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Identifying Productive Resources in Secondary School Students' Discourse About Energy

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IDENTIFYING PRODUCTIVE RESOURCES IN SECONDARY SCHOOL STUDENTS’ DISCOURSE ABOUT ENERGY

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A DISSERTATION
Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy (in Physics)

The Graduate School
The University of Maine
December 2013

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Benedikt Walter Harrer

(Date)
A growing program of research in science education acknowledges the beginnings of disciplinary reasoning in students’ ideas and seeks to inform instruction that responds productively to these disciplinary progenitors in the moment to foster their development into sophisticated scientific practice. This dissertation examines secondary school students’ ideas about energy for progenitors of disciplinary knowledge and practice. Previously, researchers argued that students’ ideas about energy were constrained by stable and coherent conceptual structures that conflicted with an assumed unified scientific conception and therefore needed to be replaced. These researchers did not attend to the productive elements in students’ ideas about energy.

To analyze the disciplinary substance in students’ ideas, a theoretical perspective was developed that extends Hammer and colleagues’ resources framework. This elaboration allows for the identification of disciplinary productive resources—i.e., appropriately activated declarative and procedural pieces of knowledge—in individual
students’ utterances as well as in the interactions of multiple learners engaged in group learning activities.

Using this framework, original interview transcripts from one of the most influential studies of students’ ideas about energy (Watts, 1983. Some alternative views of energy. Physics Education, 18/5, 213-217) were analyzed. Disciplinary productive resources regarding the ontology of energy, indicators for energy, and mechanistic reasoning about energy were found to be activated by interviewed students. These valuable aspects were not recognized by the original author. An interpretive analysis of video recorded student-centered discourse in rural Maine middle schools was carried out to find cases of resource activation in classroom discussions. Several cases of disciplinary productive resources regarding the nature of energy and its forms as well as the construction of a mechanistic energy story were identified and richly described.

Like energy, resources are manifested in various ways. The results of this study imply the necessity of appropriate disciplinary training for teachers that enables them to recognize and productively respond to disciplinary progenitors of the energy concept in students’ ideas.
Our technology-driven society is consuming more and more energy although traditional energy resources, especially fossil fuels, are approaching extinction. In order to help our students become energy-conscious citizens, we need to provide them with an effective education in science, including energy. Research has shown that students have many ideas about science when they enter a classroom. Teachers need to know about these ideas to be able to help their students learn.

In the past, researchers thought that most of students’ ideas about energy were misconceptions that are different from scientific knowledge. They focused on finding and cataloging these misconceptions in students’ ideas about energy. In their opinion, such a catalog would make it easy for teachers to spot the misconceptions and replace them with correct science ideas.

More recently, researchers have become convinced that students’ ideas about science are not all problematic. By carefully examining these ideas, they have found
valuable pieces of knowledge that are similar to how scientists think. This dissertation examines secondary students’ ideas about energy and finds pieces of knowledge in them that are similar to how physicists think about energy.

For example, students think of energy as something that can flow from one object to another, just as physicists do. Students also categorize different forms of energy according to certain rules. This is a common practice of scientists. Sometimes, students try to come up with an explanation for why and how energy flows from a certain object to another one. When scientists do this, they call it creating a mechanistic explanation.

Research has shown that instruction is especially effective when teachers recognize examples like these in their students’ thinking and help their students use these resources to learn. The results of this dissertation project can inform professional development that helps teachers to get better at recognizing scientifically valuable knowledge in their students’ ideas and using it to help students become responsible citizens.
DEDICATION

To my dad, Walter August Harrer.

1943 – 2012
ACKNOWLEDGEMENTS

This dissertation would not have been possible without the support from the National Science Foundation under grants No. DUE 0962805, No. DRL 1222580, and No. DRL 0822342. However, I am also indebted to many individual people for encouraging me to pursue my long-held dream of studying abroad to earn a doctorate and for supporting me to make this dream come true.

My passion for physics education research was sparked and fostered in the group for physics education at the Ludwig-Maximilians-University in Munich. I am indebted to Hartmut Wiesner, Martin Hopf, Bernadette Schorn, Christine Waltner, Eva Heran-Dörr, Alexander Rachel, and Verena Tobias for their mentoring and support, and I will never forget the many hours I spent experimenting in the demo lab and co-teaching with Christoph Siegmund and Michael Lang.

While visiting Munich on sabbatical, Michael C. Wittmann invited me to join his research group, the Physics Education Research Laboratory (PERL), at the University of Maine. The prospect of a bilingual “doctor father” made my decision easy to pursue a PhD in Maine. From day one, Michael supported my enthusiasm for physics education and encouraged me to follow and explore my ideas. I am grateful for the many opportunities he created that allowed me to conceive of and write this dissertation, and the guidance he provided me along the way.

One of these opportunities was meeting my co-advisor Rachel E. Scherr. Working with her in the first Energy Project Summer Research Institute at Seattle Pacific University (SPU) in 2010 introduced me to the philosophy and methodology of research that I employed in this dissertation. It was a pleasure being apprenticed into the practices of video research during this experience and subsequent collaborations.
I will be forever grateful for the intensive guidance that helped me develop my research skills and make significant progress in scientific writing.

During his time as a post-doctoral fellow at the University of Maine, I was fortunate to find a dear friend and mentor in Brian W. Frank. Many unforgettable hours of arguing physics and education made me question what and how I know, and helped me become a better researcher and teacher. Exploring Maine’s nature and cooking with Brian and his wife Bethany made me feel at home in this country.

While pursuing my doctoral degree, I was fortunate enough to not only be part of one but two research groups. I am grateful for all the inspiring conversations and collaborations over the years with my colleagues in PERL and in the Energy Project group at SPU. I am especially indebted to John R. Thompson, Natasha M. Speer, and Donald B. Mountcastle for being on my dissertation committee, to Hunter G. Close (now at Texas State University at San Marcos, TX) for serving as the external reader for this thesis, and to Sarah “Sam” B. McKagan and Abigail R. Daane for allowing me to stay with them during my extended visits to Seattle.

Ludwig Wagner, master baker and pâtissier, and his late wife Herta strongly supported my decision to depart on the adventure of continuing my education overseas. I am not only grateful to them for their endorsement but especially for giving me the opportunity to experience learning as a form of increasingly sophisticated disciplinary practice. My apprenticeship and work in their pastry kitchen were inspiring for me in my personal and professional life.

Without the support of my family and friends in Germany, I would have never had the courage to leave a familiar environment, to be crazy, bold, and idealistic, to believe in myself enough to go out and start over my life in a foreign country. I will be forever grateful.

Last but not least, I am indebted to my fiancé and most important collaborator Virginia J. Flood. With her, I have found a partner in life who not only tolerates
and encourages my many interests but who eagerly discusses learning theory with me over the breakfast table, and who enjoys editing and proof-reading my scientific writing. Her ongoing intellectual and emotional support allowed me to realize my dream.
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Chapter 1
INTRODUCTION

1.1 Historical context

In today’s technology-driven age, science instruction that authentically addresses the theoretical and practical issues around societally relevant scientific domains is crucial. Of particular concern is our consumption of energy at ever-increasing rates as traditional energy resources, especially fossil fuels, are approaching depletion. In order to provide our students with an effective science education that allows them to become responsible citizens, we need to increase our understanding of how people learn and how they can best be supported in their learning.

Research on the teaching and learning of ideas about energy has a long and rich history. With the world-wide energy crisis in the 1970s, researchers across disciplines in science and education started to question contemporary approaches to energy education and sought to find new and more effective ways of preparing energy-conscious citizens. In the US, early research in energy education was mostly focused on attitudes toward energy and conserving energy, and the development of energy curricula addressing socio-political issues (for a review, see Morrisey & Barrow 1984). In contrast, research efforts in other countries—in particular, the UK, Germany, and New Zealand—focused more on how to teach students a rigorous, scientific energy concept. Curricular sequences were developed around scientific conceptualizations of energy and research conducted on students’ “everyday notions” about energy (an extensive review can be found in Duit 1986).
Since the 1970s, the interest in research on energy education\(^1\) has increased every decade. The number of publications containing the keyword “energy” in journals that bear the designation “education” in their title in the last three years alone (≈ 16,600) is almost equal to the number of similar publications in the entire 1990s (≈ 17,500). It is more than half the number of such articles published between 2000 and 2010 (≈ 32,000).

Educational researchers were particularly interested in the investigation of students’ ideas about energy, aiming to reform instructional practice in the topic (Duit, 1986). This work was primarily conducted within a perspective of conceptual change that assumes students’ pre-instructional ideas about energy to be naive and part of stable, coherent conceptual structures that constrain predictions about scientific phenomena across contexts (e.g., Chi, 2008; Driver & Easley, 1978; Posner, Strike, Hewson, & Gertzog, 1982). These conceptual structures are considered difficult to change and viewed as hinderances to learning. Informed by this view, curricular materials and learning trajectories continue to be developed, aiming to cause disequilibrium and replace learners’ initial, naive ideas with more sophisticated and scientific understandings of energy (e.g., Duit & Treagust, 2012; Neumann, Viering, Boone, & Fischer, 2013; Trumper, 1990; Schnittka & Bell, 2011). This conceptual change is expected to occur via theorized internal cognitive processes that are not directly visible to the researcher or teacher.

In recent years, an alternative approach to conceptual change has gained growing support in the science education literature. Many researchers and teachers believe and have found evidence that students’ ideas about scientific concepts are highly context-dependent and fragmented (e.g., diSessa, 2008). Students’ ideas are no longer seen as theory-like and disadvantageous. This new perspective on students’

\(^1\)as measured by the number of journal articles about energy in international educational journals according to scholar.google.com
knowledge helped explain students’ difficulties with learning certain topics in science (especially physics; e.g., Wittmann, 2006). Research on students’ difficulties and misconceptions has been productive and generative for the development of successful curricula and new approaches in physics education research (Hammer, 2000). However, an ever increasing body of research shows that many student ideas contain elements of—or resemble—scientific counterparts and are therefore highly productive for the development of sophisticated, disciplinary understandings of science (e.g., Cheng & Brown, 2010; diSessa, 1988; Gupta, Hammer, & Redish, 2010; Hammer, 1996a). Furthermore, conceptual change is not necessarily seen as occurring within an individual’s mind but instead in social interactions during which discourse about scientific phenomena becomes increasingly regimented and over time more closely resembles disciplinary practice (e.g., Pea, 1993; Scherr et al., 2013).

Instead of developing and disseminating curricular materials and learning progressions (see chapter 2), this alternative approach focuses on preparing teachers to be responsive to their students’ ideas (e.g., Coffey, Hammer, Levin, & Grant, 2011; Hammer, Goldberg, & Fargason, 2012). In order to be able to respond appropriately to students’ productive ideas in the moment, teachers require disciplinary training in the domain they are teaching. Such disciplinary training must include fostering the development of skills to recognize productive ideas and, once recognized, respond to them productively to help learners develop more sophisticated understandings. However, before effective professional development on responsive teaching in the context of energy can be designed, more research is necessary to investigate students’ productive ideas about energy and how teachers can identify and use them (see, for example, Hammer et al., 2012).
1.2 Development of a research focus

This dissertation project started out as an effort to research how teachers in rural Maine middle schools attend and productively respond to the disciplinary substance in their students’ ideas about energy. Results from this research were supposed to inform the design of professional development activities to foster responsive teaching in Maine physical science classrooms. In order to carry out this research, I visited classrooms to observe and video record naturally occurring activities in formal learning environments.

I was convinced that I had to study the video recorded students’ ideas about energy before I could study the teachers’ attention to them. I needed to know what “was there” for the teachers to attend to. Reviewing the relevant (but rather dated) literature on students’ ideas about energy, however, I realized that research on students’ ideas in the past has primarily focused on the ways in which they differ from experts’ views, and how these differences were hindrances for learning. Only recently, few studies have started to investigate the productive aspects of students’ ideas about energy by highlighting the disciplinary substance in those ideas; students’ and experts’ ideas have been found to be more similar than previous research has led us to believe (e.g., Gupta et al. 2010; Hammer et al. 2012; Lancor 2012). Careful study of this newer literature on students’ ideas persuaded me that systematic research into the manifestations of productive knowledge pieces—or resources—is necessary to inform professional development on responsive teaching (Hammer et al. 2012; see also section 2.5.4).

Such research efforts are constrained by a lack of consensus on clearly defined theory and methodology. With this dissertation, I therefore seek to contribute to the research on students’ productive ideas about energy in manifold ways: 1) a critical review of past studies on students’ ideas about energy motivates the need
for new research in the area; 2) a theoretical framework is developed, extending the existing resources perspective (Hammer, 2000; Hammer, Elby, Scherr, & Redish, 2005), to alleviate concerns raised in the review of prior literature; 3) a methodology is proposed based on this theoretical framework that allows the study of students’ productive ideas about energy; and 4) multiple examples show the application of the theoretical and analytical frameworks to find productively activated resources regarding energy in student discourse.

1.3 Overview of this dissertation

The main purpose of this project is to show that and how secondary school students have ideas about energy that contain valuable disciplinary substance which is worth being attended to by researchers and teachers alike. The following is an overview of the structure of my argument in this dissertation and the questions that each of the chapters in this document answers.

In Chapter 2, I review past research on students’ ideas about energy and identify several issues regarding the theoretical and methodological approaches in this work to answer the questions: “How have students’ ideas about energy been studied in the past?” and “Why is it necessary to perform more research on students’ ideas about energy?” I analyze selected publications in detail and provide an overview of the connections between representative examples of different approaches to highlight four common issues: 1) the assumption of stable conceptual structures, 2) the assignment of students’ ideas to categories of conceptions about energy, 3) the assumption of a unified scientific conception of energy, and 4) the view of students’ ideas as hinderances for learning.

To address the four issues in previous research on students’ ideas about energy, I further develop and extend Hammer et al.’s “resources framework” (Hammer, 2000).
Hammer et al. (2005) in Chapter 3. The extended framework provides useful concepts for my study of students’ productive ideas about energy. In particular, the constructs “resource,” “resource activation” and “productiveness of resources” are defined and explained in detail in this chapter. Answers to the question “What makes resources productive?” allow me to evaluate students’ ideas in terms of their disciplinary value in later chapters.

In order to show how to use the theoretical constructs of the resources framework, I then apply it to a subset of the data from one of the most cited studies about students’ energy ideas (Watts, 1983a) in Chapter 4. Watts conducted interviews with secondary students about different physical concepts, among them energy. He coded students’ answers to interview questions into what he called “alternative frameworks.” The proposed resources framework allows me to show that productive aspects can be found in these answers that Watts did not attend to. In my analysis, I present evidence for the claim that students’ ideas are not merely alternative, non-normative, and stable conceptions about energy that need to be overcome with instruction. Instead, I demonstrate how to find disciplinary value in students’ explanations of physical scenarios. I describe three cases of resources regarding the nature of energy, using indicators to reason about energy (and its forms), and mechanistic reasoning about energy.

