded 0).

Table 3a: Example coding for specific Data in transcript

	Data type present (1)/absent (0)										
Transcript	**NO**	**NES**	**NMS**	**NEG**	**NMG**	**REO**	**RMO**	**RES**	**RMS**	**REG**	**RMG**
Interviewer: What does the tree need in order to grow? ***RKC***: The air, yes, all kinds of plants take in carbon dioxide as animals take in oxygen, plants take carbon dioxide and they exhale oxygen for us to breathe. ***Interviewer***: I'm going to ask you for different things… How does water help the tree to grow? (Does it change in any way? Where does it go?) ***RKC***: It helps create glucose for the food that, not food, but sugar I guess that the tree grows on and draws its energy from through photosynthesis again. I use that word a lot. I believe it's $6H_2O$ and CO_2 turn into $C6H1_2O6$ with is glucose and then $6O_2$ which is oxygen. So oxygen is like a byproduct of (inaudible)	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**

Rubrics for classifying types of Warrants in students' arguments: Like Table 3a, Table 3b represents a snapshot of coding for specific Warrants that emerged from data for all the 16 students. It also shows a number of codes and their labels (in parenthesis) regarding Warrants as identified from the data. These codes too fall into three categories organized from the least to the most sophisticated.

Codes with least sophistication: these include;

- Analogical (A) indicated by statements which point to inference based on resemblance of enablers/processes that are otherwise dissimilar
- Tautological (T) shown by statements that reassert the already mentioned data, suggesting that these are sufficient to justify their Claims
- Other properties of enablers Matter (OEM)-associate properties of matter inputs/outputs to non-key matter enablers for a specific process and/or some properties of one type of matter input/output to others
- Other properties of enablers Energy (OEE) which associate properties of energy inputs/outputs to non-key energy enablers for a specific process---may also associate some properties of one type of energy input/output to matter/others
- Other properties of Actors (OA)-attributes properties of energy and/or matter inputs/outputs to Actors for a specific process.

Codes with moderate sophistication: these are;

- Citation of Evidence (CE)-responses associate needs with readily noticeable effects
- Special Properties of Actors Matter (SPAM) where students, rather than view enablers as inputs for specific processes, describe the actor instead-as characterized by matter necessary for a specific process

Codes with most sophistication: These include;

- Special Properties of Enablers Energy (SPEE)-present enabler as either characterized by energy necessary for a specific process, as a reactant for a specific process or the sun as the only source of energy
- Special Properties of Enablers Matter (SPEM) which present the enabler as either characterized by matter necessary for a specific process or point to the enabler as a reactant for a specific process

I also included statements that suggest Backing under Warrants because these were too few to be discussed separately. In addition, this element of argument seemed to serve a similar purpose as Warrants (i.e. they link Data to the Claim made). These were indicated by statements that suggested Principle of conservation of Matter (PCM) and/or Principle of conservation of Energy (PCE). For each student's argument, as in Data (Table 3a, this Chapter), I used the code one (1) to indicate that a specific Warrant type is present, and code zero (o) to indicate that a specific code is absent. As an illustration, from Table 3b below, only SPEM (Pink highlight) was present (indicated by code 1) from the transcript in the table. All other Warrant types were absent (all indicated by the code 0).

<u>Table 3b: Example coding for specific Warrant present in transcript</u>

Warrant type present (1)/absent (0)

Transcript	**A**	**T**	**CE**	**SPEME**	**SPEE**	**SPAME**	**SPAE**	**PCME**	**PCE**	**OEME**	**OEE**	**AO**
Interviewer: I'm going to ask you for different things ... How does water help the tree to grow? (Does it change in any way?)												
RKC: It helps *create* glucose for the food that, not food, but sugar …draws its energy from through photosynthesis again. **I believe it's** 6H2o and CO2 turn into C6H12O6 with is glucose …	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**

Step 3: Reliability Checks

To work toward reliability checks, besides worksheets labeled All Data and All Warrants described in the previous subsection (see under Identifying Levels of Claims), I developed an exemplar worksheet and a procedure for a colleague to help me with reliability check coding. The colleague who helped me with the reliability checks was not familiar with the nature of the coding I was doing all along. An example of the exemplar worksheets that I developed for the reliability check is included in Appendix D, Tables D1 (Tree Growing), D2 (Flame Burning) and D3 (Car Running).

Before starting on the reliability coding, I discussed all coding materials with my colleague who was blind to the condition and student identity. For two students, he coded pre-post for the process of Tree Growing, Flame Burning, and Car Running (a total of 12 arguments). My colleague and I agreed on the types of Data and Warrants present in the transcripts for the two students 82% of the time, and when disagreements occurred, we discussed and reached a consensus. Although for the most part the disagreements arose from interpretations of codes and color coding, the discussions lead to some changes to my codes that reflected his codes. Following this, my colleague coded other two students' work that I similarly purposefully selected. This time, we agreed on types of Data and Warrants present in the transcripts over 90% of the time.

Step 4: Finding patterns of association among Claims, Data, and Warrants

The final step in my data analysis related to Research Question 1 involved looking for patterns of association among Claims, Data, and Warrants in students' arguments. In particular, I looked for patterns that connected students' Data and Warrants with Levels of Achievement in Claims established in the project's earlier research (Mohan, et al. 2009). Details of the patterns that emerged from data analysis are included in the next chapter.

Data Analysis for Research Question 2

I was also interested in the Claims that students made about transformations of matter and energy during Carbon Transforming Processes after targeted instruction. Therefore, I constructed and compared a paired pre-post Table each for Tree Growing, Flame Burning, and Car Running (a total of 3 tables). This was based on Argument Levels of Achievement from pre-post-interviews from the 16 08-09 students. This comparison helped me to document how secondary school students' arguments developed after targeted instruction. Thus, in responding to this question, I followed a similar procedure as in question 1 to generate comparative tables. These tables are included in the next chapter.

Chapter 3: Findings

In the previous chapter, I outlined examples of the data analysis I did in an attempt to respond to my research questions. This analysis suggests that students present different kinds of Data, Warrants and/or Backing in support of the different kinds of Claims they make in their oral arguments about matter and energy transformations in Carbon Transforming Processes (CTPs). In this chapter, I discuss two key finding in relation to Research Question 1: (a) characteristics associated with Data, Warrants, and/or Backing and (b) associations of these elements to the already established achievement levels for Claims (e.g. see Table 2, previous chapter) about the same processes. In relation to Research Question 2, I compare these characteristics before and after more targeted instruction.

Characteristics associated with Data, Warrants, and/or Backing-Research Question 1

My overall goal of this study was to use the already developed *Levels of Achievement Framework* regarding Claims about CTPs (Mohan et al., 2009) as a template to try to construct a *Levels of Achievement Framework* regarding Data, Warrants and/or Backing---these were the elements that emerged from my data analysis. This framework helped me to focus on argumentation as I attempted to make sense of students' texts about matter and energy transformation. What I wish to argue here from my data analysis is that different students tend to use different types of Data, Warrants, and Backing to support different Claims. But before I return to this point, I first present the types of Data and Warrants that emerged from my data analysis.

Types of Data

Overall, I found that students presented Data that fell into at least 11 types (5 needs & 6 results) in defense of different types of Claims they made about Carbon Transforming Processes. I present a summary of these types of Data including examples of each in Tables 4a an4b, this Chapter). These are organized in the order from the least to the most sophisticated: That is, low level (NO, RMO, REO), medium level (NEG, NMG, REG, RMG) and high level (NES, NMS, RES, RMS). For a brief review about the distinctions among these categories of codes, see under "Rubrics for classifying types of Warrants in students' arguments," preceding Chapter 2.

These different types of data show that students tend to treat inputs and outputs for specific CTPs in different ways. On the one hand, some students treated needs as inputs for chemical reactions involving matter and/or energy transformations. This is evident from students' responses in Tables 4a and 4b. To illustrate, I discuss an example each from the processes of Tree Growing, Flame Burning & Car Running. This discussion is organized around 3 categories into which these Data types fall: Low, Medium, and High.

Students provided Data (inputs or outputs) to support their accounts in the form of (a) "obvious facts,"---general observations which may or may not be empirically verifiable, (b) specific observations which may be empirically verifiable or (c) a combination of these two. For example, almost all students agreed with RKC's account of "what does a tree need in order to grow?" RKC responded, "it needs water for nutrients or nutrients in the soil, sunshine for photosynthesis and a space to grow and fresh air." These Data were used, however, to support different kinds of Claims by different students.

Table 4a: Types of needs and exemplar responses

Data type (Initial)	**Description**	**Exemplar Responses for TG A), FB B), & CR C): What does:**		
		A) a tree need in order to grow? ...	**B) a flame need to keep burning...?**	**C) a car need to run...?**
Needs Other (NO)	Needs that suggest conditions---refer to OTHER THINGS/NEEDS that do not relate to either matter or energy	SAM: ... shade	TNC: ... any surface ...it can burn	AJK: ...needs something to actually drive it.
Needs Energy General (NEG)	Needs that suggest non-specific forms of energy and/or energy source	SLP: Sun...	AJB: ...Energy	NAC: An energy source
Needs Matter General (NMG)	Needs that suggest non-specific forms of matter and/or treats results as input	STB: Well the tree...needs like more air...	JMJ: CO_2...or a fire	NAC: It needs ...air?
Needs Energy Specific (NES)	Needs that suggest specific forms of energy and/or location of energy for a specific process	EJR: It needs...sunlight	DRH: ...needs... energy that's stored in...wood	RWD: It needs the energy bonds...
Needs Matter Specific (NMS)	Needs that suggest specific forms of matter and/or specific matter resource for that (specific) process	EJR: It needs water...nutrients...carbon dioxide from the air...	NAC: ...wood and oxygen	BKD: Oxygen. It needs gasoline...

Table 4b: Types of results and exemplar responses

Data type (Initial)	Description	Exemplar Responses for TG A), FB B), & CR C): What does:		
		A) a tree need in order to grow? …	**B) a flame need to keep burning…?**	**C) a car need to run…?**
Results Matter Other (RMO)	Results that suggest specific forms of matter for other processes and/or specific matter resource for other processes and/or treats inputs as results and/or physical observations and/or energy/matter inputs as matter results	NC: ...if it's a really hot day, the water evaporates.	TNC: ...candle is melting the waxes...then the thing is like getting tinier	STB: (It turns into) Like smoke …the exhaust gets dirty
Results Energy General (REG)	Results that suggest non-specific forms of energy for a process	(Missing)	AJB: It's used and it produces energy	AJB: It's ...turned into...energy
Results Matter General (RMG)	Results that suggest non-specific forms of matter and/or treats results as input	AJB: ... make …photosynthesis and the air that release…	SAM: … flame get higher and more strong ... releases other gases	AMB: ... gas runs out … used towards the car, it releases gas...
Results Energy Specific (RES)	Results that suggest specific forms of energy for a specific process	EJR: (Sunlight energy is transformed into) Either kinetic or stored …	EJR: (Energy of wood/wax) is released as either the light of the flame or as heat…	DRH: (Energy of gasoline is transformed into) Light and heat…
Results Matter Specific (RMS)	Results that suggest specific forms of matter for a specific process	RWD: Carbon dioxide and sunlight and the water … *create* the glucose.	BKD: They are...the by-products...are CO_2 and H_2O	BKD: ...it comes out of the tailpipe as ...water…CO_2

Low level types of Data, examples of Needs Other, Results Energy/Matter Other: Some students mentioned Data that described conditions or triggers for the event rather than materials or forms of energy that are transformed during an event. I was interested in this category because it might suggest force-dynamic reasoning, where students focus more on causes that lead to the processes as effects than on how the processes transform matter and/or energy. In other words, this is a case where students view matter and/or energy as enabling the natural tendencies of organisms and objects to change rather than being transformed and conserved during processes of chemical change (Pinker, 2007).

Indeed, students in this category treated needs as enablers for actors to fulfill their natural tendencies (Jin & Anderson, in press). I describe these as Needs Other (NO). For the most part, these students' responses focused on visible processes, perceived or otherwise, in terms of "action-result" with little recognition of matter or energy involvement in any way. As an illustration and in contrast to BKD briefly discussed under *"High level types of Data"* below, STB's responses to questions about Tree Growing demonstrated a different kind of reasoning of the nature described by Jin and Anderson (in press).

When asked, "Okay. … from those pictures it (the tree) starts as a tiny seedling and then years later it's a tree that weighs so much more than that. So where does that extra weight come from over time?" STB responded, "I would have to say the like the branches because in the first picture, the smaller tree, it's like there is not very many branches and then as it, it's just small, and then when it gets bigger. Well the branches have a lot of leaves on them and yeah." Indeed, when probed further about whether "the area around the tree would be changed at all beside the fact that the tree is growing" she replied, "Well the tree is bigger so it needs like more air, it takes up more space and yeah." From these responses, STB seems to be focused on readily observable comparisons such as branches rather than inputs for chemical changes leading up to matter and energy transformation. Again, although she recognizes the tree's need for air, it is in a way that suggests that it (air) is physically rather than chemically needed to fill up the space in the tree.

TNC's responses to the same questions as it relates to Flame Burning were similar to those of STB. Regarding the question about needs of a flame to burn, she says it needs "any surface so it can burn …" and in the process providing needs that suggest conditions rather than inputs with little relationship or reference to either matter or energy. Moreover, in relation to whether the needs change in any way, she points to the idea that the "...candle is melting the waxes...then the thing is like getting tinier." Thus, she focuses on results that are visible in nature with little reference to transformation of the suggested needs into the presented results. Other students' responses resembled those of STB and TNC by providing Other Needs (NO) that suggests conditions, characterized by little relationship to either matter or energy.

Some students also used other results for either energy and/or matter (REO/RMO). To Demonstrate, and in reference to Tree Growing, the interviewer raised the question, "Does it (the tree) use all those things in the same way, the soil, the carbon dioxide, water, sunlight? Do they all help the tree in the same way or do they work a little differently? Do they change in any way?" STB reasoned, "The sun and the air help with photosynthesis and *then the water makes it so it doesn't get dehydrated.*" Whereas, the interviewer perhaps deliberately tries to guide and then probe for how the tree uses inputs (CO_2, water, & sunlight), STB resort to reasoning that describes inputs in general (sun & air or NEG/NMG) rather than specific ways as presented in the prompt.

Equally important is STB's view of water as being used by the plant to prevent it from dehydration. Although the resultant results (in italics, preceding paragraph) points to a specific form of matter input (i.e. water), this is for another process: That is, plant support which involves little transformation rather than growth which involves transformation of water into other forms (results). I have included more similar examples in tables 4 above, this Chapter.

Medium level types of Data, examples of Needs and Results Matter/Energy General (NMG/NEG, RMG/REG): Other students provided needs that suggest non-specific forms of energy and/or matter including their sources (NEG/NMG). My focus on this category was based on the idea that it might reveal student reasoning that is neither fully force-dynamic nor model-based. Said in other words, this category might suggest student reasoning that is inconsistent with the principles of matter and/or energy.

Take the case of student SLP. When the interviewer asked, "What does the tree need in order to grow?" She replied, Sun and water. And soil. Somewhere to be placed in the ground." This response suggests that, while SLP views one of the needs of Tree Growing as being water (Matter), her reasoning is much more focused on general needs (sun rather than sunlight/light energy or NEG) and conditions (place on the ground or NO). This kind of reasoning was also revealed in other cases regarding needs for Flame Burning as illustrated by TNC's response saying, 'if you're making like a fire, it could be paper or something that could keep the fire burning." This too was similar to DRH's reasoning about Car Running: "It needs the gas, that's the energy, and somebody controlling the car."

High level types of Data, examples of Needs and Results Matter/Energy Specific (NMS/NES, RMS/RES): A few students presented Data that pointed to materials (NMS) or forms of energy (NES) for transformations in chemical processes. I was interested in this category because it might suggest principled reasoning, where students focus more on how the processes of TG, FB, and CR transform matter and/or energy. As an illustration, EJR, in his response to the question where the mass of the tree comes from, treated these needs as raw materials for transformations in matter and energy. He said, "The mass comes from the food that the tree is producing during photosynthesis, which is mostly carbon and hydrogen pieces bonded together and that is then stored away and eventually enough of it is stored away so that it starts to grow and continues growing."

EJR's reasoning is similar to that of BKD in the sense that it presents matter as a reactant during the process of Car Running. From Table 4a above, when asked, "What does a car need in order to run?" he replies, "Oxygen. It needs gasoline…" This response suggests BKD's treatment of and therefore reasoning about inputs to car running in terms of specific forms of matter (e.g. gasoline). In addition (see Table 4b, this Chapter) when asked, "Where do (those) needs you mentioned go? Do they change in any way or do they remain the same? He replies, "it comes out of the tailpipe as water …CO_2…" Thus, BKD'S reasoning suggests his understanding of needs of car running as inputs for, in this case, matter transformation. Accordingly, he recognizes that the matter of gasoline is transformed into the water and CO_2 that is eventually released into the atmosphere as byproducts of combustion.

To sum up, relatively few students provided "Data" in the scientific sense of empirically verifiable observations. This may be in part a result of the questions we asked; we rarely challenged students to justify their Claims in detail. For future studies, we will include requests for more detailed justifications of their Claims.

Types of Warrants

Similar to Data, I found that students used Warrants and/or Backing that fell into at least 10 types to bridge Data to different types of Claims they made about Carbon Transforming Processes. As in types of Data, I have organized these types of Warrants in the order of the least to the most sophisticated as follows: Low level (A, T, OEM, OEE & OA); Medium level (CE & SPAM); high level (SPEM, SPEE, PCM & PCE). For a summary of the various types of Warrants and an example of each, see Table 5, this Chapter.

These different types of Warrants seemingly support the notion that students tend to bridge the Data they present to the Claims made for specific Carbon Transforming Processes in different ways. On the one hand, some students used Warrants that, besides being analogical in nature (e.g. see Example 2, previous Chapter), were, as an illustration, tautological in nature. This is evident from students' responses in Table 5 below (this chapter). To demonstrate, I discuss an example each from the three processes-Tree growing, Flame Burning and Car Running. This relates to my second finding discussed after Table 5.

Table 5: Types of Warrants and exemplar responses

Warrant type (Initial)	**Exemplar responses for TG A), FB B), & CR C): Why does a**		
	A) tree need those things? How do they help…?	**B) a flame need those things?... How do they help…?**	**C) a car need those things to run?...**
Analogical (A)	**SLP**: ..water is like the food **(for tree)**	**B)JAH: flame** needs a food source like others…	**STB:** ...It's like water for the car.
Tautological (T)	**NAC**: It makes it grow bigger…	**AJK**: It's used to like keep the flame like going…	**TNC: Like the car** needs gas to move…
Other properties of enablers Matter (OEM)	**TNC**: It **(mass)** comes from all of the things that went into the tree.	**RWD**: It **(H_2O)** has high energy bonds and it's flammable...	**STB**: It **(gas)** keeps it hydrated I guess.
Other properties of enablers Energy (OEE)	**SJF**: ... air...sometimes can carry energy	**STB**: …energy…comes from when you strike the match, ...and the friction from when you strike it.	**BKD: No, ...the oxygen isn't** used for energy and the gas (gasoline) isn't.
Other properties of Actors (OA)	**SJF: They (Cells)...**made of some type of molecule …	**B) TNC: The flame** ... has energy to burn away the candle…	**C) TNC**: Well it **(engine has its)** energy …**run…**
Citation of Evidence (CE)	**SJF**: ...without the sunlight – it couldn't fully…photosynthesis	**NAC**: ...in … fifth grade camp… certain materials…made a flame…	**SLP**: ... without gasoline a car wouldn't move ...
Special Properties of Actors Matter (SPAM)	**JMJ**: ...As long as the tree has … right amount of water...	**AJB**: ...the atoms that make up the flame...	**(Missing)**
Special Properties of Enablers Matter (SPEM)	**EJR**: The carbon dioxide in the air contains molecules, atoms...	**RKC**: ...also needs oxygen...because it uses the oxygen to keep on burning	**SAM: …(gasoline)** has carbon in it ... everything has carbon in it
Special Properties of Enablers Energy (SPEE)	**JAH**: Sunlight contains energy...	**BKD**: It **(energy)** comes from the energy in the wood	**SAM**: It **(gasoline)** gives it energy…
Principle of conservation of Matter (PCM)	**JMJ**: ...carbon just doesn't come out of nowhere... recycled…	**NAC**: ...there's always the same amount of mass in the world...	**AMB**: ... it's releasing the same amount…put in..
Principle of conservation of Energy (PCE)	**RKC**: Energy just can't be created...	**AMB**: ...energy can't just be created out of nowhere	**RKC**: ...you can't…create energy or destroy **(it)**…

My second finding therefore suggests that there are differences regarding Warrants students provided to link the data to the claims they made. As in types of Data, I have organized the discussion of Warrants that emerged in three categories, each with a specific example-low, medium, and high.

Similar to Data categories, my interest in these categories was based on my hypothesis that they might indicate either force-dynamic reasoning in which case students view Data as: fulfilling natural tendencies of actors (e.g. Pinker, 2007)--low category; characterized by special properties that align with scientific principles of matter and energy--high category; or both of these two--medium category. Again, these categories are products of my conceptual organization for purposes of discussion. Thus others may view them differently.

Low level types of Warrants, examples of A, T, OEM, OEE, OA: Some lower level students assumed that the Data themselves (tautological) were sufficient to justify their Claims. To a large extent, students who used Warrants that were tautological in nature tended to repeat, with minor modifications, statements as used in the interviewer's prompt. Suggestively, students who use these kinds of warrants limit their focus to enablers, actors, and results with little reference to hidden mechanisms that drive matter and energy transformations. To illustrate, when RKC, in his pre-interview, was asked "How does a tree use water to make food for itself?" he said, "Water is very important and it has to be clean water too because if it's polluted then the tree could not survive." RKC's response indicates an understanding that water is important for the tree to grow. Yet when asked for a Warrant that connects the tree's need for water with a Claim about matter and energy, he basically reasserts his original Data. Thus, he falls short of making the actual connection between water and photosynthesis. I describe this view as being Tautological (T) in the sense that, rather than point to the characteristics of inputs that drive chemical changes for processes such as TG, it presents inputs as physically being enough to drive processes.

AJK's reasoning about Flame Burning resembles that of RKC. This is in the sense that he reasserts data, suggested in the interviewer's prompt, as a justification for the claim he makes. From Table 5 above, when asked, "Why does a flame need those things? How do they help it to keep burning?" he replies, "It's used to like keep the flame like going…" This response implies AJK's view of data in flame burning, rather than as characterized by matter and energy thus necessary for chemical changes, as being naturally necessary.

Moreover, in reference to Car Running, TNC also uses tautological statements to link the suggested data to the Claim he makes. In response to similar questions about CR, he says, "Like the car needs gas to move…" Consequently, in their responses, RKC, AJK, and TNC seem to focus on visible, as opposed to hidden, processes in their attempts to bridge suggested Data to Claims made.

Other students attempted to bridge Data to Claims using Other properties of Enablers Matter (OEM). I describe this type of warrant as either reasoning that associates; properties of matter inputs/outputs to non-key matter enablers for a specific process or some properties of one type of matter input/output to others. For instance, when RWD was asked "So how does oxygen help the flame to keep burning?" He replied, "It (O_2) has high energy bonds and it's flammable." In this case, RWD attributes special characteristics of matter inputs such as gasoline (has high energy bonds) to

Oxygen, a non-energy reactant. Similarly, we asked BKD "Are oxygen and gasoline used for energy?" Compared to RWD, BKD presents a reversed view of inputs (O_2 & gasoline). In his response, he thinks that "the oxygen isn't used for energy and *the gas (gasoline) isn't.*"

Medium level types of Warrants, examples of CE & SPAM: Some students used Warrants that focus on readily noticeable effects in a specified process as opposed to effects as demonstrating hidden mechanisms. I describe this as Citation of Evidence (CE). An example of this type of Warrant is provided by SJF. In response to the question, "Do you think sunlight could play any role in that process? How does that work?" SJF reasons, "Yes, because without that – without the sunlight – it couldn't fully produce photosynthesis to help it grow." This response tends to associate sunlight to photosynthesis but with little focus on how that happens: That is, rather than view sunlight as a form of energy that is involved in the chemical process of photosynthesis, SJF views it as somehow related to this process.

Another medium level Warrant that emerged from data analysis is what I refer to as Special Properties of Actors Matter (SPAM). I describe this as students' reasoning that, rather than focus on enablers as inputs for chemical transformations in a specified process, focus on the actor instead as characterized by matter necessary for a specific process. This Warrant is different from SPEM, illustrated under *High level types of Warrants* below, in the sense that whereas SPEM describe inputs that actors (e.g. tree, flame, and car) obtain from their surroundings for chemical changes, SPAM describe actors themselves as miraculously constituting those characteristics. Here is an example from data analysis. In the interview, we asked TNC, "You said that a tree has carbon. So, where does the carbon come from? She said, "It comes from the tree." Consequently, this response suggests that TNC is unlikely to view the carbon of the tree as a chemical component of carbon dioxide that was once in the air around the tree.

High level types of Warrants, examples of SPEM, SPEE, PCM, &PCE: On the other hand, some students used Warrants that were characterized by Special Properties of Enablers for Matter and/or Energy (SPEM/SPEE) to bridge the presented Data to the Claims made. In some cases, some students used, implicitly or otherwise, either the Principle of Conservation of Energy (PCE) or Principle of Conservation of Matter to link Data to the Claims made. Compared to less sophisticated responses, more sophisticated responses were likely to be characterized by these types of Warrants in the constructed arguments. This is illustrated by an example each for the three Carbon Transforming Processes of Tree Growing (TG), Flame Burning (FB), and Car Running (CR).