Having shown the feasibility of applying the extended resources framework to the research on students’ ideas about energy, I devote the remainder of this dissertation to the study of real-world classroom discourse in rural Maine middle schools. Guided by the question “Do students in a rural Maine middle school classroom using the Project-Based Inquiry Science curriculum activate productive resources about energy,” I develop an analytical framework and detail the methods used to collect and analyze video recordings in Chapter 5. My study is an interpretive one that draws
from methodologies adapted from anthropology to gain insight into how resources regarding energy are activated in actual middle school classroom environments.

The analysis of selected video episodes for cases of productive resource activation is then presented in Chapter 6. In particular, I again find cases of resources regarding the ontology of energy, forms and indicators of energy, as well as mechanistic reasoning with energy. I argue the disciplinary productiveness of the activated resources using a historical-philosophical analysis of the energy concept in physics. I further show how resource activation can emerge from interactions of multiple learners. Finally, I argue the claim that the activated resources are productive for achieving the learning goals of Project-Based Inquiry Science: Energy.

In a conclusion (Chapter 7), I summarize and synthesize the results from my analyses. I discuss some educational implications of my findings and propose next steps for further, related research on the teaching and learning of energy.
Chapter 2
A PROBLEMATIZATION OF RESEARCH ON STUDENTS’ INITIAL IDEAS ABOUT ENERGY

2.1 Introduction

Rigorous studies of students’ ideas about energy appeared in the 1970s, following the “energy crisis” and the international awareness of socio-political issues related to energy (Duit, 1986). This research was intended to serve as a foundation for the development of curricular sequences about energy for students from Kindergarten to college. In recent years, the development of learning standards in K-12 science education (AAAS, 2009; NRC, 2011) has renewed interest in strategies for teaching and learning energy. This current research is based, in part, on some of the first, by now thirty year-old, studies on students’ ideas about energy.

Researchers developing learning progressions in science education, for example, have made extensive use of prior research on students’ ideas about scientific phenomena (Sikorski & Hammer, 2010). Learning progressions are intended to delineate the possible pathways for learners’ development of a sophisticated understanding of a particular topic, e.g. atomic theory (C. L. Smith, Wiser, Anderson, & Krajcik, 2006), scientific modeling (Schwarz et al., 2009), or force and motion (Alonzo & Steedle, 2009). Each progression details the initial ideas learners are expected to have when they enter the progression and describes what learners are supposed to have learned at the end (Duncan & Hmelo-Silver, 2009). Pathways between these lower and upper bounds are characterized by intermediate stepping stones that represent different levels of sophistication (NRC, 2007).
In the content area of energy, researchers have investigated both status quo learning progressions and progressions based on reformed curricular materials. Lee and Liu (2009) used a survey instrument to document how students develop their understanding of energy in typical U.S. middle schools. Nordine, Krajcik and Fortus (2011) developed a new approach to middle school energy instruction and assessed the development of students’ ideas about energy throughout the unit. Neumann et al. (2013) proposed an initial learning progression of energy and designed a multiple choice survey instrument to evaluate the development of student understanding of energy over the course of the progression. Currently, more research on learning progressions for energy is underway. Recent progress was reported on at the Energy Summit 2012 in Michigan.

Current learning progressions literature (Lee & Liu 2009; Nordine et al. 2011; Neumann et al. 2013), as well as other investigations into the teaching and learning of energy (e.g., Mann & Treagust 2010; Taber 2009; Tang, Tan, & Yeo 2011) are grounded in early research on students’ initial ideas about energy. In this chapter, I critically review these influential historical studies by highlighting the connections between them and arguing that they rely on a common theoretical framework. I show that these studies 1) adopted the position that learners have coherent and stable mental structures; 2) identified these structures by categorizing student responses; 3) assumed a unified scientific conception of energy; and 4) saw students’ ideas as counterproductive for the learning of this scientific conception. These notions have been substantially challenged by contemporary scholars. In the remainder of the chapter, I motivate the use of a new perspective for studies on students’ ideas about energy by problematizing prior studies’ common theoretical framework.

1For more information about this international conference, see http://esummit-msu.net (accessed 10/20/2013)
2.2 Overview of the reviewed literature

In the review presented in this chapter, I focus on the theoretical assumptions and methods employed in what I argue to be the most influential studies of K-12 students’ ideas about energy. These studies were selected based on the number of citations (from scholar.google.com) and their frequency of appearance in the current literature mentioned above. Reviews of literature concerning the use of conceptualizations of energy in physics appear in the appropriate contexts of the analyses in chapters 4 and 6.²

Historically, two primary methodologies have been used in this research on students’ ideas about energy: written instruments (surveys and writing tasks) and Interviews about Instances (I-a-I; see section 2.3). Some studies have incorporated the I-a-I approach into written surveys. See Table 2.1 for a chronological overview of the papers that are reviewed in this chapter, sorted by their used methodology.

Based on an initial survey of the literature about students’ ideas about energy, the I-a-I approach could be identified as the most influential methodology in this area. I have selected three studies that were based on this technique for an in-depth review and critique. Two of the selected studies (Trumper, 1990; Watts, 1983a) have been cited by numerous current studies on the teaching and learning of energy, among others by the recent studies about learning progressions for energy mentioned above. The third (Stead, 1980) was selected because in it, the I-a-I methodology was introduced for research into students’ conceptions of energy, and the other two are based on this earlier work.

Beyond studies using the I-a-I approach, a review of other heavily cited historical (Duit, 1981; Solomon, 1983), as well as some more recent papers (Herrmann-Abell &

²In particular, a historical-philosophical review of the development of scientific conceptions of energy (including the use of metaphors and models) is given in section 6.1, a review of the concept “energy forms” is presented in section 6.2, and a review of the importance of mechanistic reasoning, especially in the context of energy, can be found in sections 4.4.3 and 6.3.
DeBoer, 2009, 2012; Nicholls & Ogborn, 1993) is provided in this chapter to further illuminate the landscape of this body of work.

Table 2.1. Chronological overview of the reviewed studies (with number of citations) about students’ ideas on energy, sorted by methodology.

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<td>Logman, Kaper, &amp; Ellermeijer 2010</td>
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</tbody>
</table>

Entries between columns signify studies using surveys based on the I-a-I method, or a mixed approach of surveys and interviews.

Citations are reported according to scholar.google.com, as of 10/12/2013.

*Citations for (Stead 1980) could not be determined accurately with google scholar.

My goal for this chapter is to analyze this collection of influential studies on students’ ideas about energy and trace their connections and similarities. In particular, I highlight the persistent presence of four theoretical underpinnings in this work. These four issues are:

(Issue 1) the adoption of a theoretical perspective of thinking and learning that sees students as having stable, coherent conceptual structures that constrain ideas about energy at the beginning of instruction and that need to be overcome and changed via mental conflict;

(Issue 2) the belief that students’ understanding of scientific concepts can be investigated by generating generalized categories into which students’ responses are coded (I refer to categories or classes into which student responses were sorted or...
coded in any way as “bins” throughout my critique of this issue in order to avoid confusion with specific meanings of the word “category” in the literature);

(Issue 3) the belief in a unified scientific conception of energy; and

(Issue 4) the characterization of wrongness in students’ responses (i.e., a focus on how they contrast with the scientific view) and the view of learners’ ideas as hindrances to the learning of a scientific conception of energy that need to be overcome.

2.3 Review of research using an Interviews about Instances approach

The Interviews-about-Instances approach was developed by Osborne and Gilbert (1979a, 1979b, 1980a, 1980b) as a methodology to investigate learners’ ideas in science. Osborne and Gilbert thought that children had strong beliefs and expectations about the world when they came into instruction. They argued that many words, used in both the contexts of everyday life as well as science, have clear meanings for learners that usually differ from the scientific definitions. According to this perspective, these beliefs and meanings are embedded in stable conceptual structures that provide the learner with a sensible understanding of the world from his or her point of view (Osborne & Gilbert, 1980b).

Osborne and Gilbert defined learning as a modification of existing conceptual structures. They believed that modification can only take place when a learner’s understanding of the world is brought in conflict with a new scientific perspective presented in instruction. In Osborne and Gilbert’s view, the more a teacher knows about students’ pre-existing conceptual structures, the better he or she can provide appropriate challenges in their instruction to foster conceptual change for the student.

In their development of the I-a-I approach, Osborne and Gilbert (1980a) enlisted a definition of “concept” that was described by Markle and Tiemann (1971) as
follows: “A concept is a class or category consisting of many members which differ in some ways, but which are alike in certain key ways, causing us to treat them alike” (p. 160). According to this view, someone who has understood the concept of a chair can identify one, even though the observable characteristics of one chair may differ quite drastically from another. This ability to recognize a member, or instance, of a concept and distinguish it from a non-member (non-instance) was widely viewed as evidence for concept understanding by psychologists of the time (Markle & Tiemann, 1971).

In an Interview about Instances, a researcher typically presented the interviewee with up to 20 cards with pictures, mostly line drawings, of what the researchers believed to be familiar situations for the students. Some of these situations were selected as instances of the concept by the researchers, others were considered non-instances. For each card, the students were asked whether the picture represented an instance of the concept. Students’ reasons for deciding whether a card depicted an instance or not were elicited (Osborne & Gilbert, 1980b). Subsequently, students’ responses during the interview were coded into categories.

Osborne, Gilbert, and their collaborators at the University of Waikato, New Zealand, and the University of Surrey, UK, used the Interviews about Instances methodology extensively to study children’s understanding of many concepts in science, particularly physics. The first use of this approach in research on children’s ideas about energy was reported by Beverly Bell née Stead at the University of Waikato (Stead, 1980).

2.3.1 Stead: Energy in the Learning in Science Project (LISP)

As part of The Learning in Science Project, researchers investigated “the language, the beliefs and the expectations which children bring with them to science classes” (Stead, 1980, p. 3). These 11-16 year-old students’ views of the world were called
children's science, emphasizing coherent science-like understandings of phenomena that were considered at odds with a scientists' perspective (Osborne, Freyberg, Tasker, & Stead, 1980). This premise that students “have” specific “beliefs and expectations” or “hold” certain “views of the world and meanings for words” (Stead, 1980, p. 6), but also that their understandings of phenomena are coherent and structured like scientific mini-theories, is evidence for Issue 1 outlined above.

Stead used 16 cards depicting various scenarios in her Interviews about Instances to explore students’ views of the concept energy. Depicted were, for example, a person on stairs, a weightlifter holding a bar stationary over his head, a rock on a table, a Toboggan on an icy slope, a television set, and a cow eating grass on a meadow in the sun. Stead considered all but two of these pictures (rock on a table and car on a lift) instances of energy conversions or transfers. These are two major aspects of what she identified as the scientists’ view of energy (see 2.3.1.1). Each situation was explained to the 52 students, and they were asked “Can you tell me about energy here?” (Stead, 1980, p. 2).

2.3.1.1 Stead’s “scientists’ view” of energy

Apparent in this work is Stead’s assumption of a unified scientific conception of energy (Issue 3). The following tenets can be gleaned from Stead’s portrayal of the “scientists’ view of energy” in her report (Stead, 1980, pp. 2-3; emphases in quotes as in the original):

(a) Energy is conserved. It can neither be created nor destroyed.

(b) Energy has forms. Examples are potential (stored) energy, kinetic energy (associated with movement), and internal energy (associated with the temperature of a body).
(c) Energy forms can be converted into each other. “To use energy” means “to use energy in one form and convert it into another form.”

(d) The amount of energy that is converted is called “work done.”

(e) The amount of energy transferred due to a temperature gradient is called “heat transferred.”

(f) A flow of energy from one body to another due to a temperature gradient, called “heat transfer” or “heat flow,” results in an increase of internal energy of the second body.

(g) The internal energy of a body can be “lost” to the surroundings via convection, conduction, radiation or work. A hot gas in the cylinder of an engine, for example, can lose internal energy in doing work.

(h) An alternative definition of internal energy is the kinetic energy (associated with random motion) of and potential energy between atoms and molecules.

While the principle of energy conservation (a) can be seen as a universally accepted natural law, the description of energy in terms of “forms” and “transfer” or “transformation,” as well as the use of phrases like “heat flow” or “heat transfer” were hotly debated in the literature about teaching and learning of energy (e.g., [Jewett, 2008] Kaper & Goedhart, 2002 [Schmid, 1982] Warren, 1983). A historical-philosophical analysis of how the concept of energy is used by physicists and in physics literature—including examples of different models of energy—is presented in Chapter 6.

In the appendix to her report, Stead gave a “scientific description of the energy involved in each situation described on the interview cards” (Stead, 1980, p. 3). For examples, see Figure 2.1. While these are appropriate descriptions of energy involvement in each situation, they are by no means the only ways to describe the
scenarios in terms of energy. The rock on the table, for example, might be considered as part of the rock-earth system that has potential energy stored in the gravitational field, using a forms-model of energy similar to Stead’s (Kaper & Goedhart, 2002).

Figure 2.1. Instances 1 (p. 25) and 5 (p. 26) with Stead’s scientific description of the energy involved (Stead, 1980).

2.3.1.2 Stead’s characterization of energy in “children’s science”

In order to characterize the concept of energy in the viewpoint of children’s science, Stead classified students’ responses into five bins, according to the students’ use of the word energy (Stead, 1980, p. 3):

- everyday sense (energetic, having energy)
- human-centered viewpoint (thinking about non-living instances; e.g., bike, candles)
- attribution of human or living characteristics to inanimate objects
- energy as fuel; reification of an abstract idea (expression of an abstract idea as a concrete substance, e.g. “Uses petrol and that’s energy,” p. 10)
• energy as a concrete rather than abstract idea (more general than energy as fuel, e.g. “Yes, it (the wind) is an energy,” p. 12)

Stead provided quotes as example responses for each of these bins. These quotes were associated with several (up to about 20) students. It is unclear whether they are compilations of multiple students’ responses or exemplary individual student responses. The question of context-dependence of students’ ideas about energy was also not explicitly explored. According to the data presented in Stead’s report, several students’ answers were placed in different bins when they were responding to different situations (instances). Students’ responses seem to have been generalized, and instead of a deep investigation into individual students’ ideas, a detailed characteristic of each bin, based on several students’ responses, was given (Issue 2).

2.3.1.3 Stead’s identification of student “confusions”

In addition to these bins that Stead viewed as different from (though sometimes connected to) the scientific viewpoint and therefore problematic for the students’ learning of an accurate scientific energy concept, she identified three areas of “confusion” that students’ ideas showed as further implications for teaching (Stead, 1980, pp. 14-20). She used several student quotes as support for her claim that these students confused the scientific principle of conservation of energy with the everyday notion of conserving energy. Other students were seen as confusing different physical phenomena (e.g., energy vs. gravity, friction, force). Finally, many students were found to use different (incorrect) definitions for forms of energy and confuse forms (e.g., nuclear, light, solar, mechanical, heat, kinetic, stored) with sources (e.g., steam, oil, hydro, battery) and things that use energy (e.g., engine, body).

Aside from having placed students’ responses into another four categories (Issue 2), this also shows Issue 4, a characterization of students’ ideas in terms of how they were seen as at odds with the “scientific view.” Only few students in the oldest age
group were identified as having ideas that were aligned with this scientific conception of energy.

2.3.2 Watts’ alternative frameworks for conceptualizing energy

As part of his dissertation on “alternative frameworks in school science” (Watts, 1983b), D. Michael Watts, working with John Gilbert at the University of Surrey, used the I-a-I approach to investigate students’ alternative frameworks of conceptualizing energy (Watts, 1983a). In the forty interviews about instances Watts conducted with 13-16 year old secondary students, he used different pictures from Stead’s study. Watts considered some of them “clear cut examples,” others “borderline cases” (situations from a physicists’ world) of the concept energy (Watts, 1983a, p. 213). For examples, see Figure 2.2.

![Figure 2.2](image)

Figure 2.2. Instances “Melting ice” and “Eating a meal” (Watts, 1983a).

Using Driver and Easley’s (1978) notion of alternative frameworks, Watts described students’ ideas as “well-developed” understandings of phenomena that “are part of a complex structure which provides a sensible and coherent explanation of the world” (Watts, 1983a, p. 213). This approach indicates Watts’ belief that students’ ideas could be characterized as stable, coherent conceptual structures (Issue 1).

Similar to Stead, Watts sorted students’ responses in bins, which he called “frameworks.” The seven “most popular and persistent” (p. 214) frameworks, some based on findings by Duit (Duit, 1981, see section 2.4.1) and Stead (Stead, 1980, see section
Three of these frameworks are reviewed in Chapter 4, all of them have been described in detail in other reports (e.g., Logman et al., 2010):

1. human centered energy
2. depository model of energy
3. energy is an ingredient
4. energy is an obvious activity
5. energy is a product
6. energy is functional
7. a flow-transfer model of energy

Some students’ responses were coded into different bins while responding to different situations (instances). This context-dependence of students’ ideas about energy was not explored further in Watts’ paper, leading to a critique similar to that of Stead’s study.

Citing Arons’ (1965) definition of energy, Watts seemed to see the scientific conception of energy as an abstract quantity that has been empirically and theoretically found to be conserved. However, he did acknowledge that a substance-like notion of energy as exhibited by students whose responses were binned into framework 7 was sometimes explicitly taught in school science. This comparison of a scientists’ definition of energy with a school science notion supports the claim that Watts believed in a unified scientific definition of energy (Issue 3).

Following the description of each framework, Watts pointed out how it was at odds with this scientific definition (Issue 4). For example, he made clear that framework 2, the notion of energy being able to be “had” by something or someone, was “a long way from the complex mathematical treatment for what the physicist means” (Watts, 1983a, p. 214).

According to Watts, the described frameworks were not meant to be used for categorizing students “in the way they think” (Watts, 1983a, p. 216). Instead, they
were supposed to be a tool for the analysis and description of students’ complex responses. In a later paper by some of Watts’ colleagues (Pope & Denicolo, 1986) it was emphasized that the coding into frameworks was a mere means of reducing data, and not meant to contribute to the research on cataloging students’ misconceptions. It was clarified that the frameworks did not emerge from single students, but were rather the result of analyzing the entire body of student responses for common characteristics. However, it was not made explicit in detail how the frameworks were supposed to be or could be used.

2.3.3 Trumper’s extension of Watts’ frameworks

Ricardo Trumper adapted the I-a-I methodology used by Stead and Watts in his efforts to investigate Israeli high school students’ ideas about energy in order to develop a curriculum with the goal of causing students to recognize the inconsistencies in their own conceptions of energy and reconcile them with the scientific concept (Trumper, 1990, 1991). A questionnaire was developed (Finegold & Trumper, 1989; Trumper, 1990), in part based on the work by Duit (1984, see section 2.4.1), but additionally incorporating 15 pictures of instances and non-instances of the concept energy.

Trumper saw children as having “a rich and varied network of ideas” (Trumper, 1990, p. 343). He, like Stead and Watts, thought this network was based on their prior experience in the world which caused them to “hold frameworks” (p. 347) about energy and “adhere” (p. 343) to certain beliefs (Issue 1). Trumper asserted that these conceptions needed to be changed and for that, “a major accommodation is necessary” (p. 349).

A major focus of this study was on finding bins that as many of the students’ responses as possible could fit in (Issue 2). In the pilot study, Finegold and Trumper (1989) had found it necessary to divide Watts’ second (depository) framework into two
separate frameworks, a passive and an active depository framework: “2a. Depository—some objects have, and expend energy; 2b. Active deposit energy causing or needed for things to happen;” (p. 98, emphases in the original).

Like Stead and Watts, Trumper also believed in a unified scientific conception of energy (Issue 3). Finegold and Trumper (1989) reported that almost all students’ definitions of energy were classified into the bins 2a, 2b, and 7 (flow-transfer model of energy). In the actual study (Trumper, 1990), this last framework was appended with “(7b) The accepted scientific concept: ‘When two systems interact (i.e., when a process takes place), something, which we name energy, is transferred from one system to the other’” (p. 347). Trumper concluded that the scientifically accepted view (framework 7b) almost never appeared, before or after instruction.

Citing Nussbaum and Novick (1982), Trumper argues that “students’ alternative frameworks, when at variance with scientific conceptions, play a crucial interfering role in learning science” (Trumper, 1990 p. 343). As in the two studies reviewed before, this reflects the belief that students’ ideas about energy are counter-productive if they do not conform with what the researchers assumed to be the scientific conception of energy (Issue 4).

### 2.3.4 Other adaptations of the I-a-I approach

Several studies, including recent ones (e.g., Logman et al., 2010), have attempted to replicate or adapted Watts’ and Trumper’s work and used their proposed alternative frameworks to analyze students’ responses in different variations of the Interviews-about-Instances approach. Some of these adaptations are briefly reviewed in this section to show how influential Watts’ research was through the years. Because these studies were based on the previously reviewed research, they exhibit the same issues.
In an attempt to approximate classroom situations, Gilbert and Pope (1986) departed from the one-on-one interview format in favor of video recording small groups of students discussing Watts’ pictures. The students were told that the aim of the study was to investigate their understandings of certain words and that they should challenge each other and try to convince another of their meanings of the words. In four of five cases, the interviewer then left the room. Only one group of students discussed the pictures in the presence of an interviewer, who intervened at certain times with additional questions. The students’ responses were coded using Watts’ frameworks. Unfortunately, I was unable to acquire a copy of the original 1982 report, which presumably provides more details about the analysis.

Bliss and Ogborn (1985) adapted the I-a-I technique to develop a questionnaire involving pictures of instances and non-instances of the concept energy that was administered to 17 thirteen-year old girls. The questionnaire presented the students with ten pictures (depicting some of the same instances as in Watts’ study) and asked them to consider whether “ENERGY is needed or is being used for what is happening in the picture” (p. 196, capitalization in the original). They were asked to select three instances and one non-instance of this concept, and explain why they chose each picture. Watts’ frameworks were used as a “heuristic basis” (p. 199) for exploring patterns in the students’ choices. Bliss and Ogborn discussed the various frameworks in detail and emphasized the need for more research on the connections between them.

Reminiscent of Trumper’s early studies, Logman et al. (2010) used a questionnaire with some of Watts’ original pictures with the intent of developing a new approach to teaching energy. Logman et al. reinterpreted Watts’ original frameworks and explored relationships between them. Students’ responses were coded into these bins.

according to the three standards “conforms,” “contradicts,” and “undecided” (p. 83). The researchers found that students’ responses could mostly fit into more than one framework, and that one framework (7, the only “correct” framework according to their new definition) mostly co-occurred with others. Logman et al. believed that the connections they had found between the frameworks would prove productive for future educational design.

In addition to studies investigating K-12 students’ ideas about energy, researchers have also used adaptations of the Interviews-about-Instances technique to investigate pre- and in-service teachers’ ideas about energy. Trumper researched energy conceptions held by Israeli pre-service high school biology teachers [1997], and Trumper, Raviolo and Shnersch [2000] compared Israeli and Argentinian pre-service elementary teachers, using a questionnaire from Trumper’s prior studies with students and analog methods of analysis to arrive at parallel conclusions about pre-service teachers. Kruger and colleagues [Kruger 1990; Summers & Kruger 1992] used the I-a-I technique to survey British primary teachers’ conceptions of energy.

In all of these (in part more recent) adaptations of the I-a-I approach, we can find the four issues. Researchers have assumed students’ (or teachers’) stable and coherent conceptual structures (Issue 1). They binned students’ and teachers’ responses in interviews into categories (Issue 2), compared them with an assumed unified scientific conception of energy (Issue 3) and saw the “mis-understandings” and “confusions” as problematic for learning this scientific concept (Issue 4). These issues can also be found in other research on students’ ideas about energy that has not relied on the Interviews about Instances technique. Some of these studies are reviewed in section 2.4.
2.4 Review of other research on students’ ideas about energy

In addition to the previously reviewed research on students’ ideas about energy that has used the Interviews about Instances approach, some other studies have used different approaches to investigate students’ understandings of the energy concept. In this section, I review a selection of historical studies and one very recent study to illustrate that the four issues can not only be found in research using the I-a-I approach.

2.4.1 Duit’s survey: Students’ conceptions of energy in Germany, Switzerland, and the Philippines

Reinders Duit’s work has been highly influential on research about the teaching and learning of energy. Duit had identified five key aspects of the scientific conception of energy (Issue 3) that he thought were important for students to learn in order to become responsible citizens who could appreciate and understand the problems associated with energy in our society (Duit, 1981, pp. 6-5):

1. Energy as a quantity
2. Energy transfer
3. Energy conversion
4. Energy conservation
5. Value of different energy forms

Duit further emphasized the view that energy is an abstract quantity, and that all five aspects are important for a proper understanding of the scientific concept.

In order to test students’ understanding of these aspects of the energy concept before and after formal instruction in Germany, Switzerland, and the Philippines, Duit (1981, 1984, 1986) developed a survey using a theoretical perspective that was common in studies about students’ cognitive structures of certain scientific concepts conducted throughout the 70s (e.g., Preece, 1977; Shavelson, 1974). It contained...
items that were intended to elicit students’ associations and definitions with words related to the concept of energy (Issue 1). Students were first asked to write down associations they had with certain words. Then, students were instructed to give their definitions of the words *energy*, *power*, *work*, and *force*.

In accordance with the theoretical perspective on concept understanding outlined in section 2.3, Duit also included a task in the survey that asked students to provide examples (instances) of the concepts they had just defined (Issue 1). In another task, students were encouraged to use each of these words in a description of a physical scenario.

In addition to examining students’ meaning of certain words related to energy, Duit introduced another dimension: the ability to apply a concept to explain certain processes. Duit presented three scenarios (pictures and description) of moving objects on curved paths, and asked students to predict what happens to the object, along with an explanation of their reasoning. Duit’s goal with these tasks was to find out whether students used newly learned knowledge about energy or “conceptions stemming from everyday experiences even after physics instruction” ([Duit] 1981, p. 11). Duit was mostly interested in changes of responses to all these tasks between administrations of the survey before and after instruction. He acknowledged that responses to each task by itself were not sufficient for making general claims about students’ understanding of energy. However, he pointed out that together, word associations, definitions, examples, and applications of the concept would provide a stronger basis for such claims.

For the analysis of students’ responses, bins were developed in an elaborate process that is detailed in the report. Duit coded students’ answers to the various tasks and placed them into the bins he had developed (Issue 2). For example, for students’ associations with the words energy, power, work, and force, six bins had been created: Things, Processes, Qualities (of things or processes), Phenomena,
Words (Concepts) from areas like school or the working world, and Physical Concepts including formal concepts like units, formula, and terms. After students’ responses had been coded into these bins, a quantitative analysis was conducted.

Duit concluded that before formal instruction, grade 6-10 students in Germany and Switzerland mostly associated energy with electricity and fuel. Also, Duit thought that students were not considering conservation of energy. In the Philippines, Duit found energy to be associated with strength, in comparison to associations with endurance and a stored quantity in Germany and Switzerland. He compared the Philippine students’ notion of energy to the meaning of force in everyday German. Duit saw these everyday notions as an impediment to the learning of an appropriate concept of energy because he thought that students had difficulties relating energy to non-technical phenomena (Issue 4) and that they saw energy “as a sort of luxury item” (p. 31).

The survey has been used in one form or another in numerous studies (see also section 2.3.4). Finegold and Trumper (1989) used a version of the survey in addition to interviews to explore students’ ideas about energy in Israel and Trumper (1997) performed a similar study with Israeli pre-service high school teachers. A replication of Duit’s study of students’ associations with words related to energy in Germany was conducted by Crossley and Starauschek (2010).

2.4.2 Solomon’s free-writing tasks

Joan Solomon administered free-writing tasks to students in an attempt to capture children’s ideas about energy before instruction (Solomon, 1983). About 300 secondary school students (11 to 14 years old) were asked to write three or four sentences using the word energy. Solomon’s intent was to capture students’ ideas without prompting them with certain scenarios or questions. She coded the students’ responses into the two bins “Living associations” and “Non-living” (Issue 2) and
found that all students’ associations with energy shifted toward Non-living over the
course of three grades.

Based on the responses to the free-writing task and some class discussions,
Solomon then identified four “themes” of ideas about energy. She acknowledged that
these four themes could be considered alternative frameworks (see section 2.3.2),
but explicitly refuted this theoretical perspective because of her belief that students’
ideas were not preconceived, worked-out, static frameworks. Rather, she believed
students’ ideas to be socially constructed, context-dependent, and not necessarily
coherent notions. Notably, Solomon’s theoretical perspective on students’ ideas and
her methodology of investigating naturally occurring ideas have similarities with the
approach that is presented in this dissertation. However, her research was carried out
with the assumption that students have “strongly-rooted” (Solomon, 1983, p. 225)
informal ideas about energy that differ from a scientific understanding of energy
(Issues 3 & 4). Solomon identified the four themes in an attempt to find categories
of student thinking that would fit a wide range of students’ responses, and explored
their connections. In this process, some answers had to be excluded from the analysis
(Issue 2). For example, she excluded the response “The monster threw an energy
bolt” from her analysis of students’ free writings because it “made little sense on any
system or classification” (Solomon, 1983, p.225).

Using her own argument from a criticism of Watts’ work (see section 2.5.3),
her referring to “the ‘physics knowledge’” (Solomon, 1983, p. 228, emphasis added)
additionally suggests that she assumed a unified scientific conception of energy
(Issue 3). Solomon’s sentiment that “only science formalizes and restricts words to
one defined and orthodox meaning” (Solomon, 1984, p. 56) further supports the
claim that she believed in a unified scientific conception of energy. In addition, she
compared students’ ideas to this scientific conception and regarded them in part as
incompatible with the scientific view, making them a challenge for instructors to overcome (Issue 4).