With regard to questions about TG, RKC in his post-interview provides a more acceptable Warrant about water and an explicit claim about matter saying, "It helps create glucose for the food that, not food, but sugar … that the tree grows on …. I believe it's $6H_2O$ and CO_2 turn into $C_6H_{12}O_6$ with is glucose and then $6O_2$ which is oxygen. So oxygen is like a byproduct …." Although he incorrectly uses the term "create", his response is much improved because it correctly links and therefore shows his understanding that water is a reactant in the chemical process of photosynthesis. In fact, his Warrant makes the general principles underlying this process explicit through conserving matter by identifying its reactants and products.

Indeed, later on in the interview, when asked, "Do you think water is used up" in photosynthesis? He said, "No. It's not used. It's not like you use it and it's gone. It's just exists in another form and its' in the leaves." Thus, he shows use, and therefore understanding of the idea that the matter of water is neither created nor destroyed. Consequently, he provides Backing for his Warrant about why water is needed for the process of Tree Growing.

Regardless of whether students were talking about matter (e.g. RKC above) or energy (e.g. SAM, discussed next), more sophisticated responses focused on special properties of needs. Accordingly, students' reasoning seemed to suggest the idea that these properties enabled, through hidden mechanisms, transformations of matter and energy which were then manifested in results, either as part of the increase in mass, or as products of transformations of matter and/or energy. As an illustration, SAM's response to questions about CR reveals reasoning of enablers as constituting special properties of either matter or energy. When asked, "Why does a car need those things to run? How does that happen?" He says, "It (gasoline) gives it energy…" Again, like RKC, SAM correctly associates the (chemical potential) energy of gasoline with Car Running. BKD too, in relation to questions about FB (see Table 5, this Chapter) presents similar reasoning, "It (energy) comes from the energy in the wood…"

Furthermore, a few students' use of Backing, besides Warrants, seemed to function as well to either connect Data to the Claims they made or to justify the Warrants they used. Notably, their use of Backing to reason about Carbon Transforming Processes was either explicit or implicit. RKC from the preceding paragraph exemplifies an implicit use of Backing in his response to the question about whether matter is used up during TG.

In brief, relatively few students provided Warrants and/or Backing that aligned with scientific principles to link Data to Claims made. As earlier noted about Data, this may be partly due to the nature of the questions we asked, and future studies will be enriched with the inclusion of requests for more detailed justifications of their Claims. I view such probing as another opportunity to possibly identify further challenges that students face in their accounts about Carbon Transforming Processes. This in turn may lead to designing kinds of instruction that attempt to respond to the identified challenges.

Associations of Data and Warrants to Claims- Research Question 1

In this section I (a) describe patterns of association between the types of Data and Warrants that students used and the levels of achievement of their Claims and (b) suggest possible Levels of Argument based on common patterns of association among Data, Warrants, and Claims.

Patterns of association among Data, Warrants, and Claims

I found patterns in students' use of elements of argument-Data, Warrants and/or Backing as well as their Claims. I present a summary of these patterns in Table 6, as well as a summary of the nature of the differences in elements after the same Table below.

After identifying characteristics associated with Data, Warrants, and Backing, I used the established levels of achievement for Claims (see Table 2 in the previous chapter) to identify the kinds of Data, Warrants and/or Backing, for all the 16 participants, that align with those Claims. Some alignments are suggestive from the examples provided including the two examples in the data analysis section, Chapter 2:

- For example, the kinds of *Data, Warrant, and/or Backing* (both appeal to scientific principles) provided by EJR and RKC (see also ANW, Example 1 in data analysis section) seem to align with Level 4 Claims described as ***"Linking processes with matter and energy as constraints"*** (see Table 2, chapter 2).
- By contrast, the *readily noticeable Data* and *analogical Warrant* provided by JAH and TNC (see also JMJ, Example 2 in data analysis section, previous chapter), seem to align with Level 2 Claims described as ***"Force-dynamic accounts with hidden mechanisms"*** (see Table 2, chapter 2).

To move toward identifying patterns, and based on how matter and/or energy are involved in Carbon Transforming Processes (characteristics of elements of argument), I conceptually arranged and tabulated the types of Data (columns) against Levels of achievement (rows) that emerged for all the 16 students in Table 6a below. I repeated the same procedure for Warrants (see Table 6b below). This was on a scale from low to high, low being characteristics least associated with the principles of matter and/or energy (Blue highlight), and high being characteristics most associated with these principles (Green highlight). Medium level types of elements (Brown highlight) are characterized by, for example, reference to these principles in general ways, use of easily noticeable effects of processes, and a focus on the actors rather than on enablers. In particular, the two tables below show the proportions of two variables, *Data (6a)* and *Warrants (6b)* at each level of achievement.

These proportions are based on the overall total number of elements (Data & Warrant) for each category: That is, I computed the overall proportions by summing up percentage proportions of each type of Data (Table 6a) and Warrants (Table 6b) for each category. The categories were, Low, medium, and High (3 categories for each level, a total of 9 proportions for Data, and 9 for Warrants). The reason for focusing on overall proportions rather than individual proportions was to try to reduce complexity in presenting results. I have included details about proportions of individual types of elements at each Level of Claim in Appendix E, Tables E1 (Data) and E2 (Warrants).

Associations between types of Data and levels of Claims. To illustrate computation of the overall proportions, and based on Table E1 (Under Appendix E), I added percentage proportions falling under the category low for Data types Needs Other (0%), Results Energy Other (3.9%) and Results Matter Other (7.7%), a total proportion of 11.6% (Low level, Claim level 4). For each Claim level and category, I repeated the same procedure. The result is tabulated in Table 6a below. I should note here that I repeated the same computational procedure for overall Warrant proportions based on Table E2 (see under Appendix E). I briefly discuss the resultant proportions for Data, next.

Table 6a: Overall Percentage (%) of types of Data at each Level of Claim

Claim level		**Low level**	**Medium level**	**High level**	**Total %**
4	% of Total (26)	11.6 (3)	7.6 (1)	80.8 (22)	100
3	% of Total (96)	20.8 (20)	15.6 (15)	63.6 (61)	100
2	% of Total (171)	35.1 (60)	27.5 (47)	37.4 (64)	100

Table 6a indicates that, overall, students tend to use Data that align with scientific principles (High level column) to support their accounts of Carbon Transforming Processes (CTPs). However, compared to less sophisticated responses (those at Level 2), more sophisticated responses (those at level 4) are less likely to include low level types of

Data in accounts about CTPs of Tree Growing (TG), Flame Burning (FB), and Car Running (CR). This is indicated by generally fewer types of Data I designated Low or medium: That is, the proportions of low level types of Data (Low level column) are lower than those at high level (High level column, Claim Level 4). Moreover, the proportion of these Data types tend to generally increase from upper left part of the Table toward the upper right part of the Table.

Compare to high level types of Data, the proportion of low level types of Data is particularly high at achievement level 2. In contrast to level 4 Claims which tend be characterized by a high category of Data types, level 2 Claims tend to be characterized by both of these Data types. This is evident from a similar overall percentage proportions for high (37.4 %) and low (35.1%). This indicates that, less sophisticated responses are nearly equally likely to include high level and low level types of Data in accounts about CTPs. This likely point to the idea that students' reasoning about inputs and outputs in Carbon Transforming Processes tend to be disconnected: That is, perhaps they view inputs as fulfilling specified processes with little recognition of matter and/or energy transformation and outputs as a natural consequence of processes.

Additionally, Table 6a shows that, generally, students at level 3 tend to use both low and high level types of Data. This is indicated by the fact that, although the proportions of Data at this level are higher (Level 3, High level), these overall, tend toward average. It is important to note here that the analyzed data from which patterns emerged were from pre-post interviews, initially analyzed blind to either of these conditions.

Table 6b: Overall Percentage (%) of types of Warrants at each Level of Claim

Claim level		Low level	Medium level	High level	Total %
4	% of Total (13)	7.7 (1)	0.0 (0)	92.3 (12)	100
3	% of Total (96)	42.7 (41)	9.3 (9)	48.0 (46)	100
2	% of Total (167)	66.6 (111)	9.0 (15)	24.4 (41)	100

Types of Warrants associated with levels of Claims. Like Table 6a above, Table 6b indicates that, overall, students tend to use Warrants that align with scientific principles (Level 4, High level column) to support their accounts of Carbon Transforming Processes (CTPs). For example, compared to less sophisticated responses (those at Level 2), more sophisticated responses (those at level 4) are less likely to include low level types of Warrants in accounts about Tree Growing, Flame Burning, and Car Running. This is shown by generally fewer low and medium types of Warrants at level 4. Indeed, out of a total of 13 types of Warrants (low Category), students used only 1 (or 7.7 %) of these at this level. In contrast, to illustrate, students used 12 (or 92.3%) of the high Warrant category at the same level. That is, the proportions of low level types of Warrants (Low level column) are hardly present at level 4. Similar to Data, the proportions of the types of Warrants included in Table 6b tend to increase from upper left part of the Table toward the upper right part of the same table.

Table 6b also suggests that although less sophisticated responses include some high level Warrants (i.e. 24.4 %, High level column), they are more likely to be characterized by low level Warrants (i.e. 66.6%, low level column) in accounts about Carbon Transforming Processes. This is overall indicated by a particularly higher proportion of low level Warrants at achievement level 2 (66.6 %, Low level column) compared to either levels 3 (42.7%) or 4 (7.7%). Additionally, in contrast to high level, the proportions of these types of Warrants tend to, generally, decrease from lower left part of the Table toward the lower right part of the same table.

Furthermore, with regard to level 3, Table 6b generally shows that students tend to use both low and high level types of Warrants. Illustrative of this is the fact that, although the proportions of high level Warrants at this level are higher (48.0%, High level column) than those to the left side (42.7%, Low level column), all cells at this level are nearly equally represented at each level of elements. Consequently, students' use of Warrants at this level, overall, tends toward average. On the whole, my analysis showed patterns of association between these two elements and Claims. These patterns are summarized in Table 7 below, and a discussion of each is presented after this Table.

Table 7: Descriptions of characteristics associated with levels of achievement

Level	Statements contain:		
4	**Data** that consist of: • Specific **Matter and/or Energy Needs** but also **hardly any related Other/General observations** • Specific **Matter and /or Energy Results** but also **hardly any related Other/General observations**	**Warrants** characterized by: • **Special Properties of Matter** to link **Data** to an empirically verifiable **Claim** • **Special Properties of Energy** to link **Data** to an empirically verifiable **Claim** • **Supporting Backing** that use general principles of Matter/Energy	**Claim** consistent with conservation of matter and energy (e.g. Jin et. al., in preparation)
3	**Data** that consist of: • Specific **Matter and/or Energy Needs** but also: related Other and/or General observations; **Other Needs** with little connection to Mater and/or Energy • **Specific Matter and /or Energy Results** but also: related Other **and/or General observations; Other Result** with little connection to Matter and/or Energy	**Warrants** characterized by: • **Special Properties of Matter** but also related Other properties to link **Data** to the **Claim** made • **Special Properties of Energy** but also related Other properties to link **Data** to the **Claim** made • **Suggestive Backing** that uses general principles of Matter/Energy but also **Some; Analogies, Tautological statements, and Citation of Evidence** to link **Data** to the **Claim** made	**Claim** that includes accounts of matter and energy but is not fully consistent with conservation laws
2	**Data** that consist of: • **Other/General observations** that may or may not relate to specific matter and/or energy • **Some Specific Matter** and/or **Energy Needs** mainly based on beliefs/guess work but also **Other Needs** that have little connection to specific Matter and/or Energy needs • **Some Specific Matter** and/or **Energy Results** mainly based on beliefs/guesswork but also **Other Results** that have little connection to Specific Matter and /or Energy results	**Warrants** characterized by: • **Analogies, Tautological statements, and Citation of Evidence** to link Data to the **Claim** made • **Other Properties of Enablers and/or Actors** to link **Data** to the **Claim** made • **Some Special Properties of Matter and/or Energy** mainly based on beliefs/guesswork	**Claim** that mentions matter and energy in context of force-dynamic accounts

Argument Levels of Achievement

I used coded characteristics of elements from all 16 participants that align with each Level of Claim (3 rows) to construct a 4-column Table consisting of Level, Data, Warrant and/or Backing, and Claim. In this table, I designated Argument Levels of Achievement in students' work regarding transformations in matter and/or energy based on the emergent types of elements discussed in the preceding subsection. But before presenting this summary, I would like to illustrate how I got there from the types of elements that emerged discussed under types of Data and types of Warrants in the preceding subsection.

Students used different kinds of Data, Warrants and sometimes Backing to support the Claims they made and these fell into recognizable patterns. Less sophisticated responses (mostly by younger students) used elements that were mainly characterized by, for instance, individual beliefs, readily noticeable observations and interpretations based on personal experiences (see Table 7, this Chapter).

To illustrate, most students' Data and Warrants were similar to those provided by JMJ (Example 1, Chapter 2): That the matter of wood/wax will not only "disappear" during Flame Burning but also that both of these "*... are kind of like flames' food.*" Students who provided these kinds of Data (e.g. *readily noticeable)* and Warrants (e.g. *analogical)* tended toward Level 2 reasoning. This is illustrative from Table 6a which shows that students at this level are more likely to use Needs Other (NO), Results Energy Other (REO), and Results Matter Other (RMO) to defend the Claims they make about how matter and/energy are involved in the Carbon Transforming Processes of Tree Growing, Flame Burning, and Car Running. This is in addition to being more likely to use Analogies (A), Tautological statements (T), Other properties of Enablers Matter (OEM), Other properties of Enablers Energy (OEE), and Other properties of Actors (AO) to defend the same Claims (see Table 6b).

By contrast, more sophisticated responses were more likely to include elements that appeal to scientific principles. These responses' elements were similar to those provided by EJR: That light energy (input) is not only transformed into stored (chemical potential) energy (output) but also stored in the bonds of molecules (Warrant). Students' responses that provided these kinds of Data and Warrants (*consistent with scientific principles)* tended toward Level 4 reasoning. This is illustrated in Table 6a which shows that such responses are more likely to be characterized by Needs (that are) Energy Specific (NES), Needs (that are) Matter Specific (NMS), Results (that are) Energy Specific (RES), and Results (that are) Matter Specific (RMS) to defend the Claims made about Tree Growing, Flame Burning, and Car Running. Moreover, these responses are more likely to be characterized by Warrants that align with scientific principles to connect the presented data to the Claims made about these processes.

Examples of the identified types of Warrants (see Table 5, this Chapter) students use at this level include those that focus on Special Properties of Enablers Energy (SPEE) and Special Properties of Enablers Matter (SPEM). Again, responses that tend toward level 4 sometimes factor in, implicitly or otherwise, either the principle of conservation of matter or energy to link the presented Data to the Claims the made.

Other students' responses showed elements that appeal to scientific principles and at the same time, for instance, used other elements that have little relationship to mater and/or energy in reasoning about Carbon Transforming Processes. That is, these responses tended to provide elements that were overall inconsistent with model-based reasoning in the constructed arguments. Such students' responses are exemplified by DRH's. Here is how he responded to questions regarding needs of a car to run, "It needs the gas, that's the energy, *and somebody controlling the car.*" In spite of the fact that he recognizes that a car needs gas (gasoline) as an input (NMS) into the process of CR, DRH alongside this reasons that "somebody controlling the car" [Non-matter (NO) input] is part of the need for this process. This is in addition to his idea of gasoline "being energy" (OEM). Responses that use a combination of these kinds of elements that are inconsistent with scientific principles seems to align with Level 3 Claims described in part as "*...cannot successfully conserve matter/energy.*"

Thus, the kinds of Data, Warrants and/or Backing that students used in support of their Claims, viewed together, suggest a type of proposed learning progression that includes most of Toulmin's elements of arguments-***Argument Learning Progression***. To back up a moment, it is probably helpful to make a note about Levels regarding this proposed Argument Learning Progression.

The levels suggested here should not be viewed as levels into which students' work precisely fit. Rather, that these are attempts to classify approximations of coherence of students' arguments about matter and energy transformations in Carbon Transforming Processes (Wilson, 2005; in Alonzo & Steedle, 2008). In framing these stages of development therefore, I do not suggest that students' arguments fit neatly into particular levels but that these lean more toward particular levels than they do others. I illustrate this perspective in figure 2 below which represents a way of thinking of these "Levels as stages in a general transition from force-dynamic to model-based reasoning" (C. W. Anderson, personal communication, December, 2008).

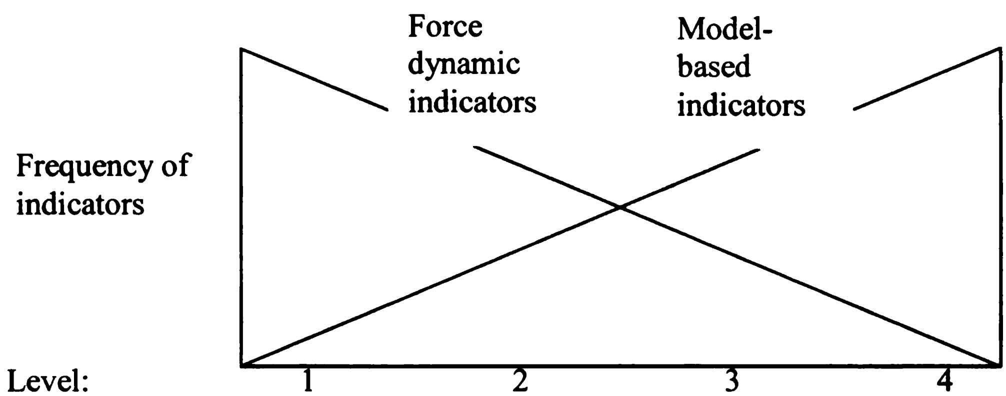

Figure 2: Frequency of indicators against levels of achievement

With reference to the questions we asked about Tree Growing, Flame Burning, and Car Running, for instance, students provided as indicators (e.g. phrases, words, and statements) of any number that I eventually used to identify the emergent types of Data (see Table 4a & 4b, this Chapter). These Data could fall anywhere between Level 2 (e.g. Needs/Results Other) and Level 4 (e.g. Needs/Results Matter/Energy Specific). Students similarly used, for example, phrases and ideas that signaled different types of the identified Warrants (see Table 5 above, this Chapter) to link the Data they identified to the Claims they made about Carbon Transforming Processes. These Warrants in a comparable way tend to fall anywhere between Level 2 (e.g. Analogical & Tautological) and Level 4 such as Special Properties of Enablers Matter/Energy; Principle of Conservation of Matter and/or Energy.

Moreover, although less sophisticated responses used more level 2 indicators, some of these responses were also characterized by some higher level indicators.

However, this was in a way suggestive of either contradictions between needs and results or guesswork indicated by a number of terms or phrases (e.g. I think, probably, I guess, and I don't know). To demonstrate, when TNC was asked about needs of a tree to grow, she replied, "It takes in the air and it gives off CO_2" In this case, whereas TNC seems to factor CO_2 into reasoning about Tree Growing, she presents it as a product rather than input of the same process. Similarly, SLP's response to whether the needs/inputs she identified in Car Running changed in any way, she said "Carbon dioxide maybe, I think."

In comparison with less sophisticated responses, more sophisticated responses tended to have more Level 4 indicators. However, a few of these students' responses also used lower level indicators but often quickly included higher level indicators as the interview progressed. Here is an exemplar response from a question about Flame Burning:

> I: The melting candle loses weight as (it) burns, how does this happen?
>
> EJR: The wax of the candle will melt and then often it will pour over the side and spread onto the table or whatever it's sitting on, or else it will slowly evaporate into the air.
>
> I: You said it slowly evaporates into the air, what form is that?
>
> EJR: I guess it would be wax vapor or something like that, and it (is) basically the molecules of the wax spread apart and far enough…

From this interaction, EJR, like SLP, expresses an element of doubt when he uses the phrase "I guess" in his response to how the candle loses weight and in what form. A possible interpretation of EJR's response unlike SLP, based the idea that he quickly resorts to using more of model-based reasoning (Pink highlight), is that this suggests the level of difficult of the subject matter regarding Flame Burning. Thus, whereas EJR's reasoning overall tends toward Level 4, he rarely draws on a few indicators and therefore elements of argument that characterize lower levels. Accordingly, this is suggestive of another level, in this case Level 3 (see Table 7 above) where students tend to concurrently use high and low level indicators.

I conceptualize Level 3 as being characterized by student responses with indicators (constituting either Data or Warrants and/or Backing) that seem, overall, inconsistent with scientific principles. An example of L3 Data is suggestive in JAH's response to the question about needs for Car Running. He responds that a car "needs oxygen for the combustion, gasoline, *it needs a person to drive it* and I guess that would be all …" Although JAH recognizes inputs/needs for this process to proceed in the form of gasoline and oxygen (mater), he, like DRH discussed earlier, mentions other needs that do not relate to either matter or energy (in italics) as being necessary for this process.

In another example regarding where the heat generated during Car Running comes from, another student (RWD) said, "Some of it's from the energy from the gasoline. And, *the other part of it is from the oxygen*" Thus, RWD not only draws on the notion that gasoline is characterized by (chemical potential) energy necessary for Car Running, but also draws on a more force-dynamic idea that oxygen has energy (in italics).[1] In particular, with reference to matter, RWD uses both special properties of

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[1] While chemists might regard this response as better than one that locates the energy only in the gasoline, I think that RWD's response indicates that he is thinking of oxygen and gasoline as separate energy sources, rather than of oxygen as an element that reacts chemically with gasoline.

enablers (SPEM) and other properties of enablers (i.e. OEM, Table 5, this Chapter) in their accounts.

A general pattern that implicitly emerges from the preceding responses, as well as other responses from all the 16 students therefore, is the notion that students seem to accumulate ideas over time, each (student) presenting an image of an ongoing construction of a toolkit of some kind (Anderson et. al, personal communication, May 14, 2010). It would seem that each student draws from their kinds of toolkits any number of tools so to speak (e.g. ideas, words, phrases, & statements) to use in reasoning about Carbon Transforming Processes (CTPs). Compared to less sophisticated arguments, more sophisticated arguments draw more on indicators that align with scientific principles. Accordingly, the resultant Argument Learning Progression regarding CTPs I propose here, like ecological progression, is one of complexity with different dimensions to it such as time, instruction, and instructional tools. In this progression, for instance, students might, perhaps with more focused instruction as suggested in the pre-post development I discuss next, to move over time from less sophisticated reasoning (force-dynamic) toward more sophisticated reasoning (principled or model-based reasoning) about CTP in a way that represent a continuum (Wilson, 2005).

Comparison of characteristics of elements at two different points in time-Research Question 2

A note about what this study does and does not do. The results I present regarding *Research Question 2* should be viewed more as would results from a pilot study. This study does not assess the effectiveness of the instructional intervention we used. It is focused on how students' arguments developed rather than what caused this development. The reason for this is that although teachers of the participating students were expected to use designed instructional tools/Tools for reasoning (see Appendix B; see also Jin & Anderson, in preparation), we do not have reliable data about how teachers used them.

Certainly, an inclusion of the details of the instructional intervention would enrich a similar future study particularly focused on the effects of using these tools themselves. So, my hope is that the findings regarding Research Question 2 will potentially inform future investigations. For example, what actually helps students to move, if at all, from one level to another? How does that movement look like in terms of gender and socio-economic status? How do these relate to teachers' years of teaching experiences, if at all? Responding to such questions would likely point to other factors that potentially support students in moving toward a scientific way of reasoning about Carbon Transforming Processes. This way, a possibility exists for designing instruction that would be responsive to the goal of helping all learners in pursuit of scientifically literate citizenry.

Even without evidence about the instructional mechanisms of change, pre-post comparisons can be valuable for developing learning progressions. When we see changes in patterns of Data and Warrants for arguments about the same processes from the same group of students at two points in time, that potentially provide evidence that the changes involve learning rather than differences among individual students (C. W. Anderson, personal communication, July 7, 2010). Moreover, findings regarding Research Question 2 can point to problem areas for students and accordingly suggest targeted interventions.

I now return to the idea of comparison of students' argument Levels of Achievement from pre-interviews with those from their post-interviews. Whereas the preceding discussion, overall, show the specific types of elements of argument that emerged (see Tables 4a, 4b & 5, this Chapter), it does not show how these elements changed during pre-post-interviews.

To examine what and how the identified types of elements shifted, I compared the total number of each of these elements in the pre-post-interviews by tabulating them in Tables 8a (Data) and 8b (Warrants). Together, these tables summarize the patterns that emerged which I briefly discuss after each table. This likely provided a way of illustrating the sort of change in students' responses that emerged from data analysis. I was interested in how, overall, elements changed during pre-post-interviews. This change, in the total number of types of elements in each category (low, Blue; medium, Brown & high, Green) is indicated by the numbers in the columns labeled Change (column C) on Tables 8a and 8b below. For a full description of these categories, see under "Patterns of association among Data, Warrants, and Claims," this Chapter.