2.4.3 Other studies using written survey instruments

In this section I briefly examine two more studies, which were explicitly based on the previously reviewed research. Since these studies have been situated as expansions of prior research on students’ ideas about energy, it is not surprising that even this more recent work on the topic exhibits the four issues.

Nicholls and Ogborn (1993) created a novel instrument to probe for “basic dimensions of thinking” (p. 73) behind students’ ideas about energy. Students aged 10-11 and 13-14 were presented with a 9x22 grid that had “aspects of energy” (p. 74) on one axis (e.g., “it is energy,” “it can need energy”) and “entities” on the other (e.g., “person,” “food,” “electricity”). They were asked to place a mark in each intersecting box if they thought an aspect of energy applied to the respective entity. Correlations between the two dimensions in the younger students’ responses were analyzed and a two-dimensional model was created that mapped the responses in four quadrants. Four bins were defined, one for each quadrant: Living things, Energy-using devices, Foods/Fuels, and Natural phenomena. The older students’ responses were found to correspond only to two bins, users and sources of energy.

Most recently, Herrmann-Abell and DeBoer (2009, 2012) reported about a survey created by the American Association for the Advancement of Science (AAAS) to investigate students’ understanding of energy. The survey was designed to elicit “misconceptions” about energy that were drawn from the studies reviewed in this chapter (Herrmann-Abell & DeBoer, 2012, p. 2). It was based on a set of predetermined “scientific ideas” about energy (AAAS, 2009) using a forms language (Kaper & Goedhart, 2002). Students’ responses to the survey items were grouped together in
bins. The researchers concluded that students in higher grades, although performing better on certain items, held similar “misconceptions” to middle school students.

Again, these studies share the assertions that students’ ideas were stable structures (Issue 1) that could be investigated by categorizing them in bins (Issue 2). Students’ ideas were compared with an assumed unified scientific conception (Issue 3), and if at odds with this scientific view, characterized as obstacles to the learning of an appropriate concept of energy that needed to be overcome (Issue 4).

2.5 Problematization of previous literature and motivation of a new theoretical perspective

In my review and analysis of prior research on students’ ideas about energy, I have identified four issues that I discuss in more detail in this section.

2.5.1 Issue 1: Stable conceptual structures

This past work on students’ ideas about energy relied on a theory of learning as the change of stable conceptual structures (e.g., concepts, alternative frameworks) and beliefs about the world. For example, researchers using the Interviews about Instances approach saw concepts as classes of members with common characteristics (instances). With this perspective, researchers believed that teachers needed to know as much as possible about the initial conceptual structures that students bring with them at the beginning of instruction. Researchers using the I-a-I approach, for example, assessed students’ concept understanding by probing for instance recognition.

All of the reviewed studies, except for Solomon’s work, used a “coherence” perspective on conceptual change theory (diSessa 2008), in which students’ understandings of phenomena are seen as coherent frameworks or mini-theories that share certain structural characteristics with scientific theories. In a letter to Physics Education (Solomon 1984), written in response to Watts’ study, Joan Solomon challenged
this assumption. She criticized Watts for calling students’ views “frameworks,” and pointed out that discussions with children or adults oftentimes reveal that a person’s perspectives are not static, may be conflicting, and are context-dependent. Solomon’s own study on students’ ideas about energy (Solomon, 1983) was explicitly positioned in opposition to what Robin Millar (1989) called the “Alternative Conceptions Movement” (see section 2.4.2).

Another criticism of the notion of stable and coherent frameworks comes by way of a paper by Wolter Kaper and Martin Goedhart (2002) that investigated a particular model of energy for instruction. These researchers pointed out that Watts (and others using his frameworks) did not “explicitly check the coherence of each of his seven ‘frameworks’. Therefore it may be said that he used the term ‘framework’ rather loosely” (p. 82). I might add that this is not merely a problem of term use, but that the theoretical construct “alternative framework” was not applied in a satisfying manner. In Chapter 3, I propose an alternative view that does not assume stable coherent structures, but instead relies on a “knowledge in pieces” perspective.

2.5.2 Issue 2: Inventory of generalized categories

The goal for researchers investigating students’ ideas about energy was to categorize and catalog the conceptions about energy that students had constructed and held when they came into formal instruction. Assuming stable and coherent conceptions allowed these researchers to sort learners’ responses into “bins” according to their alignment with descriptions of these categories that had been constructed using similar characteristics of a variety of student responses. Some studies investigated the frequencies of occurrences of each category (e.g., Trumper, 1990). Others were mostly concerned with the exploration of connections between different categories (e.g., Logman et al., 2010).
Responses were omitted from analysis if they could not be placed in one of the researcher-constructed bins. Watts (1983a) conceded that many of his study participants only displayed loosely connected ideas about energy that he could not categorize into frameworks and therefore ignored. Even after Trumper extended Watts' frameworks (Trumper, 1990), he still reported that 4% of student responses could not be classified.

This attempt to create a comprehensive inventory of generalized categories (bins) of student responses was intended to inform the design of curricula that broadly addressed a general student population. The assumption was that most students' strongly held stable conceptions about energy could be challenged and changed if the most prevalent misunderstandings were known and the curricula were carefully crafted to address them.

diSessa (2008) suggested that attempts to analyze and categorize students' ideas using a grain size of theory-like conceptions are problematic because they disregard the complexity of learners' ideas. In general, he criticized this approach for its inability to accurately define the underlying structure of coherence and its disregard for the context-dependence of these ideas. diSessa argued that knowledge exists in pieces, and that a smaller grain size is necessary for rigorous inquiry into students' ideas.

With this smaller grain size it becomes possible to richly describe individual students' ideas about energy. Instead of classifying their responses in terms of systematic, theory-like energy conceptions (generalized categories), smaller knowledge pieces can be used to characterize a students' ideas about energy. Even ideas that are not classifiable into bins, like the ideas that were omitted in the studies referenced above, can and should then be considered. I return to the issue of grain size in Chapter 3.
2.5.3 Issue 3: Comparing ideas with “the scientific conception”

Watts remarked that Framework 4, “Energy is an ‘obvious’ activity” (Watts 1983a, p. 214), corresponded to the everyday meaning of “energy.” In a letter to Physics Education, Solomon (1984) countered that the word energy had multiple meanings in everyday life. She argued that only in science, words had a defined, agreed upon meaning. The work on students’ ideas about energy has operated under this assumption of a single, unified and agreed-upon scientific conception of energy.

Many researchers defined this conception as an abstract balancing quantity in reference to writings by Felix Auerbach (1913) and Richard Feynman (2011). By asserting a unified scientific conception of energy, these researchers did not consider the difference between a purely mathematical definition of a concept and a definition that is based on how professionals in the field use it. The formalized mathematical definition of the concept energy is abstract and suggests it is a quantity solely used for accounting purposes.

However, scientists certainly talk about energy as if it is localizable, substance-like, and flows—for example to describe certain processes qualitatively—in order to make sense of a mathematical description. Gupta and colleagues (Gupta et al. 2010), for example, discussed different ontological conceptualizations of energy that physicists use productively to reason about problems in abstract fields like quantum mechanics.

Reinders Duit (1986) argued in detail that it might be more appropriate to speak of concepts of energy in physics, rather than of one unified concept. He identified different ways scientists use the concept of energy to describe phenomena, not just across different disciplines of science, but in different sub-disciplines of physics. In Chapter 6 I present a historical-philosophical analysis of the energy concept in
physics that shows ways in which physicists use and define the concept of energy to describe processes and solve problems.

2.5.4 Issue 4: Students’ ideas as obstacles to be overcome

In the research on students’ ideas about energy, learners’ responses were judged as correct or incorrect. Researchers saw incorrect ideas as obstacles on the way to a proper understanding of the “scientific concept” of energy that needed to be overcome. This belief has been criticized by Pea for casting a negative light on the use of “existing intuitions and creative, generalizing competencies of the learner as an instructional resource” (pp. 266-267). Smith and colleagues pointed out that the view of students’ ideas as problematic for learning “conflicts with the basic premise of constructivism” (p. 115). According to this basic premise, students use their prior knowledge productively to build new understandings.

The view that students’ ideas can be used productively to foster their development of sophisticated scientific understandings has seen great empirical support. Clement, Brown, and Zietsman described how “anchoring conceptions”—parts of students’ intuitive knowledge that are compatible with commonly accepted scientific knowledge—can be successfully incorporated into instruction using bridging analogies and socratic discussions. Minstrell proposed the construct of facets to describe disciplinary valuable aspects in students’ expressed ideas. These “slight generalizations from what students actually say or do in the classroom” (p. 47) have been used to create tools for formative assessment and design lessons that incorporate students’ current understandings.

In a similar vein, Hammer developed the resources perspective to highlight students’ productive disciplinary knowledge (for a more detailed review of this perspective, see Chapter 3). Together with Goldberg and Fargason, he
showed how an elementary teacher was able to tap into the productive resources students brought into the classroom with their ideas about energy by adapting her instructional moves and respond to these emergent ideas in the moment. On a larger scale—in a study of classroom interactions of 20 teachers with their students—Pierson (2008) found a positive correlation between teachers’ discursive practices that take into account and respond to their students’ mathematical ideas in the moment (responsiveness) and students’ learning achievement in mathematics.

The theoretical framework presented in Chapter 3, which is based on the resources perspective, enables me to expand on Hammer’s work and identify, in a more systematic way, resources students bring with them that could be used productively in their development of a sophisticated disciplinary understanding of energy. In Chapter 4, I use this framework to present an alternative analysis of a selection of transcripts from Watts’ Interviews about Instances (Watts, 1983a, 1983b). I find that students had productive ideas about energy that Watts did not acknowledge.

2.6 Conclusion

In this chapter, I reviewed prior research on students’ ideas about energy. I identified four key issues with this prior research: (1) The assumption of students’ coherent and stable conceptual structures, (2) the focus on developing and cataloging bins into which students’ responses could be categorized, (3) the assumption of a unified scientific conception of energy that these bins could be compared to, and (4) the belief that students’ ideas that were not aligned with this scientific conception were counter-productive to the development of a scientific understanding of energy. These four issues echo Hammer’s characterization of prior research on students’ ideas in physics, as described in section 3.2. I provided evidence that these issues are pervasive throughout the literature on students’ ideas about energy. Using findings
from science education and cognitive science research, I argued that these issues are problematic and a different theoretical framework is necessary for further studies on students’ ideas about energy. I further argued that the reviewed studies represent the most influential work in this field. In light of the issues discussed in this chapter, I find them to be a problematic basis for current research on the teaching and learning of energy.

In the next chapter, I develop an extension of the *resources framework*. This framework is based on a knowledge-in-pieces perspective that allows me to analyze student ideas in interviews (see Chapter 4) and classroom discourse (see chapters 5 & 6). I find that students activate resources that can be used productively on their journey toward a scientific understanding of energy.
Chapter 3
THEORETICAL CONSIDERATIONS

3.1 Introduction

As I have shown in the previous chapter, prior research on students’ ideas about energy adopted a particular view of conceptual change. Students’ ideas were mostly seen as obstacles to the learning of an assumed unified scientific conception of energy. Teachers and instructors in this paradigm were encouraged to challenge these “wrong” ideas and initiate their replacement with a “scientifically agreed upon” concept.

My work is motivated by a distinctly different conceptualization of learning. Inspired by Lemke (1990), I see the learning of science as the ongoing development and refinement of scientific discursive practices. Lemke suggested different classroom strategies for establishing “thematic patterns” (“what different ways of saying ‘the same thing’ have in common,” p. 87) of talking about scientific content. Especially the strategies involving student-teacher dialogue rely on instructors’ recognizing the seeds of disciplinary value in students’ discursive actions in the classroom. Teachers who recognize the potential within students’ ideas can provide appropriate scaffolding to mediate the development of these seeds into increasingly sophisticated and robust ways of talking about and understanding science.

In this chapter, I develop a theoretical framework in which students’ ideas are viewed as containing valuable and productive resources for negotiating energy (addressing especially Issues 1 and 4 in Chapter 2). This framework allows me to analyze students’ ideas for their productiveness in learning environments.
3.2 Resources: Identifying a student’s productive knowledge pieces

Hammer (1996a, 1996b) identified several unifying features in prior science and physics education research that used the constructs “preconceptions,” “alternative conceptions,” or “misconceptions” to describe students’ ideas. He summarized this work with the term “misconceptions perspective.” Like other researchers who have criticized this perspective, Hammer questioned the assumption that students’ ideas were unproductive for learning. For example, Smith et al. (J. P. Smith et al., 1994) wrote:

In focusing only on how student ideas conflict with the expert concepts, the misconceptions perspective offers no account of productive ideas that might serve as resources for learning. Because they are fundamentally flawed, misconceptions themselves must be replaced. What additional relevant ideas students might have available remains a mystery. An account of useful resources that are marshaled by learners is an essential component of a constructivist theory, but the misconceptions perspective fails to provide one. (p. 124)

According to Hammer, the misconceptions perspective views conceptions as “(i) [. . .] strongly held, stable cognitive structures; (ii) differ[ing] from expert conceptions; (iii) affect[ing] in a fundamental sense how students understand natural phenomena and scientific explanations; and (iv) [having to] be overcome, avoided, or eliminated for students to achieve expert understanding” (Hammer 1996b p. 1318).

The problematization of research on students’ ideas about energy I presented in the previous chapter (see section 2.5) echoes Hammer’s characterization of prior work on students’ ideas. Hammer’s characteristic (i) is almost identical to my Issue 1, the assumption of stable conceptual structures. Characteristic (ii) is related to Issue 3 in that students’ conceptions were compared to experts’. However, my Issue
3 goes further: a unified scientific conception was assumed. Characteristic (iv) and Issue 4 again are almost identical: students’ ideas (or conceptions) were seen as obstacles to be overcome.

As an alternative to the misconceptions perspective, Hammer and colleagues developed the resources framework, elaborating on diSessa’s knowledge in pieces (KIP) perspective (diSessa, 1988, 1993). The resources framework provides accounts of the nature of students’ ideas in physics that highlight students’ productive knowledge pieces for learning physics (Hammer, 1996a, 2000; Hammer et al., 2005). In the remainder of this section, I review the resources framework as developed by Hammer and his colleagues and elaborate on several key elements of the theory that have not been clearly defined previously. In particular, the concepts of “activation” and “productiveness” of resources are further developed.

### 3.2.1 Ontology of resources

Hammer’s resources framework was inspired by an information-processing model of cognition (diSessa, 1993; Hammer, 2000; Minsky, 1988). In the resources framework, the mind is seen as a dynamic, complex system of cognitive elements (Brown & Hammer, 2008; Conlin, Gupta, & Hammer, 2010a; Hammer et al., 2005). Hammer et al. call these cognitive elements “resources” (Brown & Hammer, 2008; Hammer, 2000; Hammer et al., 2005). Resources can range in grain size from small, basic elements like diSessa’s phenomenological primitives, or p-prims (diSessa, 1983, 1993), to complex conceptual structures like coherent theories about physical phenomena. In other words, resources can be basic pieces of declarative and procedural knowledge, or bigger knowledge structures that are comprised of multiple such pieces (Tuminaro & Redish, 2007; Wittmann, 2006).

Hammer distinguishes between conceptual and epistemological resources (Hammer, 2000; Hammer et al., 2005). Conceptual resources describe pieces of knowledge about
the physical world, while epistemological resources describe a learner’s knowledge about knowing and learning. Epistemological resources have been studied extensively in the context of learners’ framing of particular activities and situations (e.g., Hammer & Elby, 2002; Hammer et al., 2005; Scherr & Hammer, 2009). Conceptual resources have been identified in various topic areas of physics, for example kinematics (Frank, Kanim, & Gomez, 2008), electricity and magnetism (Cheng & Brown, 2010), wave physics (McBride, Zollman, & Rebello, 2010; Wittmann, 2002), and quantum mechanics (Gire, Manogue, Henderson, Sabella, & Hsu, 2008). Other researchers have identified metacognitive (Hammer et al., 2005), mathematical (Tuminaro & Redish, 2007), procedural (Black & Wittmann, 2007), and semiotic (Arzarello, Paola, Robutti, & Sabena, 2008) resources.

### 3.2.2 Mechanism of activation

According to Hammer et al. (2005), resources exist in the mind in various states of activation. To illustrate this proposition, the authors provide a discussion of Sherry, a student who is considering how big a mirror would need to be in order for her to be able to see her entire body:

> We think of Sherry (during class discussion) as activating resources for thinking about physical objects, to reason about the size of a mirror question, resources that could contribute to thinking about how large a doorway or canvas would need to be to contain an object or picture. By contrast, standing in front of her bedroom mirror activates different resources, perhaps the same ones she uses for understanding apertures; if looking at yourself ‘through’ a mirror is like looking at a tree through a window, then it’s obvious that you don’t need a person-sized mirror, any more than you need a tree-sized window. (p. 93)
This example illustrates that in a given situation, students have a variety of resources at their disposal and activate ones that they, consciously or not, deem useful for the problem at hand. Hammer (2000) describes how multiple resources can be activated simultaneously when a learner is prompted with a certain problem, and even proposes that an instructor can facilitate the activation of resources in students.

The concept of resource activation allows for the description of cognitive processes in terms of resources: When activated, resources manifest themselves in observable activity (e.g., speech, gestures) and become accessible for study. Hammer et al. write, “We view students’ everyday thinking as involving myriad cognitive resources, and we frame our questions in terms of when and how students activate those resources” (Hammer et al., 2005, p. 90). The manifestation of activated resources in student activity becomes the unit of analysis for studying students’ ideas.

Hammer et al. refer to examples of resource activations in different contexts, but do not describe the specific mechanism or cognitive structures through which activation occurs in the minds of students. A cognitive mechanism for the activation of p-prims was proposed and described by diSessa (1993). P-prims are “being cued to an active state on the basis of perceived configurations, which are themselves previously activated knowledge structures” (diSessa, 1993, p. 112). diSessa’s description provides more detail about the steps involved with the mechanism of activating a p-prim. However, I have not found direct references to this description of the cognitive process of activating p-prims in Hammer et al.’s work.

I propose a definition of resource activation that is gleaned from the various examples that Hammer and colleagues have written about in the past. Because of this, the definition remains vague with respect to the underlying cognitive structure and mechanism but is compatible with diSessa’s mechanistic account. I understand the activation of resources to mean the conscious or unconscious recognition of
applicability, as judged by the learner, and application of a resource to a certain situation.

For example, consider the activation of a p-prim described by Hammer (1996a), “closer means stronger” (p. 102). Hammer argues that students might recognize this resource as applicable to considerations about the seasons on earth and conclude from its application that warmer temperatures in the summer months are caused by the earth’s proximity to the sun. According to Hammer, this account of students’ inappropriate resource activation provides a mechanistic explanation for a commonly observed “misconception.”

My definition of activation is also consistent with a mechanism for framing an activity in terms of resources. Hammer et al. (2005) describe the process of framing as “(1) the forming of [a] set [of resources], and then, once it is formed, (2) the use of those resources to interpret utterances, sensory inputs, and so on” (p. 101). In other words, a learner (not necessarily consciously) recognizes a certain set of (epistemological and conceptual) resources as applicable to a situation and applies these resources in order to make sense of the situation.

3.2.3 Disciplinary productiveness of resources

Valuing students’ ideas as productive is an important aspect of the resources perspective. Hammer and colleagues have not offered a definition of productiveness independent of cases and circumstances they analyzed. In this section, I develop a way to determine productiveness across cases.

In many reports of analyses of students’ resources, the use of the word “productive” is equivalent to or at least in accordance with “a physicist would deem these resources appropriate for the situation.” Consider, for example, Hammer’s (1996a) description of a student’s idea during a classroom discussion about an experiment with a pendulum. The student, Sean, is reasoning about whether the string of the
pendulum slows down the pendulum bob by proposing an analogy to gravity acting on an object on a surface. Hammer writes:

If we think of Sean’s idea as an act of conceiving specific to the situation, then we may consider it an imaginative and productive line of reasoning, because, in the situation, Sean’s idea was not inconsistent with Newtonian reasoning. By a Newtonian account, a force directed perpendicular to an object’s motion, such as the force of the string on the pendulum bob or the gravitational force on the ball, cannot affect the object’s speed.

In fact, Sean’s account of the role of the string or of gravity in these situations may be seen as an intuitive version of the physicist’s notion of an holonomic constraint, which has the property that its influence can be taken into account implicitly through an appropriate selection of coordinates. Sean’s reasoning about the string and gravity as imposing a constraint on the motion on the bob or ball, but as otherwise unimportant, is rigorously defensible. Thus, instead of being concerned about a misconception, we may see in Sean’s reasoning the seeds of Newtonian understanding. (p. 115, emphasis in the original)

Hammer explicitly explores the connection between Sean’s idea and a Newtonian account of the situation. He identifies the students’ reasoning strategy as a precursor of what an expert physicist might do in making sense of a scenario like this. Hammer calls Sean’s activated resources productive because he, as a physicist, recognizes that their activation was appropriate in this situation.

In another example, Hammer et al. (2012) characterize a students’ ideas about energy involved in the scenario of a toy car that is launched by a rubber band:

It is not difficult to recognize nascent understanding of energy in Jeffrey’s reasoning. First, he abstracted across a rubber band and a steep hill,
recognizing them as similar in a way he described as having ‘the same energy.’ Second, he associated energy with speed: the rubber band and a steep hill have the same energy, he seemed to be thinking, because they can both make a toy car go ‘the same speed’. We do not claim that Jeffrey is ‘almost there’; we suggest only that his reasoning here involves productive conceptual and epistemological resources: In this moment he is thinking of energy as something that can take different forms, and his reasoning about those forms is connected to his sense of mechanism in how a rubber band or a steep hill can make a toy car start moving.

(pp. 59-60)

Again, the authors evaluate the appropriateness of the activated resources for the situation at hand. They appeal to the reader’s expertise and knowledge about energy when they call the resources productive because of their similarity to normative disciplinary ideas.

The descriptor “productive” is frequently used, but Hammer and others do not explicitly define what it means for a resource to be productive outside of the cases they present. While it is often possible to infer why Hammer et al. see resources in particular cases as productive, their work does not offer a universal account of productiveness independent of local cases. Based on the presented examples and other, similar accounts of students’ productive resources (e.g., [Hammer 2000] [Loverude 2002]), I propose a definition of *disciplinary productiveness* of a resource as the *appropriate activation in a particular context, as judged by the community of physicists via the instructor or researcher*. With this definition, a resource is compared to the wealth of disciplinary knowledge (conceptual, procedural, epistemological, etc.) of the community of physicists in order to evaluate the resource’s productiveness.
As an illustration of the application of the definition proposed above, consider a hypothetical example of the productive activation of a resource. Imagine a learner recognizes the p-prim “closer means stronger” as applicable to the situation of two equally charged particles (for example electrons) in empty space and applies it to this situation. This activated resource leads her to conclude that the force between these two particles will be stronger, the closer the particles are to each other. In this case, a physicist could recognize the activation of this resource as appropriate, since $F \propto \frac{1}{r^2}$. In this context, then, the resource “closer means stronger” can be argued to be productive for the development of a conceptual understanding of Coulomb’s Law because it is an appropriate intuition that can be built upon. However, if applied to the context of explaining the seasons on earth (see section 3.2.2), the resource is inappropriately activated (from the disciplinary point of view) and can therefore not be seen as disciplinarily productive.

3.3 Extending the framework: From individual cognition to multiple learners

The resources framework was originally developed to explain individual cognition. However, learning, especially in classrooms, mostly occurs within social settings. Brown and Hammer (2008) conjectured that a resources perspective could bridge the discontinuity between descriptions of cognition as occurring within individual heads and descriptions of cognition as occurring in the interactions between participants in a learning environment. Brown and Hammer have argued for the individual mind as a complex dynamic system comprised of cognitive elements (resources) from which organized cognition emerges (Brown & Hammer, 2008). They added that, “On still larger scales, this approach could be continuous with models of social and cultural
dynamics, again as complex systems but at a larger scale of organization” (p. 139). In this section, I develop this continuity further.

Consider a scenario in which multiple learners contribute to the solution of a problem in a middle school classroom. What is the ontology of resources in interactions of multiple learners? In a video of classroom events, I found sequences of talk comprised of several student contributions that, when considered together, constituted what would be the manifestation of a resource had it been uttered by a single student. For example, at one point, three students provide a mechanistic account of how energy ends up in a banana from the sun. One student says “the tree absorbs energy,” a second student says “sunlight,” a third student says “from the sun,” and the second student concludes “the tree makes sugar and then makes the banana.” Together, when taken as a unit, these utterances compose a sequence of mechanistic reasoning, contributing to a complex idea about how energy gets into a banana. Each individual utterance, viewed in isolation, could not be considered mechanistic (for a detailed analysis, see section 6.3).

In the past, researchers (e.g., Conlin et al., 2010a; Conlin, Gupta, & Hammer, 2010b; Scherr & Hammer, 2009) have invoked a theory of distributed cognition (Hutchins, 1995, 2001) in order to describe epistemological resources as distributed across the members of a group of learners. They argued that this description is compatible with an account taking individuals as cognitive units but exists at a different scale. According to Scherr and Hammer, “One focuses on the complex system made up of an individual’s manifold cognitive resources; the other focuses on the system made up of resources across the situated group” (Scherr & Hammer, 2009, p. 173). However, the focus of this research was on the description of students’ epistemological framing of an activity. In this thesis, I am describing the construction of ideas about energy by groups of students to characterize these ideas in a way that, in the long run, will allow instructors to recognize and foster them. Sometimes, these
ideas are irreducible to individual students, like in the case of my video of middle school students working together in the pursuit of mechanistic reasoning about the energy in a banana.

Hewett and Scardamalia (1998) wrote in more general terms:

Consider, for example, a conversation between two people who are trying to solve a problem. Conversations typically involve a back-and-forth exchange in which each utterance is tied, either implicitly or explicitly, to the utterances that preceded it. Discourse is dynamic; none of the participants know with absolute certainty where a particular thread will lead or what new ideas will emerge. This co-construction of a progression-of-thought is one interpretation of the phrase ‘distributed cognition’ from a cognitive point of view. (pp. 78-79)

Moore and Rocklin (1998) viewed a classroom, which is comprised of individual students, as a self-organizing, dynamic system, and argued that “there are characteristics of the system that cannot be found by considering characteristics of individuals alone” (p. 103). For the resources framework, this means that there are phenomena in a classroom that cannot be identified or described using resources as they have been defined for individuals. I argue that the example I have given above is such a phenomenon: It cannot be fully understood using individuals’ resources, but rather has to be seen as emerging from (inter)actions in the conversation (see section 6.3).

I was unable to find any literature that has defined the core concepts of the resources framework for analyses of interactional sequences from which the construction of knowledge emerges. What a resource is and how it is activated in an interaction of learners need to be defined. My definition of disciplinary productiveness outlined in section 3.2 allows me to evaluate the disciplinary value of a resource. However, I provide a second dimension of productiveness that enables me to assess the value
of a resource within an interaction. In the remainder of this section, I propose new
definitions that extend the resources framework to allow for the description of pro-
ductive ideas that groups of students express, but that are irreducible to individual
students.

3.3.1 Resources as emerging from groups of actions in conversations

Just as Brown and Hammer (2008) have argued that an individual’s mind can
be modeled as a complex system, a classroom can be seen this way, as well (e.g.,
Cameron & Larsen-Freeman 2008; Staples 2008; Yoon 2008). A classroom as a
complex system is comprised of interactions between participants, objects and their
environment. Cognition emerges from and is distributed across these interactions
(e.g., Goodwin 2000; Hewitt & Scardamalia 1998; E. R. Smith & Semin 2004). Cognitive resources, at this larger scale, are then emerging from groups of actions in conversations. Using this definition, a resource can be found in the collective explanation of a mechanism pursued by a group of students.

The organization of conversations and discourse in classrooms has long been a
focus of educational research (e.g., Bloome, Carter, Christian, Otto, & Shuart-Faris
2005; Heap 1985; Watson 1992). Researchers in science education, in particular,
have been interested in the discursive practices of the science classroom (e.g., Pea
1993; Roth & Roychoudhury 1994; Siry, Ziegler, & Max 2012), inspired by Lemke’s
argument that teaching, learning, and doing science are inherently discursive activi-
ties (Lemke 1990). The units of analysis in these studies have been “conversational
turn taking, actions on objects, the use of ways to attract attention, and achieving
joint reference, and other nonverbal interactions for making sense” (Pea 1993, p. 268).
The methods employed by this past research inform my investigation of resources as
groups of actions in conversations (for a detailed description, see Chapter 5).
I believe that my treatment of resources as emerging from collections of conversational actions complements Hammer et al.'s original theory of cognitive resources. Just as individual students’ ideas can be described in terms of resources within the original framework, collectively expressed ideas can similarly be characterized.

3.3.2 Situated productiveness as contribution toward a shared goal

The example of students seeking a mechanistic account of how a banana comes to contain energy is a smaller piece of a larger discussion in which students trace energy within a scenario. The students’ mechanistic reasoning can be seen as *disciplinarily productive* because the pursuit of a mechanistic account is appropriate from a disciplinary viewpoint. However, resources that appear in conversational sequences can be evaluated for a different dimension of productiveness beyond their disciplinary value. In this section, I use elements of Engle’s Productive Disciplinary Engagement (PDE) framework (Engle & Conant, 2002; Engle, 2012) to develop this new dimension, *situated productiveness*. Situated productiveness allows me to describe how resources become productive in a discussion, based on its outcome. If a resource allows the group to make significant progress toward an emergent, shared goal (Lemke, 1995), it can be considered productive for the situation at hand.