Before I proceed with the larger discussion about pre-post patterns, let me point out here that rather than focus on patterns emerging from individual types of Data and Warrants, I present overall patterns for these two variables. As in associations of Data and Warrants to Claims (Table 6a & 6b, this Chapter), this was my attempt to reduce complexity in emergent patterns. Thus, the overall emergent patterns are based on the total number of types of elements in each category in each of these tables. This was computed from shifts in each type of Data (Appendix F1) and Warrant (Appendix F2). For example, for Table 8a, I added the number of each type of element under the category Other (NO, REO & RMO, see Table F1) for Pre and then for Post. Next, I computed change from the sums, which in this case was 1 or 2.4 % (blue highlight, Column C). I repeated the same procedure for other Data categories (Table 8a) as well as for Warrant categories (Table 8b).

Table 8a: Overall (%) Pre/Post Data comparison

Data category	**Pre (A)**			**Post (B)**			**Change [B-A] (C)**
	Needs	**Results**	**Sum**	**Needs**	**Results**	**Sum**	**Sum B – Sum A (%)**
Low level (other)	23	18	**41**	15	27	**42**	1 (2.4%)
Medium level (General)	26	9	**35**	22	11	**33**	-2 (5.9%)
High level (Specific)	41	18	**59**	41	46	**87**	28 (38.4%)

Table 8a provides overall comparisons between the numbers of types of Data in the pre-post-interviews. This includes data from all the 16 students irrespective of whether they did all or part of the interviews. The upper part of the Table (Low level row) shows what I consider to be low category (or Other), the middle part (Medium level or General row), and the lower part of the same Table (High level row) shows high level category (Or Specific).

The numbers in the cells in column C are similarly identified and these indicate how each category of Data changed, with percentage change in parenthesis. For instance, results suggest that overall, there was virtually no change in students' response about Data in the low level category (Other). This is indicated by an overall increase by 1(or 2.4%) ---I expected an overall decrease though. Similarly, there was overall no change in students' response about Data in the medium category (General). This is based on the fact that there was an overall marginal decrease, as expected, by 2 (or 5.9%) in the differences in sums for pre-post. Viewed together, results from these categories perhaps suggest that students' ideas tend to persist over time with a likely persistent force dynamic view of phenomena including Tree Growing, Flame Burning, and Car Running.

The most expected shift occurred in the high category (High level row): That is, there was a resultant increase by 28 (or 38.4%) in the difference in Sum for the Pre-Post in column C on the lower part of Table 8a. Another pattern that is noticeable from Table 8a is that overall and compared to Needs, students talked more about Results in their post than pre responses. For details about shifts in specific types of Data, see Appendix F (Table F1). For example, there were a total of 18 total types of Results from all of the 16 students' pre-interview responses. By contrast, there were a total of 46 types of Results from their post-interviews, a total increase of 28. The total types of Needs in these students' responses remained at 41 (no increase). Together, these patterns suggest that maybe students were beginning to think more about the consequences of the processes as well as their causes and less about transformations in matter and/or energy.

Another interesting general pattern from Table F1 (see under Appendix F) is that students talked more about Results in their post-interviews. The overall number of Needs statements at all levels tended to remain unchanged, while the number of Results statements increased by 28. This suggests that students may be showing a greater tendency to think about processes as involving elements that can be traced through time.

Overall, and given that I expected the number of each type of Data to first decrease from the upper part of the Table (lower level Data) and then increase toward the lower part of the same Table (higher level Data), these results suggest a pre-post change that was marginal. Among other reasons, this could be due to the nature of the comparison that I did---I included all of the 16 students' data whether or not they completed their pre-post-interviews. I will return to this point after a brief interpretation of Table 8b below.

Table 8b: Overall (%) Pre/Post Warrant comparison

Warrant category	Pre (A)	Post (B)	Change [B-A] (C)
Low level	86	67	-19 (24.8%)
Medium level	13	11	-2 (16.7%)
High level	48	59	11 (20.6%)

Table 8b shows comparisons between the total number of types of Warrants in the pre-post-interviews from all the 16 students irrespective of whether they did all or part of the interview. The upper part of the Table shows what I designated low level category of Warrants (For specific examples of types of Warrants, see Appendix F2). In the middle part of the Table, I designated as medium level category of Warrants. Finally, on the lower part of the Table I include high level category of Warrants.

As in Data, I first expected a decrease in the number of the low level category of Warrants (column C) and then an increase in the high level category toward the lower part of the table on the same column in the pre-post-interviews. Unlike Data, all categories of Warrants showed the expected trend: That is, a general increase from force-dynamic types of Warrants at the top part to more scientifically verifiable ones at the lower part of Table 8b. For shifts in specific types of Warrants (e.g. Analogies, Other properties of Actors, & Special Properties of Enablers Energy) see Appendix F2.

Based on Table 8b, there was overall a small shift in the direction of using Warrants that tend to align with scientific principles. This suggests that, to a limited extent, students were beginning to lean more, in their responses about Carbon Transforming Processes, toward scientific reasoning in their attempts to link Data to Claims made. However, this shift is not attributable to any intervention in any way. Rather, this could be attributed to, as earlier noted, reasons beyond this study. For example, although participating teachers were expected to use the units we developed (e.g. Systems and Scale, Plants, Animals and Decay) into which tools for reasoning were built to teach, we know little about how they used them (see also under Comparison of characteristics of elements at two different points in time-Research Question 2).

One factor that I wish to check here is whether the number of pre-post interviews students did had anything to do with the results in Tables 8a and 8b. To do this, I identified and excluded all data (pre-post) from students with partial participation (either did pre or post)--a total of 7 students' data. The remaining 9 students' overall data is presented in Tables 9a (pre-post Data), and 9b (pre-post Warrants). For details about pre-post shifts in individual Data and Warrants, see Appendix F3 and F4 respectively. A commentary is included after each of these tables.

Table 9a: Overall (%) Pre/Post Data comparison with partial data excluded

Data category	**Pre (A)**			**Post (B)**			**Change [B-A] (C)**
	Needs	**Results**	**Sum**	**Needs**	**Results**	**Sum**	**Sum B – Sum A (%)**
Low level	19	15	**34**	12	22	**34**	0 (0.0%)
Medium level	21	4	**25**	19	11	**30**	5 (18.2%)
High level	32	15	**47**	41	44	**85**	38 (57.6%)

After excluding all data from students who had not completed pre-post interviews, the trend in change (Table 9a, column C) in the overall number of types of Data basically mirrors that of 8a. To illustrate, even after excluding partial data, Pre-post low level category of Data (Other) showed no change. With regard to medium level category, exclusion of partial data yielded unexpected overall increase by 5 (or 18.2%). Similar to table 8a, these two categories of Data suggest that students' responses at low levels of achievement tend to include data that refer to, for instance, conditions and specific forms of matter for other processes and that this tend to persist over time. This is with a likely consequence of persistent force dynamic view of phenomena, in this case Tree Growing, Flame Burning, and Car Running.

As in Table 8a, the most expected change occurred in the high level category, an increase by 38 (or 57.6 %, column C). This possibly point to the idea that, over time, students' responses at high level category are characterized by reasoning that tends toward scientific ways of thinking. Despite the expected change at the high level category, the patterns from Table 9a remain fairly unclear. This is in the sense that against this expected increase (column C), was an overall unclear expected decrease in those categories designated lower level (for shifts in the number of various high level types of Data see Appendix F, Table F3). This could be, among other reasons, due to the way we asked the questions. I should note that at the time of conducting interviews, we were engaged in an iterative development of the interview protocol. Thus, a possible future study might include an examination into whether, compared to the old protocol, the revised protocol generates same or different kinds of elements of argument, if at all.

Table 9b: Overall (%) Pre/Post Warrant comparison with partial data excluded

Warrant category	Pre (A)	Post (B)	Change [B-A] (C)
Low level	63	59	-4 (6.6%)
Medium level	11	11	0 (0.0%)
High level	34	56	22 (48.9%)

Unlike Data, excluding all data from students who had not completed pre-post interviews showed a mixed trend in change (Table 9b) of the total types of Warrants they used to link Data to their Claims about Tree Growing, Flame Burning, and Car Running. That is, whereas I expected a decrease in the overall number of low level category of Warrants in the pre-posts, this was by what I consider a little (i.e. by -4 or 6.6%, column C). Additionally, there was overall, no change in the medium level category. While there was an overall expected net change in the high level Warrants category of 22 (or 48.9%), the overall little change of low level category of warrants in students' responses about Carbon Transforming Processes likely point to mixed results.

Summary

In brief, students seemed to provide different types of Data and Warrants, ranging from low to high level, to support their accounts about the processes of Tree Growing, Flame Burning, and Car Running. Whereas most less sophisticated students' responses utilized Data and Warrants that were more in the form of "obvious facts," which may or may not be empirically verifiable, a few more sophisticated students' responses tended to employ the types of elements that were more aligned with scientific principles in the sense that these were increasingly elaborated during the interviews, sometimes with

Backing. Furthermore, other students' arguments tended to utilize both lower and higher level elements at the same time in their accounts of Carbon Transforming Processes.

Although a few students' accounts included elements that align more with scientific principles (e.g. EJR) in their post-interviews, others' accounts such as that of TNC included similar elements (those they used in their pre- interviews) in their post-interviews. Furthermore, compared to Data, students' responses tend to include more of low level Warrants at level 2 than they do at level 4.

On the one hand, this likely indicates that more sophisticated responses tend toward what Toulmin (1958) calls Basic argument. This is in the sense that these responses seem to follow more of the rules of scientific reasoning by including all the elements of a Basic argument (Claim, Data, & Warrant). On the other hand, less sophisticated responses tend to focus less on, from Toulmin's viewpoint, elements of Basic arguments. Illustrative of this is the idea that most of these responses are more often than not characterized by Data and Warrants that hardly link to each other and/or to Claims made. That is, although it may be true that some of these students' responses may include Data that are scientifically verifiable, these are often linked to Claims that may or may not align with scientific principles of matter and/or energy. This is in addition to using Warrants that neither relate to the Claims made nor the Data used. These patterns of association among Data, Warrants, and Claims were used as the basis for the suggested Argument Levels of Achievement (Table 7), which summarizes the kinds of Data and Warrants associated with each level of achievement for Claims.

There were also patterns of change between students pre- and post-interviews. Students generally increased the overall number of high-level category statements for both Data and Warrants, while numbers of low level category statements showed mixed patterns. Students' responses also showed an increase in the number of times that Results of processes were cited at all levels. Overall, this study's findings suggest implications to teaching and learning science discussed in the next chapter (Chapter 4).

Chapter 4: Discussion and Conclusion

In this Chapter, I (a) briefly discuss limitations of this study in relation to data collection process in terms of intentions and likely unintended questions raised that are beyond the purpose of this study, (b) present assumptions that I brought into this study and (c) suggest contributions of this study to the field of science education in terms of implications for research and practice and teaching and learning of science as well as suggest future directions in research.

Limitations of the study

The data used for this study have important limitations. In the process of interviewing respondents (see Appendix 1), we tried to develop an environment that elicited students' ideas about Carbon Transforming Processes. For example, we explained to respondents that we were seeking their ideas about these processes to help us design classroom tools/materials for use in teaching and learning science. At the same time, we tried to establish a working relationship with respondents by stating that they were free to ask questions at any time during the interview. However, there were limitations in the data collection process including the following:

- The only data source for this study was clinical interviews. Thus the study lacks triangulation that would allow me to associate characteristics of students' interview performances with deeper characteristics of their reasoning about carbon-transforming processes.
- Although I was interested in the analysis of pre-post interviews, I was not able to specifically say how instruction affected interviews: That is, we knew little about the specific instruction students received. As a consequence of this limitation for

Research Question 2, I only focused on documenting how students' interview responses changed at two points in time and not what changed them.

- I used the Practices of Responsible Citizenship framework as part of the rationale for the study, but I could not focus on how students' arguments were connected to other practices of environmental literacy---students were not really trying to persuade the interviewer about issues regarding, for example, environmental choices. Indeed, our protocol was not designed to elicit students' ideas about environmental choices, explicitly or otherwise. Thus, students may not have made complete arguments that include environmental choices with the result that I could not document their cultural practices in context.
- Additionally, given that I was interested in the nature of arguments rather than what caused them, I included only demographic information that I believe was sufficient to respond to the research questions for this dissertation study. Thus, I cannot address a question about patterns by demographic information, for example gender and socioeconomic status, of participants.

These limitations notwithstanding, findings from this work can provide important contributions to the field of science education some of which I briefly discuss next. As a way of setting the stage for this discussion, I begin by pointing out some of the assumptions that I brought into this study.

Assumptions

I focused this dissertation study on how students constructed arguments to support claims made regarding transformations of matter and/or energy in three carbon-transforming processes: Tree growing, Flame Burning, and Car Running. I bound my study within our large environmental literacy project and literature about argumentation as inquiry. These contexts provided me with the opportunity to focus on developing a Learning Progression perspective for argumentation. Based on this view, this dissertation study was driven by a number of implicit assumptions associated with the field of science education.

First was the idea that information from data analysis relating to argumentation should be informative about the challenges students face in reasoning about phenomena and therefore identify the likely supports they need as they work toward achieving science literacy (e.g. NRC, 1996). In this study, the informative information comes from data analysis about socio-ecological events for matter and energy transformation. This assumption relates to the mastery of the principles of matter and energy as an educational end-goal.