Engle and Conant defined the concept of *disciplinary engagement* as “some contact between what students are doing and the issues and practices of a discipline’s discourse” (Engle & Conant, 2002, p. 402). They determined whether students’ disciplinary engagement is productive by carefully examining individual cases using the heuristic, “There is productivity if one can discern significant disciplinary progress from the beginning to end of students’ engagement with a particular issue” (Engle, 2012, p. 167, formatting removed). What counts as “progress” is dependent on disciplinary values, the activity in which the students are engaged in, the topic at hand, as well as the beginning state and outcome of the students’ engagement.
In the example above, the mechanistic reasoning contributed significantly to the achievement of the group’s shared goal of telling a coherent energy story. The explanation of an energy transfer/transformation chain from the sun to the banana is an important step toward the group’s attempt to provide an explanation for how a monkey obtains energy to run. With this step, the energy the monkey is using to run around has successfully been traced back to the sun. The students’ use of this particular (procedural) resource in a specific situation allowed them to bridge a gap in their shared pursuit of understanding. Therefore, the collective mechanistic reasoning can be considered productive in this specific situation.

Situated productiveness can apply to a resource like an individual’s utterance, as well as to a resource that is composed of several conversational actions. It calls for the identification of the beginning and end state as well as the shared goal of a particular conversation. Resources that were activated as the conversation unfolded can then be evaluated by the way they contributed to the significant progress toward this shared goal.

While many resources are disciplinarily and situatively productive at once, a situatively productive resource does not need to be disciplinarily productive. Consider the hypothetical example of a group’s discussion about the seasons during which a learner (inappropriately) activates the resource “closer means stronger.” If the learner’s idea is expressed in a negotiation of a mechanism for the seasons and contributes to the group’s significant disciplinary progress toward a mechanistic explanation, the resource activation was—though disciplinarily inappropriate—situatively productive.
3.4 Conclusion

Within my broader goal of describing students’ ideas about energy, it has become necessary to elaborate on and clearly define the core concepts of the resources framework. I believe that these operationalized definitions will help researchers in their application of the resources framework to their work in the future. In addition to specifying the definitions of existing concepts, I expanded the resources framework from an individual-cognition perspective to a perspective in which resources can be found across the interactions between learners. In particular, I described how learners’ ideas can be seen as productive in two ways: in terms of disciplinary productiveness and in terms of the productiveness for the outcome of a particular discussion.

The purpose of the following chapters in this dissertation is to describe students’ productive ideas about energy. I provide examples of how I am using my proposed definitions to analyze examples of students’ ideas about energy in different situations, from interviews about instances to classroom conversations.
Chapter 4
IDENTIFYING PRODUCTIVE RESOURCES ABOUT ENERGY IN STUDENT RESPONSES TO WATTS’ INTERVIEWS ABOUT INSTANCES

4.1 Introduction

As discussed in Chapter 2, a substantial portion of prior research on students’ ideas about energy has used Interviews about Instances (see section 2.3) to elicit and characterize students’ energy conceptions. The most cited of these studies was D. Michael Watts’ 1983 paper, “Some alternative views of energy” (Watts 1983a), that was based on his PhD thesis, “A Study of Alternative Frameworks in School Science” (Watts 1983b). Watts created categories for student responses that have been used by other researchers to compile and classify students’ non-normative ideas about energy (e.g., Bliss & Ogborn 1985, Logman et al. 2010, Trumper 1990).

To illustrate the application of the theoretical framework I presented in Chapter 3, I perform an alternative analysis of Watts’ interview transcript excerpts in this chapter. This new analysis of Watts’ data shows that valuable and productive resources about energy (which Watts did not acknowledge) were activated by the students. This analysis stands in contrast to the traditional emphasis of how students’
ideas differ from experts’ and that they need to be overcome on the way to a scientific understanding of energy. I provide an alternative account that addresses the four issues which I identified in previous research on students’ ideas about energy and described in section 2.5.

For the analysis, I present excerpts from interview transcripts (called “extracts” by Watts) from Watts’ description of each framework. These excerpts were selected out of 25 such “extracts” that Watts used to illustrate his frameworks for energy. I show how Watts’ classification and characterization of these student responses misses important aspects of the students’ ideas about energy. The three selected excerpts were chosen because they feature students’ responses to single drawings (as opposed to responses that referred to several of the pictures), contained some amount of dialog between the interviewer and the students (to establish a context), and were reasonably short, which allowed me to focus on a single productive resource in each one. Because of their importance to the teaching and learning of science in general and energy in particular, I decided to highlight conceptual metaphors (Scherr, Close, McKagan, & Vokos, 2012), indicators (Nordine et al., 2011), and mechanistic reasoning (Hammer et al., 2012).

To support my evaluation of resources as disciplinarily productive, I provide brief reviews of appropriate literature in the context of my analysis below. For an in-depth review of the development of energy conceptualizations in physics, see Chapter 6.

4.2 Watts’ theoretical framework and methodology

Watts used the Interviews about Instances approach (see section 2.3) to investigate what he called students’ “alternative frameworks” (Driver & Easley, 1978) of conceptualizing energy (Watts, 1983a). In his interviews, he presented students with up to 17 line-drawings of what he had determined to be “instances” or “non-instances”
of the scientific energy concept. Watts defined a concept as a class of members with common features. An instance was defined as a member of the class (Osborne & Gilbert, 1980a; Watts, 1983b) (e.g., a Jack Russell Terrier is an instance of the concept “dog”).

Using these interviews, Watts intended to investigate what “well-developed” ideas students held about energy. He believed that these ideas, which he called conceptions, “are part of a complex structure which provides a sensible and coherent explanation of the world” (Watts, 1983a, p. 213). In the interviews, Watts elicited students’ reasons for deciding whether a card depicted an instance or not (see section 2.3.2). After conducting forty interviews about instances with 13-16 year-old secondary physics and general science students in the UK, Watts sorted the responses into bins. He termed these bins “frameworks” and characterized them in relation to “concepts in the network of physics” (Watts, 1983b, p. 1.39). Watts’ work was motivated by the assumption that establishing the details of students’ alternative frameworks (and therefore their ideas) is important for instructional success in the classroom.

4.3 Resources: A framework for investigating productive ideas

I agree with Watts that it is crucial to understand students’ ideas for instruction to be effective. However, my analysis of Watts’ data is motivated by the assumption that identifying the appropriately activated disciplinary elements in students’ ideas is necessary to guide instruction (J. P. Smith et al., 1994). Instructors’ responsiveness to students’ early disciplinary ideas has been shown to foster the development of more robust scientific understandings (Coffey et al., 2011; Hammer et al., 2012; Maskiewicz & Winters, 2012).

As explained in detail in Chapter 3, Hammer and colleagues’ resources framework (Hammer, 2000; Hammer et al., 2005) provides useful concepts for my investigation.
of students’ productive ideas about energy. I see resources as basic pieces of declarative and procedural knowledge, or bigger knowledge structures that are comprised of multiple such pieces (Tuminaro & Redish 2007; Wittmann 2006). Watts’ view that students’ ideas are varied and context-dependent is aligned with a resources perspective. However, the resources perspective does not assume that these ideas are stable (Watts 1983b, p. 3.1) or coherent and that they need to be replaced with the scientific concept (or at least “moved closer to the ‘accepted truth’”) (Watts 1983b, p. 7.43) during instruction. Instead of Watts’ approach of classifying students’ responses into categories and describing “discernible common conceptual frameworks that are alternative [...] to the system of public scientific meanings” (Watts 1983b, p. 1.44), I use Brown and Hammer’s suggested approach of identifying productive resources that are “conceptual progenitors of expert understanding in students’ intuitions” (Brown & Hammer 2008, p. 145).

Learners activate resources when reasoning about physics phenomena (Hammer et al. 2005). As previously defined, I understand the term activation to mean the recognition of the applicability (as judged by the learner) and application of a resource to a certain situation. I proposed a definition of disciplinary productiveness as the appropriate activation of a resource in a particular context, as judged by the community of physicists (via the instructor or researcher).

When learners communicate their ideas, they provide researchers with evidence for the activation of particular resources. In this chapter, I reproduce and analyze excerpts from transcripts in Watts’ dissertation “A Study of Alternative Frameworks in School Science” (Watts 1983b) that resulted in the frequently cited paper “Some

\footnote{Watts’ markup conventions are not exhaustively defined; based on his descriptions, I am interpreting them as follows: ellipses indicate speaker pauses and omissions from the transcript, numbers in parentheses indicate lengths of pauses; underlined portions of text received emphasis from the speaker; words between two forward slashes are insertions or paraphrases to make the excerpt better comprehensible, especially without the context of the remaining transcript. In order to be able to refer to particular lines, I added line numbers to the transcript excerpts.}
alternative views of energy” (Watts, 1983a). I present analyses of three transcript excerpts and argue that they contain evidence for students’ activation of resources that are of disciplinary value in the context of energy.

4.4 An alternative analysis of students’ ideas

4.4.1 Energy as a metaphorical substance

One student (student C) in Watts’ study is presented with the drawing of a stick figure on an inclined plane, pushing a box (see Fig. 4.1). The student is asked in what ways the drawing is an instance of energy. The excerpt of the transcript of the student’s answer is reproduced in Datum 4.1. Watts used this excerpt to illustrate what he called the “Anthropo-centric/-morphic Framework.” He wrote in his dissertation that

This framework bridges two main categories of response and generally concerns ‘human centred’ responses. These two relate to human-like and human-caused action. The framework encapsulates responses where energy is seen as a vitalistic entity concerned with living creatures. Other active, but inanimate, objects are described analogously in humanistic terms. There is clear evidence in some responses that the descriptions are analogous, in others it is more difficult to separate analogy from a literal, animistic use of descriptors. (Watts 1983b, p. 4.27, emphasis in the original)

In his analysis of the extract in Datum 4.1 Watts focused on the human-centeredness and short-livedness of energy as only being in the stick figure but not in the “inanimate box” (pp. 4.29-4.30). In the following, I argue the claim that a careful analysis of the excerpt for productive resources provides a deeper and more
detailed insight into students’ ideas about energy than a characterization in terms of frameworks, which is bound to miss relevant aspects of these ideas about energy.

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<th>line</th>
<th>speaker</th>
<th>transcript</th>
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<tbody>
<tr>
<td>1</td>
<td>I:</td>
<td>... someone pushing a box up a hill... what about that one?</td>
</tr>
<tr>
<td>2</td>
<td>C:</td>
<td>... yes I think it would /be an example of energy/ because umh...(10)... I think that’s why we eat to .. umh... collect the energy to push things to... umh.. kind of walk... so I think I’d put it /as an example/ because he is a source of energy... he pushes on the box up the hill.</td>
</tr>
<tr>
<td>3</td>
<td>I:</td>
<td>Has the box any energy?</td>
</tr>
<tr>
<td>4</td>
<td>C:</td>
<td>... (4)... no ...because its just a box.</td>
</tr>
</tbody>
</table>

Datum 4.1. Extract 2, person pushing a box up a hill (Watts 1983b pp. 4.27-4.29).

C starts his justification for why the scenario contains energy with “that’s why we eat to [...] collect the energy to push things [and] walk” (line 2), indicating that he believes eating food provides the human body with the necessary energy to perform physical activity. Through his statement, he claims that energy stored in an object enables physical activity or work.

I use grammatical indicators (Gupta et al. 2010 Scherr et al. 2012), i.e. words like “collect” or “source of,” to identify the use of a substance metaphor, a resource that C activates when explaining the energy involvement in the scenario at hand. Energy is proposed to be a quasi-material (substance-like) entity that can be collected (accumulated). Consistent with C’s use of a substance metaphor is the description of the stick figure as a “source of energy” (line 2).

The use of a substance metaphor for energy has been described as compatible with and useful for a disciplinary understanding of energy-related phenomena. For exam-

³Several authors have rejected the notion of energy as a substance-like quantity as scientifically false (e.g., Warren 1983) or argued that attributing substance-like properties to energy could be problematic for students’ learning of a scientific energy concept (e.g., McClelland 1989). I have only found one report of an empirical investigation into whether “students conceptualize energy as a material substance” (Loverude 2002). In this study, 262 college students (non-science majors,
ple, substance metaphors have been suggested to be beneficial for the development of an understanding of energy as a conserved quantity that can be transferred between objects (Duit, 1987; Lancor, 2012; Scherr et al., 2012; Swackhamer, 2005). For these reasons, substance metaphors have been established as a central feature of energy in several instructional approaches (Brewe, 2011; Scherr et al., 2012; Schmid, 1982). Describing energy with a substance metaphor is consistent with Lakoff and Johnson’s argument that all concepts, no matter how abstract, are understood through metaphors grounded in our bodily experience in the world (Lakoff & Johnson, 2003). Gupta et al. used this perspective to argue that experts make productive use of multiple ontologies for physical phenomena (Gupta et al., 2010).

I see students’ employment of multiple ontologies, and, in particular, C’s substance metaphor, as productive for the learning of energy. I also judge that C’s activation of the resource substance metaphor would be deemed appropriate from the perspective of the community of physicists, based on its acceptance by the wider community as represented by the literature cited above (see also section 6.1).

Figure 4.1. Instances “Pushing a heavy box up a hill” and “A battery, bulb and switch” (Watts, 1983a). Reproduced from (Harrer et al., 2013a). Copyright (2013) by the American Physical Society.

pre-service K-8 teachers) were asked about a possible mass increase or decrease after a process involving energy transfer/transformation. The author assumed that the attribution of mass to energy was evidence for a students’ conceptualization of energy as a material substance. The preliminary results reported in the paper showed that responses were highly context-dependent and only few students attributed changes in mass directly to changes in energy. However, it could not be conclusively shown that these students think of energy as a material substance.
4.4.2 Movement as an indicator for energy involvement

Another student, J1, is characterizing energy in general in response to a prompt that is not specified in Watts’ dissertation. I believe that the prompt was a question like “what do you think energy is?” According to Watts, the excerpt in Datum 4.2 illustrates his “Depository Energy Framework.” Watts writes:

This framework typifies two categories of response. The first categories, those responses where students regard energy as resident within certain objects, so that batteries, chemicals, water, coal and so on, all have their own internal source of energy. The second category collates responses where such energies are seen as being intrinsically distinct and having different names. In this way, the energy within chemicals is known as chemical energy and is treated as being in a separate taxonomic group from, say, electrical energy.

For many students, to name a type of energy as being involved in a situation is itself a reasonable response. That is, to name it is to describe it - which in turn goes some way to explaining it. When pressed, the energy is discussed as a causal agent distinctive of the material or objects under discussion - inherent to their composition. The energy in turn acts upon other objects to compel them into action. As the cause is removed, or the energy consumed (‘used up’), so the activity stops. (Watts 1983b, pp. 4.30-4.31)

Again, my analysis shows that there are valuable elements in students’ ideas about energy that are not included in this characterization.

J1 says that if an object is moving, it must “have energy inside it” (line 1). The interviewer returns to J1’s idea about a moving object (line 4), and J1 reveals his commitment to the idea that an object has energy if it is moving (line 5). When
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<th>transcript</th>
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<tr>
<td>1</td>
<td>J1:</td>
<td>... if something moves its got to have energy... its got to be there... its going to have energy inside it.</td>
</tr>
<tr>
<td>2</td>
<td>I:</td>
<td>do you think that everything has got energy inside it?</td>
</tr>
<tr>
<td>3</td>
<td>J1:</td>
<td>no not really... I mean I don’t know if a table’s got energy in it... I suppose it has but I’m not really sure.</td>
</tr>
<tr>
<td>4</td>
<td>I:</td>
<td>you said something about moving... what if it /an object/ moves... what then?</td>
</tr>
<tr>
<td>5</td>
<td>J1:</td>
<td>well if it’s moving... yes... it’ll have energy inside it.</td>
</tr>
<tr>
<td>6</td>
<td>I:</td>
<td>Why do you say that?</td>
</tr>
<tr>
<td>7</td>
<td>J1:</td>
<td>.... because I think the energy ... that if it /the object/ is still... the energy’s going to be building up inside it... well potential energy... and then it moves.</td>
</tr>
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</table>

Datum 4.2. Extract 7. (Watts, 1983b, pp. 4.31-4.32)

asked about his reasons for stating this idea (line 6), J1 says that an object builds up potential energy when it is not moving, “and then it moves” (line 7).

Using the if-then structure of J1’s statements as grammatical indicators (“if [...] its got to have,” line 1, and “if [...] it’ll have,” line 5), I argue that he views the physical displacement of objects, their “moving,” as a sign of energy being present. J1 is therefore using an indicator to justify the presence of energy, which cannot be directly observed.

Physicists routinely identify observables for unobservable phenomena and use the former to make arguments about the latter. These observables serve as indicators for phenomena that are not directly accessible to measurement, like energy. Walz et al. (1993), for example, used the fluorescence of molecules as an indicator for energy transfer. Kaper & Goedhart (2002) characterized the use of the energy forms language in various physics textbooks and compiled a model of energy that is aligned with the treatment of energy in these books. In this model, different forms of energy are associated with observable, changeable properties of objects. These properties are effectively indicators for the involvement of energy.
Energy is an abstract phenomenon that can not be measured directly. In order to recognize energy involvement and make arguments about energy in a physical scenario, measurable indicators have to be identified and used (see also section 6.2). J1’s activation of the resource movement as an indicator for energy involvement is therefore appropriate and can be considered disciplinarily productive.

4.4.3 “Holding electrons up” as a mechanism for energy in a light bulb

A third student, J2, has been presented with a line drawing of a simple circuit: a battery that is connected to a bulb and a switch (see Fig. 4.1). The transcript excerpt in Datum 4.3 was used by Watts to exemplify the “Produced Energy Framework.” According to the description of this framework,

Much discussion of energy describes it as being ‘produced’. It is produced ‘by’, ‘when’, ‘as’ things happen and seems to be in addition to some event. For example, if two chemicals react they produce energy rather than, say, requiring energy for the reaction, or being energy themselves. Some students describe at length the process of production (in terms of, say, resistance to electrons within the filament of a light bulb), a mechanism which produces energy both for the needs in hand (to continue the electron movement) with a surplus amount (to appear as light in the bulb). Commonly there is only one kind of energy though many processes of production, it is produced internally within mechanisms yet released externally, is continuously produced which, since only certain amounts are used, results in the surplus. Stead [1980] has also noted such responses. She describes them as treating energy rather as a waste product, as with smoke, sweat or exhaust fumes, is ‘produced’ and ‘given off’.(Watts [1983b] pp. 4.39-4.40, emphasis in the original)
Rather than treating a student’s description of a mechanism as a by-product of his expressing an idea about energy, I highlight this mechanistic reasoning as an important and productive resource for science learning.

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<th>speaker</th>
<th>transcript</th>
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<tr>
<td>1</td>
<td>J2:</td>
<td>... umh well there’s... in the bulb there’s a little wire and it is... umh... its like a resister to the electrons flowing through and... and as the electrons flow through it’s just like a force... like a pressure... and it sort of holds them up a bit as they come through the bulb...</td>
</tr>
<tr>
<td>2</td>
<td>I:</td>
<td>and what about energy?</td>
</tr>
<tr>
<td>3</td>
<td>J2:</td>
<td>yes... and as the electrons flow through the bulb... it becomes hot and it produces energy and it gives off light</td>
</tr>
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</table>

Datum 4.3. Extract 21, a battery is connected to a bulb and a switch. ([Watts](1983b), pp. 4.40-4.41)

J2 explains that there is a wire in the bulb that acts as a resistor to the electron current that is flowing through it. Within the wire, he describes a “force” or “pressure” that provides resistance and “holds [the electrons] up a bit” (line 1). When asked about energy by the interviewer, J2 continues that “as the electrons flow through the bulb... it becomes hot” which results in energy production and the emission of light by the bulb (line 3).

I find that in his response, J2 provides a mechanistic account of how energy is produced in a light bulb. Russ and colleagues have characterized mechanistic reasoning as being “nonteleological,” “causal,” “built from experience,” and “describing underlying or relevant structure” ([Russ, Scherr, Hammer, & Mikeska](2008), pp. 5-6). Using these characteristics, they operationalized mechanistic reasoning in seven codes for recognizing signs of it in students’ discourse. I use these codes (in their proposed order of increasing sophistication, italicized below) to characterize J2’s response and show that he activates the resource *mechanistic reasoning*.

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J2 describes the target phenomenon “energy in a light bulb” when he states in line 3 that the bulb “becomes hot and it produces energy and it gives off light.” He identifies setup conditions in his description of the “little wire” in the bulb that has “electrons flowing through” it (line 1). In his description, J2 identifies several entities that “play roles in producing the phenomenon” (Russ et al., 2008, p. 14): the wire inside the bulb, the electrons that are flowing through this wire, and the force or pressure that affects the flowing electrons. Along with these entities, he also identifies relevant activities that the entities are engaged in. The electrons are “flowing through” the wire, the force or pressure “holds them up a bit” (line 1).

Furthermore, J2 identifies certain properties of entities. He characterizes the wire as “little” and being “like a resister [sic]” (line 1), and the bulb as “becom[ing] hot” (line 3). J2 also identifies the organization of entities in his description of the setup conditions (see above): the little wire is within the bulb, the electrons are flowing inside the wire (line 1), and therefore through the bulb (line 3).

Lastly, J2’s reasoning shows evidence of chaining, a description of the causal structure of the mechanism. In line 3, he specifies that “as the electrons flow through the bulb...it becomes hot and it produces energy and it gives off light.” The flow of the electrons through the wire and the force or pressure “holding them up a bit” causes the bulb to become hot and give off light, both of which involve energy. Although J2’s explanation is missing key information about how energy gets into the bulb or what it means that the bulb “produces energy,” his explanation shows a high level of sophisticated mechanistic reasoning.

Mechanistic reasoning has been found to be at the core of scientific practice in the STEM disciplines (Russ et al., 2008). Hammer argued that “the development of a sense of mechanism should be a valuable aspect of scientific inquiry” (Hammer, 1995, p. 422). The pursuit of causal-mechanistic explanations of physical phenomena has been identified as a cross-cutting concept of science that is necessary for the
development of scientific literacy (National Research Council (NRC), 2011). Therefore, I argue that J2 productively activated the resource *mechanistic reasoning* to account for a light bulb’s emission of energy.

### 4.5 The importance of recognizing disciplinary progenitors

I analyzed transcripts from Watts’ interviews about instances to reveal a dimension of students’ ideas about energy that is distinct from Watts’ original descriptions. Watts had classified students’ responses, which he viewed as emerging from their use of stable and coherent conceptions about energy, into “alternative frameworks.” His work influenced other researchers who continue to use the categories in their pursuit of cataloging students’ non-normative ideas about energy. In my analysis, I enlisted a resources framework to find evidence of productive and disciplinary features of these responses.

In this chapter, I demonstrated how detailed analyses of students’ responses reveal the activation of resources. I found evidence for students’ use of a substance metaphor for energy, the identification of an object’s movement as an indicator for energy involvement and mechanistic reasoning about energy in a light bulb. Furthermore, I illustrated how my proposed operational definition of disciplinary productiveness can be used to evaluate students’ activated resources as productive from a disciplinary point of view.
Chapter 5
A FRAMEWORK FOR ANALYZING CLASSROOM VIDEO

5.1 Introduction

While productive resources about energy can be found in students’ ideas expressed in interview situations (see Chapter 4), I agree with Scherr (2009) “that learning and expertise show best in what students do and say to learn together” (p. 1). Learners’ talk and non-verbal actions in naturally occurring learning activities can clue us in on their ideas about energy (e.g., Harrer, Scherr, Wittmann, Close, & Frank, 2012; Harrer, Flood, & Wittmann, 2013b; Scherr et al., 2012, 2013). Research conducted with this perspective uses audio-visual recordings of such activities as basic data sources for analyses of what students know. This approach is contrasted by research on learners’ knowledge in which artifacts of individual, private mental efforts (like surveys or protocol interviews) are analyzed (Jordan & Henderson, 1995).

The activation of resources depends on the context in which they are activated. A student might activate a resource within the artificial setting of an interview, but might not activate that same resource in the natural learning environment of a classroom. In order to investigate students’ ideas about energy for productive resources that are activated in actual classroom environments, I use video of everyday classroom activities to find cases of activated resources about energy.

In this chapter, I develop the analytical framework that guided the collection of video recordings, the selection of episodes, and the analysis of these video episodes. I present the settings in which I conducted this research and the methods I employed to collect the video data corpus and select the data for analysis. The analysis of

1In the following, I simply use the word “video” to refer to recordings of both video and audio.
classroom video for Maine middle school students’ resources about energy is presented in Chapter 6.

5.2 Methodology: Interpretive video analysis

My approach to the collection of data sources as well as the selection and analysis of data stands in the tradition of interpretive research (e.g., Erickson 1986; Schwandt 2000). The central premise of the interpretive paradigm is that human (inter-)action is meaningful (Schwandt 2000, p. 191): Humans (oftentimes unconsciously) create their own interpretations of interactional occurrences that become reality for them. This constructed reality influences their behavior and therefore subsequent actions (Erickson 1986, p. 126). As such, in order to understand—or make meaning of—human activity, a researcher can and must interpret it in its context and from the perspective of the interacting persons. The resulting “interpretations of interpretations” (Gregg et al. 2010) become the reconstructed original meanings of human actions (Schwandt 2000, p. 193).

In an interpretive research program, measures must be taken to avoid misinterpretations of the original meaning of human action. Carefully chosen and applied methods of analysis allow the researcher to become an objective observer of subjective meaning (Schwandt 2000, p. 193). Maxwell’s categories of validity in qualitative research (J. A. Maxwell 1992) are useful for selecting, making explicit, and evaluating appropriate methods for the interpretive analysis of video recordings.

Descriptive validity. The first and most fundamental criterion of validity in qualitative research, according to Maxwell, is descriptive validity (J. A. Maxwell 1992, pp. 285-288). This category concerns the “factual accuracy” of a descriptive, narrative account. Our own experiences as humans who constantly interact with objects or other living beings in the world prime us with expectations about what to “see” in
video (Jordan & Henderson, 1995, p. 44). These idiosyncratic biases can influence the transcription of dialog and the descriptive narration of events, and therefore significantly impact the analysis and interpretation of these events.

To avoid these biases and ensure that the analytic account of a video recorded interaction is as accurate as possible, much of the analytic work is conducted in groups (Jordan & Henderson, 1995, pp. 43-46). For example, after watching several hours of classroom video by myself, I selected episodes that I thought contained cases of certain phenomena (see section 5.4 on episode selection, below), and brought these episodes, along with initial transcripts, to “Interaction Analysis” meetings with colleagues. During these Interaction Analysis sessions, we discussed our understandings of the occurrences in the video, identified phenomena worthy of further investigation, and negotiated my initial transcripts and narratives to assure that they accurately reflected the events in the video. In particular, we used the strategies for collaborative video analysis proposed by Jordan and Henderson (1995):

The tape is played with one person, usually the owner, at the controls. It is stopped whenever a participant finds something worthy of remark. Group members propose observations and hypotheses about the activity on the tape [...]. Proposed hypotheses must be of the kind for which the tape in question (or some related tape) could provide confirming or disconfirming evidence. The idea is to ground assertions about what is happening on the tape in the materials at hand. (p. 44)

In ensuing discussions, evidence for proposed claims was evaluated by the group (e.g., by rewinding the video and re-watching particular segments) and a consensus about claims that were best supported by the available evidence was negotiated.

2These meetings were variously conducted with Michael Wittmann, Rachel Scherr, Virginia Flood, and occasionally the “Energy Research Group” at the University of Maine
No descriptive representation of video-recorded events (e.g., transcripts, content logs, narratives) can be exhaustive (J. A. Maxwell, 1992, p. 287). First off, the camera and microphone can never record the entirety of phenomena occurring in a classroom environment but are constrained by their technical specifications and their placement in the room (Jordan & Henderson, 1995, pp. 54 & 55). In addition, the researcher, guided by theory and experience, selectively attends to certain features of interactions and ignores others when watching and analyzing the recordings. However, it is imperative to highlight the features in a representation that are relevant to the phenomenon being studied and necessary for the argument being made. In the transcript excerpts presented in Chapter 6, information that does not influence the outcome of the analysis (e.g., utterances that do not seem to be attended to by others in the interaction, pauses, prosodic features) was omitted in order to increase the readability and draw attention to the important features. Transcripts without omissions can be found in the appendix.

**Interpretive validity.** Interaction Analysis also provides resources to ensure interpretive validity (J. A. Maxwell, 1992, pp. 288-291). As the name suggests, this criterion is concerned with the accurate description of the meaning of actions from the perspective of participants in the interaction. This so-called *emic* perspective explains why methodologies derived from anthropology (e.g., ethnography, Geertz, 2003; ethnomethodology, Garfinkel, 1996; conversation analysis, Sacks, Schegloff, & Jefferson, 1974; discourse analysis, Potter, 2004) are relevant for interpretive research. Interaction Analysis draws on all of these methodologies to make sense of events in interactions (Jordan & Henderson, 1995).