Second was the notion that working toward providing for students' science learning support relating to argumentation would better position them to utilize inquiry practices in their science learning roles such as critiquing sources of information (e.g. Collins et al., 1989; Duschl, et al., 2007) in classrooms.

A third assumption, closely related to the second, was that we need to understand how students approach data-driven arguments about complex socio-ecological issues such as global climate change. Embedded in this assumption was the hope that students who use the principles of matter and energy in analyzing information or responding to questions about current socio-ecological issues, such as global warming, would develop into environmentally responsible citizens (e.g. Covitt et al., 2009).

Implications for Research and Practice

Based on the assumptions in the preceding subsection and borrowing from Toulmin's (1958) model of argumentation, I note that in spite of continued work on Learning Progressions and therefore supports in student science learning, learners still struggle to use the big ideas of matter and energy in ways that align with scientific ways of thinking. To illustrate and with respect to Research Question 1, different students tend to use different types of Data, Warrants, and sometimes Backing to support different kinds of Claims. Data analysis shows students in three groups:

- On the one hand, most students (e.g., see Tables 6a & 6b, Chapter 3) continue to use the kinds of Data and Warrants that are in the low level of sophistication category even after a period of introducing them to the concepts of matter and energy transformation in Carbon Transforming Process. The likely reason for this is that these are abstract concepts and therefore not easy to grasp. This is especially evident at the low Claim level where students' responses indicate that perhaps they view socio-ecological events in force-dynamic ways (see e.g. Pinker, 2007) where actors (e.g. Trees) constantly need enablers (e.g. air) to fulfill their natural tendencies (e.g. growing).
- On the other hand, data analysis suggests that a few students (e.g. see Tables 6a & 6b) tend to use the kinds of Data and Warrants that are in the high level category of sophistication after a period of introducing them to the concept of matter and energy transformation in Carbon Transforming Process. In addition, one of the patterns from data analysis shows that students talk more about Results in their post-interviews than in their pre-interviews. Suggestive

here is the idea that students may be beginning to factor into their reasoning about Carbon Transforming Processes elements of argument that involve tracing matter and energy over time.

- Some students used elements from both force-dynamic and model-based reasoning. These students tend to use types of Data and types of Warrants from medium level category of sophistication (for details, see e.g. discuss under types of Data and types of Warrants).

At this point, I suggest implications for these findings about students' arguments related to science teaching and learning, as well as possible future directions for research.

Implications for science teaching and learning

A major goal of science education has long been to prepare all students to achieve science literacy (e.g. NRC, 2007; National Science Education Standards, 1996). Findings from this study suggest that achieving such goal remains challenging. This is on the basis that large proportions of students' arguments showed low levels of sophistication. This finding is similar to findings in other literature on Learning Progressions (LP) which suggest that most students still grapple with the problem of using reasoning that aligns with scientific ways of thinking to explain socio-ecological events (see e.g. Alonzo & Steedle, 2008; Covitt et al., 2009; Jin & Anderson, 2008).

This study develops an empirically-based Argument Learning Progression framework in terms of Levels of Achievement (see Table 7, Chapter 3). This work thus complements other empirical studies on Learning Progressions (see e.g. Mohan, Chen, & Anderson, 2008). Like other studies about Learning Progressions, this study is focused on describing students' development regarding specific practices. Knowledge from this description can support designing and selecting both curricula and instructional tools that better align with identified needs.

Other research has shown that most students struggle with defending claims they make with evidence (see e.g. Sadler, 2004) in the scientific sense. This could be because these students "are seldom supported in this scientific practice" (Krajcik & McNeil, 2009). Lack of student support perhaps accrues from teachers' own struggles with balancing promising data-driven instructional practices that emphasize a systematic way of understanding phenomena with other demands of their workplace, such as well-meaning but misguided standardized testing (see e.g. Huber & Moore, 2000) that shift away from these practices. This study suggests ways to help students construct more effective arguments and by extension, better assessment.

Like other recent studies about learning progressions (e.g. Gunckel, Covitt, & Anderson; 2009; Krajcik & McNeil, 2009; Mohan, Chen, & Anderson, 2009), my study is consistent with what Popham (2007) calls less-is-more model. This is in the sense that it can empirically "show how students build understanding of important ideas as they move through the curriculum…or experience instruction…" (Stevens, Delgado & Krajcik, 2010, p.708). Using argumentation as an instructional tool in classrooms can help support students in developing skills (e.g. Kuhn, 1991) for constructing inquiry-based arguments (Berland, & McNeil, 2009; Covitt et al., 2009; Gotwals et al., 2009) that are both based on empirically verifiable data and connected to the claims made in line with scientific principles. My proposed Argument Learning Progression therefore, viewed as a tool, can complement our efforts in trying to provide resources for both instruction and assessment of students' work

This study can also support preservice teacher preparation and teacher professional development that emphasizes important foundational ideas, in this case matter and energy, and argumentation. Together with intended instruction, this can ensure curriculum coherence (Stevens, Delgado & Krajcik, 2010) that is generally lacking across time and disciplines (Kedisou & Roseman, 2002; in Stevens, Delgado & Krajcik, 2010).

Future directions in research

My study is my attempt to contribute directly to one other broad research goals for our larger multiyear Environmental Science Literacy research program. We are working to develop and validate a learning progression framework in which we describe how learners can transition from intuitive or force-dynamic reasoning by elementary students to a level of environmental science literacy needed by informed citizens. Whereas other studies in the project describe our progress in a framework for accounts of carbon-transforming processes (e.g., Mohan et al., 2009), my study extends this framework to include students' arguments. Thus, this study attempts to make connections to our overall goal of continued promotion of our ideas about environmentally responsible citizenship (for details about Practices of Responsible Citizenship, see e.g., Covitt et al., 2009).

This study can also contribute to our goal of developing assessment resources tied to our common Learning Progression framework, including on-line and paper-and-pencil written assessments and clinical interviews. These assessments provide an empirical basis for our continued refinement of our framework as well as rich descriptions of the knowledge and practice of diverse learners as they reason about phenomena.

This study raises important questions that were beyond its design. For example, do students who support their accounts of individual processes with true arguments from empirical evidence also support positions on environmental issues? If they cite well-defined observational data and warrants in support of their accounts of tree growing, do they also favor arguments about environmental issues that are supported with well-defined observational data and warrants? When provided with alternative ideas that challenge the Claims they make about Carbon Transforming Processes, do they also appeal, if at all, to evidence to support those Claims? What is the nature of that evidence? These are questions for a possible future study.

Appendix A: Interview Protocol

Environmental Literacy Carbon Interview

FORM A

Please start by briefly introducing yourselves---include the idea that you are a member of Environmental Science Literacy Research Project from MSU. Then, briefly explain the purpose of the interview: In our work, we seek students' ideas about such processes as tree growing, girl growth, girl running, dead tree decaying, flame burning, car running, lamp lighting, and cross processes. Our goal is to use these ideas to design classroom tools/materials for use in teaching and learning science. The purpose of this interview, therefore, is to seek your help in terms of your ideas about some of these processes. Please feel free to ask questions at any time during the interview.

Next, please write down the student's names, grade (and age) here below---you may ask the student to help you spell his/her names. At this point, you may proceed to the interview items (Next Page).

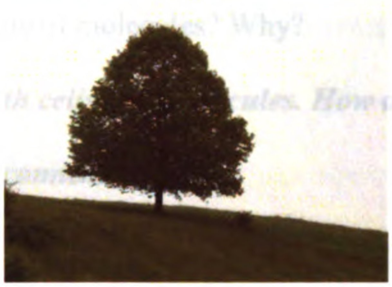
Name ____________________ Grade __________ Age _____________

The ***italicized*** questions are for higher level students.

It is possible that you may not be able to finish all the interview questions.

PLANT GROWTH

Tree Growing

	
A small tree was planted in a meadow	After 20 years it has grown into a big tree, weighing 500 lb more than when it was planted.

Actor: tree

Enablers: sunlight, water, soil, and air

Figure A.1: Oak tree

1. What does the tree need in order to grow?
2. You said that the tree needs **[sunlight, water, soil, air]** in order to grow. Follow up probes about each enabler:
    a. How does [the enabler] help the tree to grow?
    b. What happens to [the enabler] inside the tree?
    c. Is [the enabler] used up to help the tree to grow? Does it change into other things inside the tree's body? Or, do you think it will not change inside the tree's body?
    d. Does the tree use [the enabler] for energy? How does that work?
3. Follow-up probes on enablers not mentioned
    a. Some other students have mentioned [other enabler]. Do you think [the other enabler] is necessary for the tree growth?
    b. [If yes, same probes as for other enablers.]
    c. [If no] Why not?

4. Scale

    a. Do you think that the tree is made of cells? Why?

    b. Do you also think that the tree is made of molecules? Why?

    c. ***You said that the tree is made of both cells and molecules. How are the cells and molecules related? What's the connection?***

5. Matter

    a. Does the growing tree change the air? How does that happen?

    b. The tree gets heavier as it grows. How does that happen?

    c. Where do the increased materials come from?

    d. Do you think the tree's body can naturally create more and more materials? Why?

    e. Do you think the increased materials of the tree's body are changed from things outside of the tree? ***[If yes], how do these things change into the tree's body structure***

    f. ***If the student mentions glucose/starch/cellulous/carbohydrates, ask: Do you think it contains carbon atoms? [If yes], where does the carbon atoms come from?***

    g. ***[If the student talks about CO2—O2 exchange, ask]: You said that the tree needs Carbon dioxide and breath out oxygen. Where does the carbon atom of CO2 go?***

6. Energy

    a. Does the process of tree growing involve energy? ***[If yes], where does the energy come from?***

b. Why do you think the things you mentioned have energy?

c. [If the student associates energy with sunlight, ask]: Where does the energy of sunlight go? Is it used up? Does it change into other materials? Or, is it still energy? Where is it?

d. Do you think the tree stores energy inside its body? If yes, where does the tree store energy? In cells? In molecules? Where does that energy come from?

e. If students do not mention photosynthesis, ask: Is there any connections between the things you mentioned and photosynthesis?

FLAME BURNING

Burning Match

Burning Candle

Actor: flame

Enablers: fuels (wax, wick, wood), air

Figure A.2: March and Flame

1. What does the flame need in order to keep burning?
2. You said that the flame needs [**wax, wick, air, wood …**]. Follow up probes about each enabler.
   a. How does [the enabler] help the flame to burn?
   b. What happens to [the enabler] inside the flame?
   c. Is [the enabler] used up? Does it change into other things? Or, do you think it does not change?
   d. Does the flame use [the enabler] for energy? How does that work?
3. Follow-up probes on enablers not mentioned
   a. Some other students have mentioned [other enabler]. Do you think [the other enabler] is necessary for the flame to burn?
   b. [If yes, same probes as for other enablers.]
   c. [If no] Why not?
4. Scale

a. Do you think that the flame is made of materials?

b. If yes, do you think the flame is made of molecules and atoms? Please explain.

5. Matter

a. What change will happen to the match?

b. Do you think the match will lose weight? [If yes], where does it go? Is it used up? Does it change into other things? Why?

c. What change will happen to the wax of the candle?

d. Do you think the candle will lose weight? [If yes], where does it go? Is it used up? Does it change into other things? Why?

e. Does the event of flame burning change the air? How does that happen?

f. Do you think wax/wood contain carbon atoms? [If yes], where do the carbon atoms go when the flame is burning?

6. Energy

a. Does the process of flame running require energy?

b. If yes, where does the energy come from?

c. Why do you think the things you mentioned have energy?

d. [If the student associates energy with wood or wax, ask]: Where does the energy of wood/wax go? Is it used up? Does it change into materials? Or, is it still energy? Where is it?

e. Why do you feel warmth when the flame is burning? Do you think heat is released from burning?

f. [If yes], how is heat released? Do you think heat is created in combustion, or do you think it is changed from other forms of energy in combustion? Please explain.

g. If students do not mention combustion, ask: Is there any connections between the things you mentioned and combustion?

CAR RUNNING

Car Running

Tom's family went to Chicago on vacation. When they came back, Tom's dad found that their car consumed 50 gallons of gasoline for the trip.

Actor: Car

Enablers: gasoline, air

Figure A.3: Car running

1. What does the car need in order to carry the family to Chicago?
2. Why do people use gasoline instead of water to run their cars?
3. You said that the car needs [**gasoline, air**]. Follow up probes about each enabler:
    a. How does gasoline/air help the car to run?
    b. What happens to the gasoline/air inside the car when the car runs?
    c. Does the car use gasoline/air for energy? How does that work?
    d. Is gasoline/air always necessary for car running? Why or why not?
4. Follow-up probes on enablers not mentioned
    a. Some other students have mentioned gasoline/air. Do you think it is necessary for car running?
    b. [If yes, same probes as for other enablers.]
    c. [If no] Why not?

a. When your family arrives at Chicago, the gas tank is almost empty? Where does the gasoline go?

b. Do you think the gasoline is used up? Or, does it change into other things?

c. Does the event of car running change the air? How does that happen?

d. Do you think gasoline contains carbon atoms? If yes, where do the carbon atoms go when the gasoline is used by the car?

6. Energy

a. Does the process of car running require energy? If yes, where does the energy come from?

b. Why do you think the things you mentioned have energy?

c. [If the student associates energy with gasoline, ask]: When the car stops, where does the energy of gasoline go? Is it used up? Does it change into materials? Or, is it still energy? Where is it?

d. After the car runs for a while, the front part of the car will become very hot. Why?

e. [If the student mentions heat, ask]: how is heat released?

f. You said that the gasoline is burning inside the car. Do you think heat is created in burning, or do you think it is changed from something else? Please explain.

g. If students do not mention combustion, ask: Is there any connections between the things you mentioned and combustion?

Appendix B: Tools for Reasoning

Introduction

These tools were designed for teaching experiments at elementary, middle, and high school levels focusing on carbon-transforming processes in socio-ecological systems at multiple scales, including cellular and organismal metabolism, ecosystem energetics and carbon cycling, carbon sequestration, and combustion of fossil fuels. These processes: (a) create organic carbon (photosynthesis), (b) transform organic carbon (biosynthesis, digestion, food webs, carbon sequestration), and (c) oxidize organic carbon (cellular respiration, combustion). The primary cause of global climate change is the current worldwide imbalance among these processes.

Our teaching goal is to support students as they move through a learning progression leading to *environmental science literacy*—the capacity to understand and participate in evidence-based discussions of socio-ecological systems and to make informed decisions about appropriate actions and policies. As discussed in more detail in the Appendix, our research shows that in order to develop environmental science literacy, students must master three key principles: *scale, matter*, and *energy*. The tools for reasoning are designed to embody those principles. As an example of the kinds of the kinds of tools for reasoning we used, I have included the molecular models tool for reasoning in the illustration below.

1. *The Powers of 10 Tool* embodies the principle of scale. Students can use this tool to connect representations of systems and processes at multiple scales: atomic-molecular, microscopic, macroscopic, and landscape scales.
2. *The Process Tool* embodies the principles of conservation of energy and matter:

a. The top row of the tool embodies conservation and degradation of energy: Students can use this part of the tool to describe how any process involving chemical and/or physical change transforms energy without changing the total amount of energy, including some energy that is converted to waste heat.

b. The second row of the tool embodies conservation of matter. Younger students can use this tool to identify solids, liquids, and gases as reactants and products. More advanced students can use the tool more rigorously to balance mass of reactants and products and to trace atoms through processes.

3. *Molecular models* embody conservation of matter. Students can use this tool to model how all carbon-transforming processes rearrange atoms into new molecules without creating or destroying atoms.

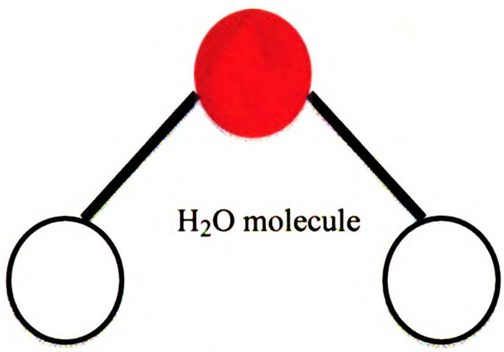
We have designed these Tools for Reasoning to be flexible enough to use in every lesson, including both lessons in our teaching modules and other lessons involving carbon-transforming processes. The teaching experiments include the following modules:

1. Systems and scale: Introductory module, designed to be used before any of the other modules
2. Plants: Plant growth and metabolism
3. Animals: Animal growth and metabolism
4. Decay and decomposers
5. Carbon cycling: Ecosystem scale
6. Human energy systems

An illustration of tools for reasoning

Tools for reasoning: Matter and Energy

Molecular Model Kits



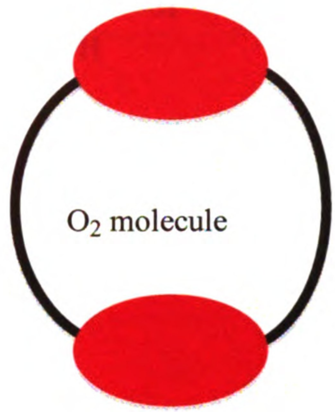


Figure B.1: Water and Oxygen molecule

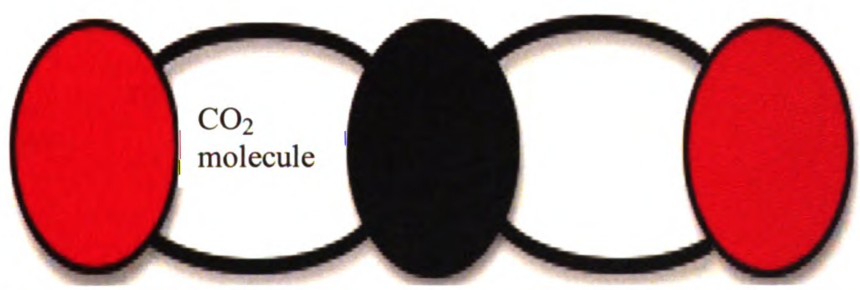
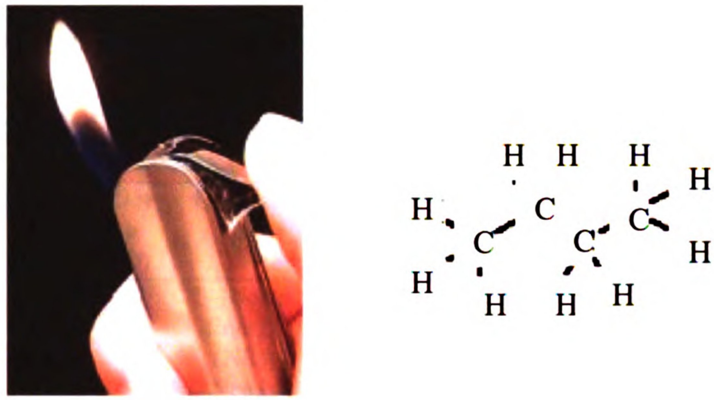


Figure B.2: Carbon dioxide molecule



Butane (C_4H_{10})

Figure B.3: Butane molecule

Appendix C: Examples of Color coding

Table C1: Example Coding for Data

Transcript	Process	Data (D)	Comment	General Code	Specific Code	Level_Explaining	Pre/post
RWD: It needs water, sunlight and carbon dioxide.	TG	D	I---Needs Energy (NE); Needs Matter (NM)	NE; NM	NMS;NES	2	Pre
SLP: Sun and water.	TG	D	I	NM	NEG; NMS	1.5	Pre
SLP: And soil.	TG	*D*	*Other needs*	*NO*	*NMO*	1.5	Pre
SLP: Somewhere to be placed in the ground.	TG	D	Condition	NO		1.5	Pre
TNC: It needs ... water.	TG	D	I	NM	NMS	1	Pre
TNC: And like nutrients. [0:02:05.6]	TG	D	I	NM	NMS	1	Pre

<u>Table C2: Example Coding for Warrants</u>

Transcript	**Process**	Warrant (W) &/or Backing (B)	Comment	General code	Specific Code	Level Explaining	**Pre/post**
RWD: It just helps it burn because if it's wet or wet material that would just stop the fire.	**FB**	*W*	T (see line 255)	Tautological (T)	T	1	**pre**
RWD: It's joined with the carbon dioxide to *create* sugar which the plant uses for food.	**TG**	W	Reactant: Except for the term "create", aligns with scientific principles	Hidden Mechanism Matter (MM)	SPEM	3	**post**
RWD: Glucose. The plant's food.	**TG**	W	Glucose is food	RM	SPEM	3	**post**
RWD: Carbon dioxide and sunlight and the water are all combined to *create* the **glucose.**	**TG**	W	Reactants: Except for the term "create", aligns with scientific principles	MM	SPEM	3	**post**
RWD: When it burns the glucose *to make its food.*	**TG**	W	Implicit--- glucose has energy	MM	SPEM	3	**post**
RWD: In it's bonds in like carbon to carbon and carbon hydrogen bonds.	**TG**	W	Aligns with scientific principles	MM	SPEM	3	**post**
RWD: *In the bonds of the carbon dioxide and the water.*	**TG**	*B*	*Thinks that CO2 & H2O have energy*	*MM*	*OFE*	3	**post**

Appendix D: Exemplar Worksheets for Reliability Checks

Given limited space (worksheet too large to fit allowed page specifications), I split the large exemplar Table (on the exemplar worksheet) into three parts one each for Tree Growing, Flame Burning, and Car Running.

Table D1: Exemplar color coding Tree Growing

	Elements: Meanings & Examples		
Process	**Claim:** Statement(s) students make about how matter and/or energy are involved in CTPs: Relate to hidden mechanisms. **Examples include:**	**Data:** Visible observation(s) about CTPs, regarding a claim that students may make: May include verbal observations- typically statements about needs of organisms or conditions for processes to occur and statements about visible results of processes. **Examples include:**	**Warrant:** Universal premises students make that link either one type of data and/or different types of data to the claim regarding specified CTPs. **Examples include:**
TG	I: ...So where does light energy (water and CO2) go? 1. EJR: It (energy) is ... converted to a stored energy) AND/OR 2. RKC: ...there would be a chemical reaction... light energy...it provides heat and things. AND/OR 3. AJB: ...it goes through the tree...	**I:** what does a tree need in order to grow? 1. EJR:..water..., nutrients... carbon dioxide...sunlight AND/OR 2. JMJ: ...sunlight, water ...*good soil* AND/OR 3. NAC: Water, sun...Oxygen AND/OR	I: So how does a tree use air (and water)? 1. EJR: ...carbon dioxide contains molecules, atoms 2. SAM: water...make it do photosynthesis ...carbon dioxide...gets used as energy AND/OR 3. SLP: The water is like the food (for the tree)

Table D2: Exemplar color coding for Flame Burning

FB	**I: ...do you think the chemical energy still exists somewhere or changing...other types of energy, or just burn up?** 1. **ANW:** It changes into heat and light energy **AND/OR** **I: ...So where does the lost material go?** 2. **RWD:** It's combined with the *burning oxygen* and *creates* CO_2. And, *anything left turns* into a liquid **ND/OR** **I: Ok. ...Why does the flame need wax and wood? What happens to them?** 3. **...wax and wood are kind of like flames' food...** without it, they'll just die off	**I: What does a flame need in order to keep burning?** 1. **ANW:** It needs oxygen, wood... **AND/OR** **I: ...So how about wax and a wood... What happens to them?** 2. **JAH:** I think part of the actual wick gets used up and then the wax just kind of melts and then reforms later.... **AND/OR** 3. **JMJ:** It will disappear...	**I: What is in wood that makes it burn?** 1. **ANW:** Wood has chemical energy **AND/OR** **I: So how does oxygen help the flame to keep burning?** 2. **RWD:** It has high energy bonds and it's flammable... **AND/OR** **I: ...So how about wax and a wood... What happens to them?** 3. **JMJ: ...** wax and wood are kind of like flames' food. ...

Table D3: Exemplar color coding for Car Running

CR	**I: ...So do you think a car moving needs air and gasoline? (What happens to those?) How does that work?** **1. EJR: ...gasoline is burned within the engine...**it is converted to water vapor and carbon dioxide... **AND/OR** **I: So where does the energy initially in the gasoline go?** **2. RWD:** It runs through the engine and then is converted to carbon dioxide **AND/OR** **3. DRH: Yeah... the spark is used to start the car** *...makes the gasoline and brings the air and the spark and the gas from behind, the molecules like makes an explosion and it makes the car the move*	**I: ...what does the car need in order to carry the family to Chicago?** **1. EJR:** It needs oxygen. It needs a source of fuel, which in the case of the car is going to be gasoline... **AND/OR** **2. JAH:** It needs oxygen for the combustion, gasoline, it needs a person to drive it and I guess that would be all ... **AND/OR** **3. DRH: ...the** gas ... and somebody controlling the car.	**I: ...what does the car need in order to carry the family to Chicago? How does that work?** **1. EJR:** ...gasoline...is ...combination of carbon and hydrogen molecules. It uses the oxygen in the air in the process of burning the gasoline... **AND/OR** **I: So where does the heat energy come from?** **2. RWD:** Some of it's from the energy from the gasoline. And, the other part of it is from the oxygen **AND/OR** **3. DRH: ...the gas,** that's the energy. ...

Note:* *All the parts should be viewed as one long Table with column headings Process, Claim, Data, and Warrant (see headings for the first part, this Appendix).

In addition to the coding worksheet labeled AllData (see tables 3a and 3b, Methods section) and the just presented three exemplars, I included the following procedure for coding, first, a sample of two purposefully selected students' responses (one more sophisticated than the other).

- On the worksheet labeled "AllData" (this workbook), and for each process (Pre/Post) please follow this procedure to do reliability coding for these two students: AH and JMJ:
- Begin by reading and identifying these elements of argument and accordingly highlight them (see exemplar workbook for definitions & examples): Claim (green); Data (blue); Warrant (pink); Backing (orange
- Next, identify the specific types of Data you have highlighted (e.g. NES, & RMS)---all possible types are provided under Data: If present, indicate by typing in "1"; If absent, indicate by typing in "0"
- Then identify the specific types of Warrant you have highlighted (e.g. A, SPEM & SPEE)---all possible types are provided under Warrant: If present, indicate by typing in "1"; If absent, indicate by typing in "0"
- Finally, identify the types of principles, either matter (PCM) or energy (PCE) conservation you have highlighted: If present, indicate by typing in "1"; If absent, indicate by typing in "0"

Appendix E: Proportions of Data and Warrant types

Lest Tables E1 and E2 seem like duplicates of Tables 6a and 6b respectively, I wish to note that they supplement each other-the latter present overall category patterns (low, medium, and high) for Data and Warrants, while the former present individual Data and Warrant types. Thus, Tables 6a and 6b are developed from Tables E1 and E2.

Table E1: Percentage (%) of types of Data at each Level of Claim

Claim level		NO	REO	RMO	NEG	NMG	REG	RMG	NES	NMS	RES	RMS
4	Count	0	1	2	0	1	0	1	5	5	5	6
	% of Total (26)	0.0	3.9	7.7	0.0	3.8	0.0	3.8	19.2	19.2	19.2	23.2
3	Count	6	3	11	4	9	1	1	9	21	11	20
	% of Total (96)	6.3	3.0	11.5	4.2	9.4	1.0	1.0	9.4	21.9	11.5	20.8
2	Count	32	5	23	11	23	5	8	6	36	8	14
	% of Total (171)	18.7	3.0	13.4	6.4	13.4	3.0	4.7	3.5	21.1	4.7	8.1
		Low Level			Medium Level				High Level			

Note: *Compared to levels 2, 3, and 4, most students used elements that were, overall, at level 2, with only a few at level 4. Students used fewer elements at level 3 than they did at level 2.Color coding is for purposes of identifying patterns.*

From Table E1 above, there were a total of 26 different citations of Data that students used to support Level 4 Claims about Tree Growing, Flame Burning, and Car Running. Out of these, students used 5 (or 19.2 %) of Data type NES compared to 0 of

Data type NO. In contrast, out of a total of 171 different citations of Data to support Level 2 Claims, students used 32 (or 18.7 %) NO compared to 6 (or 3.5%) NES.

<u>Table E2: Percentage (%) of types of Warrants at each Level of Claim</u>

Clai m level		A	T	OE M	OE E	O A	C E	SPA M	SPE E	SPE M	PC E	PC M
4	Coun t	0	0	0	1	0	0	0	4	6	1	1
	% of Total (13)	0.0	0.0	0.0	7.7	0.0	0.0	0.0	30.8	46.1	7.7	7.7
3	Coun t	8	7	12	9	5	4	5	18	22	1	5
	% of Total (96)	8.3	7.3	12.5	9.4	5.2	4.1	5.2	18.8	23.0	1.0	5.2
2	Coun t	29	27	28	16	11	13	2	17	24	0	0
	% of Total (167)	17. 4	16. 2	16.8	9.6	6.6	7.8	1.2	10.1	14.3	0.0	0.0
		Low Level					Medium Level		High Level			

Like Table E1 above, Table E2 indicates that, overall, students tend to use Warrants that align with scientific principles (Green highlight, level 4) to support their accounts of Carbon Transforming Processes (CTPs). This is with the exception of Backing (PCE & PCM) which levels 3 and 4 responses only tend to include in these accounts. However, compared to less sophisticated responses (those at Level 2), more sophisticated responses (those at level 4) are less likely to include low level types of Warrants in accounts about Tree Growing, Flame Burning, and Car Running. This is shown by generally fewer low and medium types of Warrants at level 4. Indeed, out of a total of 13 types of Warrants, students used only 1 (or 7.7 %) of the Warrant type Other Enablers Energy (OEE) at this level. In contrast, to illustrate, students used 6 (or 46.2%)

of the Warrant type SPEM at the same level. That is, the proportions of low level types of Warrants (Blue highlight) are hardly present at level 4. Similar to Data, the proportions of the types of Warrants included in Table E2 tend to increase from upper left part of the Table toward the upper right part of the same table.

Table E2 also suggests that although less sophisticated responses include some high level Warrants (i.e. SPEE, & SPEM, Green highlight), they are more likely to be characterized by low level Warrants (e.g. A & T, Blue highlight) in the accounts about Carbon Transforming Processes (CTPs). This is overall indicated by a particularly higher proportion of low level Warrants at achievement level 2 (Blue highlight) compared to either levels 3 or 4. Additionally, in contrast to high level, the proportions of these types of Warrants tend to, generally, decrease from lower left part of the Table toward the lower right part of the same table.

Furthermore, with regard to level 3, Table E2 generally shows that students tend to use both low and high level Warrants. Illustrative of this is the fact that, although the proportions of high level Warrants at this level are higher (Green highlight) than those to the left side (Blue highlight), all cells at this level are nearly equally represented at each level of elements. Consequently, students' use of Warrants at this level, overall, tends toward average.

Appendix F: Pre-Post Comparisons

Table F1provides comparisons between the numbers of types of Data in the pre-post-interviews. This includes data from all the 16 students irrespective of whether they did all or part of the interviews. The upper part of the Table (Blue highlight) shows what I consider to be low level Data (NO, REO, & RMO), the middle part (Brown highlight) medium level (NEG, NMG, REG, & RMG), and the lower part of the same Table (Green highlight) shows higher level types of Data (NES, NMS, RES, &RMS).

<u>Table F1: Pre/Post Data comparison</u>

Data type	Pre (A)	Post (B)	Change [B-A] (C)
Needs Other (NO)	23	15	-8
Results Energy Other (REO)	1	8	7
Results Matter Other (RMO)	17	19	2
Needs Energy General (NEG)	7	8	1
Needs Matter General (NMG)	19	14	-5
Results Energy General (REG)	5	5	0
Results Matter General (RMG)	4	6	2
Needs Energy Specific (NES)	8	12	4
Needs Matter Specific (NMS)	33	29	-4
Results Energy Specific (RES)	5	19	14
Results Matter Specific (RMS)	13	27	14

The numbers in the cells in column C are similarly highlighted and these indicate how each specific type of Data changed. For instance, except for NO discussed earlier, results suggest that the number of lower level types of Data increased by 7 for REO, and by 2 for RMO, which I view as substantial and marginal respectively. I expected a decrease in the number of these types of Data. In addition to this, except for NMG in which, as expected, there was a decrease by 5, there also was a marginal unexpected increase in the number of Data types NEG by 1 and RMG by 2, both of which I consider marginal. REG did not change.

The most expected change occurred in the Results Energy Specific (RES) and Results Matter Specific (RMS) by 14 each. Given that I expected an increase of these types of Data in column C on the lower part of 8a, there was an unexpected decrease by 4 for the Data type Needs Matter Specific (NMS). However, there also was an increase, as expected, by the same number (4) in Needs Energy Specific (NES). Another pattern that is noticeable from Table 8a is that compared to Needs, students talked more about Results at all levels. It suggests that maybe they were thinking more about the consequences of the processes as well as their causes.

An interesting general pattern is that students talked more about Results in their post-interviews. The number of Needs statements at all levels declined by 12 from pre to post-interviews, while the number of Results statements increased by 41. This suggests that students may be showing a greater tendency to think about processes as involving elements of argument that can be traced over time.

Table F2 (below) shows comparisons between the numbers of types of Warrants in the pre-post-interviews from all the 16 students irrespective of whether they did all or part of the interview. The upper part of the Table (Blue highlight) shows what I designated low level Warrants which include Analogies (A), Tautologies (T), Other properties of Enablers Matter (OEM), Other properties of Enablers Energy (OEE), and Other properties of Actors (OA). In the middle part of the Table (Brown highlight), I designated as medium level these Warrants: Citation of Evidence (CE) and Special Properties of Actors Matter (SPAM). Finally, on the lower part of the Table (Green highlight) I include what I view as higher level types of Warrants. These are Special Properties of Enablers Energy (SPEE), Special Properties of Enablers Matter (SPEM), Principle of Conservation of Energy (PCE), and Principle of Conservation of Matter (PCM).

Table F2: Pre/Post Warrant comparison

Warrant type	Pre (A)	Post (B)	Change [B-A] (C)
Analogical (A)	**20**	**17**	**-3**
Tautological (T)	**22**	**12**	-10
Other properties of enablers Matter (OEM)	**18**	**22**	2
Other properties of enablers Energy (OEE)	**18**	8	-10
Other properties of Actors (OA)	**8**	8	0
Citation of Evidence (CE)	**10**	7	-3
Special Properties of Actors Matter (SPAM)	**3**	4	1
Special Properties of Enablers Energy (SPEE)	**29**	29	0
Special Properties of Enablers Matter (SPEM)	**18**	21	3
Principle of conservation of Energy (PCE)	**0**	2	2
Principle of conservation of Matter (PCM)	**1**	7	6

As in Data, I first expected a decrease in the number of the lower level Warrants (Blue highlight, column C) and then an increase in higher level toward the lower part of the Table (Green highlight) in the pre-post-interviews. Unlike Data, all types of Warrants, with the exception OEM that showed an unexpected small increase by 2, followed the expected trend-a general increase from force-dynamic types of Warrants at the top part to more scientifically verifiable ones at the lower part of Table F2.

Although the most expected decrease occurred in Tautologies and Other properties of Enablers Energy, by 10 each, a small decrease of -3 each happened in Analogies (A) and Citation of Evidence (CE). Two types of Warrants did not show any change. These were Other properties of Actors (AO) and Special Properties of Enablers Energy (SPEE). Furthermore, although I have included Principle of Conservation of Energy (PCE) and Principle of Conservation of Matter (PCM) as types of Warrants, and given that only a few of the students used them, this is for purposes of discussion. These principles' increased use to defend Claims made in the post-interview was limited to a few students. The same thing also applied to CE, and SPAM. Based on Table F2, there was overall a small shift in the direction of using Warrants that tend to align with principled reasoning.

TableF3 : Pre/Post Data comparison with partial data excluded

Data Type	Pre (A)	Post (B)	Change [B-A] (C)
Needs Other (NO)	**19**	**12**	**-7**
Results Energy Other (REO)	**1**	**6**	5
Results Matter Other (RMO)	**14**	**16**	**2**
Needs Energy General (NEG)	**4**	7	3
Needs Matter General (NMG)	**17**	12	-5
Results Energy General (REG)	**1**	5	4
Results Matter General (RMG)	**3**	6	3
Needs Energy Specific (NES)	**6**	12	6
Needs Matter Specific (NMS)	**26**	29	3
Results Energy Specific (RES)	**5**	18	13
Results Matter Specific (RMS)	**10**	26	16

Table F3 shows that, after excluding all data from students who had not completed pre- and post interviews, the trend in change (column C) in the overall number of types of Data basically mirrors that of F1. However, this is with the exception of two types of Data: RMG which changed from 0 to 4, and NMS which showed more expected change from -4 to 3. Thus, even with these two changes, the patterns from Table F3 remain fairly unclear. This is in the sense that despite an expected increase in the number of various high level types of Data (Green highlight, column C), the expected decrease in those designated lower level overall was not clear.

<u>Table F4 : Pre/Post Warrant comparison with partial data excluded</u>

Warrant type	Pre (A)	Post (B)	Change [B-A] (C)
Analogical (A)	14	14	0
Tautological (T)	15	12	-3
Other properties of enablers Matter (OEM)	15	19	4
Other properties of enablers Energy (OEE)	13	7	-6
Other properties of Actors (OA)	6	7	1
Citation of Evidence (CE)	8	7	-1
Special Properties of Actors Matter (SPAM)	3	4	1
Special Properties of Enablers Energy (SPEE)	13	20	7
Special Properties of Enablers Matter (SPEM)	20	27	7
Principle of conservation of Energy (PCE)	0	2	2
Principle of conservation of Matter (PCM)	1	7	6

Table F4 shows that, although I expected a decrease in the number of lower level Warrants in the pre-post-interviews, some such as Other properties of Enablers Matter increased instead by 4 (column C). This is besides a small increase in Other properties of Actors (OA), and no change in Analogies. While there was an expected net change in all the high level Warrants such as Special Properties of Enablers Energy (by 7), the use of lower level warrants by students in their arguments likely point to mixed results.

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