The objects of study for the reconstruction of original meanings are verbal and non-verbal actions (e.g., gestures, body posture, prosody, turn-taking). An account

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3These decisions were validated through reviews of and discussions about my analyses with Michael Wittmann and Rachel Scherr.
of these meanings is always based on what participants say or do and sometimes takes into account, to some extent, participants’ own explicit interpretations. However, interlocutors might not always be aware of and articulate about their own beliefs and knowledge (J. A. Maxwell, 1992, p. 290). Therefore, researchers employ analytic methods that are based in theories of interaction to construct accounts of meanings.

Of particular importance is the concept of contextuality, a central feature of real-world discourse in the view of Interaction Analysis as well as the methodologies it is derived from, especially Conversation Analysis. Contextuality means that “sentences are never treated as isolated, self-contained artifacts. Instead, sentences (the abstract entities that are the objects of linguistic enquiry) and utterances (the stream of speech actually produced by a speaker in conversation) are understood as forms of action situated within specific contexts and designed with specific attention to these contexts” (Goodwin & Heritage, 1990, p. 287). Researchers assert that participants in an interaction co-construct the meaning of an utterance based on the conversational actions that preceded the utterance. With this premise, the analysis of an utterance has to take a similar perspective and take into account the context in which the conversational action occurred.

This sequentiality and causality of conversational actions becomes especially relevant in my analysis of classroom conversations for resources that are irreducible to individual students (see section 3.3). When students’ utterances are tied together in specific ways to pursue a certain thread in the conversation, resources can emerge that could not be recognized if individual utterances were analyzed by themselves. However, the context of an utterance is equally important for an analysis of the meaning of this individual utterance itself. A trivial example is the assignment of meaning to the pronouns “it” in the utterance “it gives it to the monkey” (Datum 6.11, line 15) that were not further specified by the student. From the context of the utterance, it can be established that the first “it” refers to “food,” mentioned by
the student in the utterance prior to the one under consideration. The second “it,” however, seems to refer to “energy,” which was mentioned only at the very beginning of the conversational sequence, or possibly some other kind of substance or entity contained in the food that is transferable to a monkey (see section 6.3).

**Theoretical validity.** The previously mentioned example of a resource that emerges from interactions between a group of students (mechanistic reasoning) is also an example of “theoretical understanding,” which is the concern of theoretical validity (J. A. Maxwell, 1992, pp. 291-293). This third category differs from the first two in its distance from the directly observable and the reconstructed meanings of observable actions. In contrast to descriptive and interpretive validity, theoretical validity is related to the application of a theory to the observed and interpreted. It is therefore dependent on consensus among researchers within the community in which this theory is being developed.

In order to reach theoretical validity, the terms describing constituents and mechanisms of a theory (e.g., resources, activation) need to be properly defined. Whether the terms of a theory are applied accurately to descriptions and interpretations of human action can only be assessed if there exist rigorous operational definitions of these terms. In Chapter 3, I have developed definitions for the relevant terms and concepts of the resources framework. These definitions allow me to apply the theory in a transparent way, so that theoretical validity can be established.

In section 6.3, for example, I describe a sequence of conversational actions about a monkey and a banana (see Datum 6.11) that is part of a larger classroom discussion. According to my interpretation, the students explain how food provides energy to a monkey and allows her to run around. I apply the construct of resource activation across multiple learners (see section 3.3) to this conversational sequence and find a resource, “food as an energy source for movement,” that emerged from the interactions of the group of learners.
Also of concern to theoretical validity is the identification of metaphors as a particular method I use to interpret participants’ intended meaning of utterances. This method, already introduced in Chapter 4, is based on the theoretical premise that metaphors permeate all human thought and action (Lakoff & Johnson, 2003). According to this perspective, we can only understand concepts, especially abstract ones like energy, in terms of prior bodily experiences that manifest themselves in metaphors—descriptions of abstract concepts in terms of concrete experiences and entities. For example, ideas about time are expressed using metaphors. The sentence “we just have to get through the semester” suggests that “the semester” extends in space and “we” can move through it.

According to Scherr et al. (2012, p. 2), “metaphors are often especially evident in the verbs and prepositional phrases used together with the terms of interest. For example, to say someone is in trouble or close to graduation conceptualizes these states as being locations, and to say that someone got an idea or has a headache poses these attributes as being possessions” (emphases in the original). In Chapter 6 I identify instances of previously described metaphors about energy in learners’ utterances by using grammatical indicators like the ones above that suggest the description of one concept in terms of another (possibly more concrete one).

Generalizability. Qualitative research has a different view on issues of generalizability than quantitative or experimental research (J. A. Maxwell, 1992, pp. 293-295). Quantitative studies typically seek to base their analyses on random, representative samples of a broader population in order to systematically extend emerging patterns beyond the studied sample. The aim of strictly qualitative research, in contrast, is to seek “concrete universals” by studying and comparing individual cases in detail instead of identifying “abstract universals” (like misconceptions or alternative frameworks, see Issue 2 in Chapter 2) by identifying general patterns in a large number of responses, for example using statistical methods (Erickson, 1986, p. 130).
I believe that this approach addresses Issue 2 raised in Chapter 2. Prior research on students’ ideas about energy has focused on finding universal characteristics of students’ ideas by classifying patterns that emerged across ideas that were expressed in interviews or surveys by (largely) representative samples of students. However, as has become evident in Chapter 4, the categorization of students’ ideas into bins is prone to miss relevant features of these complex ideas. In addition, researchers reported that certain ideas that could not be binned into any of the categories (but arguably contain valuable disciplinary substance) had to be dropped from analysis. The here proposed methodology honors the complexity of students’ ideas. Instead of finding abstract universals of ideas about energy that are generalized to a large population of students, it seeks to discover concrete universal properties of particular cases of productive resources regarding energy and their activation by certain students.

Instead of random sampling, the process of identifying cases for analysis in an interpretive study is theory-driven and deliberate (see sections 5.3.2 and 5.4). The detailed analysis of cases of resource activation in this study allows for the comparison with other cases in order to find the universal characteristics of the studied phenomena (e.g., a particular resource, students’ resource activation). I analyze each case in detail and create rich descriptions with interpretive annotations of how observed resources are manifested in each specific case.

*Evaluative validity.* According to Maxwell (1992, p. 295), the application of an evaluative framework, i.e. judging human action or its interpretation according to certain normative values, is not generally part of qualitative research. However, evaluative validity is essential for this study because my goal is to identify *productive* resources regarding energy in students’ ideas.

The evaluation of a resource as productive is a judgment that has to rest on explicit criteria. I have presented these in Chapter 3 for the two concepts *disciplinary...*
and situative productiveness. Notably, the perspective from which resources are evaluated differs between the two concepts. Disciplinary productiveness is evaluated against the norms of the scientific community: resources are judged for their disciplinary value from an etic perspective. Situative productiveness, on the other hand, has to be evaluated from the view of the participants, from an emic perspective.

While the situated productiveness of activated resources follows from the contextuality of discourse, additional analytic work is necessary to establish disciplinary norms against which activated resources can be evaluated. In Chapter 6, I conduct a historical-philosophical analysis of the energy concept in physics. I find that physicists use various metaphors and models to reason about energy, not just a singular abstract conception of energy (Issue 3 in Chapter 2). The results from this analysis are the basis for the subsequent analysis of students’ ideas for disciplinary productive resources.

5.3 Collection of the data corpus

After the theoretical grounding in the previous section, I present the methods and procedures I employed to collect the corpus of video recordings and select the video episodes containing the cases I analyze in Chapter 6. I start with a general overview of the study context in the next subsection and then detail the video recording procedure.

5.3.1 Study context: Maine Physical Sciences Partnership

My analysis of Maine middle school students’ ideas about energy in Chapter 6 is part of the research efforts of the Maine Physical Sciences Partnership (MainePSP). The MainePSP is a collaborative effort of the University of Maine together with

4The etic perspective is concerned with the features relevant to the community of researchers, whereas the emic perspective focuses on the relevance for the community under study.
48 rural Maine secondary schools and three nonprofit institutions with expertise in science education. The goal of the project is to improve physical science instruction in sixth through ninth grades throughout the state of Maine.

As part of the MainePSP research efforts, this study was conducted under the approved general MainePSP Institutional Review Board (IRB) application. All teachers had signed informed consent documents and collected signed consent forms from parents and assent forms from students. Although all participants were informed that students’ identities would be obscured in video records edited for presentation, I chose not to present any video captures in this dissertation to assure the privacy of the participating students. In the past, I have used cartoonized still pictures in research presentations. However, I believe that they do not contain any additional information necessary for the arguments I present in this dissertation.

One of the major activities of the MainePSP was for participating teachers, assisted by university researchers and staff, to choose a set of common physical sciences curricula. Several modules from the research-supported Project-Based Inquiry Science (PBIS) [Kolodner et al., 2008; Kolodner, Krajcik, Edelson, Reiser, & Starr, 2010b; Nordine et al., 2011] were chosen for use in 8th grade physical science instruction. Teachers at MainePSP schools piloted the curriculum during the 2011/2012 school year. Since Fall 2012, the curriculum has been disseminated to the remaining participating middle schools and is currently in use at these schools. This research contributes to the investigation of the implementation of PBIS: Energy in MainePSP schools.

The video recordings that form the data corpus for this study were collected in classrooms of three teachers at MainePSP middle schools. Through my participation in many of the professional development activities for teachers piloting the PBIS: Energy curriculum, I had come to know these teachers quite well. Many of them were willing to let me come and observe their classrooms. For scheduling reasons, I
chose three teachers (at three different schools) whose classes I would video record and study. These three teachers, Mrs. Carter, Mrs. MacAvoy, and Mrs. Marsters\footnote{All names of participating teachers and students in this study are pseudonyms.} were about to start the PBIS: Energy unit within only a few weeks of each other. Visiting the three teachers’ classrooms would give me the opportunity to record the same sections of the curriculum everywhere. In addition, each teacher taught more than one class. I was invited to collect video from three of Mrs. Carter’s classes, two of Mrs. MacAvoy’s classes and one class of Mrs. Marsters’s.

It turned out that the pacing was quite different in all three classrooms. Mrs. Carter’s classes worked exclusively on the introductory activities of PBIS: Energy for two weeks and only reached Learning Set 1 after I had left. Mrs. MacAvoy and Mrs. Marsters, on the other hand, spent considerably less time on the introductory section and moved into Learning Set 1 after only a few days. Mrs. Marsters was also able to finish up the unit prior to energy faster than I had expected. I missed the first day of energy instruction in her class.

5.3.2 Video recording procedure

The recording of phenomena relevant to a particular empirical investigation with a video camera is a “sampling problem” \cite{Hall2007}. In other words, what is audible/visible in the recording and therefore what can be analyzed and how depends on where a camera is pointed, whether zoom or wide angle views are used, where the microphones are placed, etc. \cite{Jordan1995}. Careless placement of audiovisual recording equipment can result in video records that are not useful for a certain, planned analysis. The more a researcher knows about the phenomena (s)he seeks to capture, the more informed the decisions about the placement of the recording equipment can be.
Initially, I planned to observe and video record the classrooms to study the teachers’ attention and responsiveness to the disciplinary substance in students’ ideas about energy. Inspired by prior research on teacher responsiveness (e.g., Coffey et al., 2011; Hammer et al., 2012), I was convinced that in order to be able to understand how a teacher responds to students’ ideas, I needed to be able to study these ideas myself. Based on these considerations, I decided to record video from multiple angles in the classrooms. I knew that much of the students’ work would take place in small groups, so I wanted to be able to record at least two of these small groups. To have an overview record of the goings-on in the classroom, I also wanted to record the entire classroom. In addition, I wished to audio record the teacher’s voice.

This selection of camera angles and microphone positions allowed me to record a large amount of student discourse in small groups but also during whole class discussions. Having this large corpus of good-quality video that can be analyzed for students’ ideas about energy allowed me to eventually shift the focus of this dissertation exclusively to these ideas (see Chapter 1).

The recording equipment I used consisted of three Canon Vixia HF R200 camcorders with zoom lenses that are capable of recording high definition video directly onto SD memory cards, three flexible miniature tripods, and three sets of Sennheiser ew112-p G3-A wireless lapel microphones. Using zoom lenses, SD memory cards, and wireless microphones allowed me to set up the equipment in rather unobtrusive ways and without having to run wires through the classrooms. With a pair of headphones, plugged into one of the cameras near me, I could monitor the audio quality and listen to the audio stream to write observational field notes (see below).

I set up the cameras, with the wireless microphone receivers connected to them, using the flexible tripods on top of wall-mounted cabinets or tall bookshelves in the classrooms. Two of the cameras were directed and zoomed in at student group
tables that were selected based on their proximity to the furniture that was used as camera mounts. The respective wireless microphones were mounted on or around those tables, as hidden as possible. The third camera was mounted with the third microphone receiver in a far corner of the classroom and set at wide angle to cover as much of the classroom area as possible. The teacher wore the third wireless microphone on her chest. This way, I could record not only her voice but also surrounding classroom audio from the perspective of the teacher.

Figure 5.1. Mrs. Carter’s classroom floor plan. (Image created using ExhibitCore Floor Planner, exhibitcore.com)

Figure 5.1 shows the layout of Mrs. Carter’s classroom. Camera and microphone symbols indicate the positioning of these recording devices in the classroom. I am sitting in the lower right corner, headphones plugged into the “classroom camera.”

In addition to recording video from three angles, I took observational field notes during all of my classroom visits. Researchers create and use field notes in various ways (Walford, 2009). While there is no generally agreed upon format for writing
field notes, the general purpose of taking field notes is to create a catalog of events that indexes the collected data corpus. Using this index allows a researcher to select episodes for analysis without having to watch hours of video (Hall 2007, pp. 12 & 13). My field notes contain general information about the class session (e.g., date and time, school, special events taking place on a certain day) and the classes (e.g., seating plans, absentees), but also sketches of inscriptions on the white board and the projected class notebook as well as specific details about the sequence of activities (with time stamps) and occasionally sections of transcribed dialog. Anything (e.g., events, utterances) that, at the moment, seemed interesting or worthy of further investigation was flagged in the field notes (see Table 5.1 for an example excerpt).

Every introduction of recording equipment into a natural classroom environment causes so-called “camera effects” (e.g., Jordan & Henderson 1995, pp. 55 & 56; Roschelle 2000, p. 719). Students and teachers change their behavior when they know they are being observed by a third party but eventually get accustomed to the additions to the classroom. The presence of camera effects can be empirically investigated. Usually, camera effects show in explicit mentioning of the equipment or the researcher in the room, side glances, or “acting out for the camera.” This unusual behavior occurs less often over time and eventually only shows very rarely and especially when students are not engaged in classroom activities.

I took several measures to minimize possible camera effects. Every teacher explained my presence in the classroom at length to her students well ahead of my visit, and again when I first came to each classroom. In order to allow teachers and students to get used to my (and the equipment’s) presence, I attempted to visit each classroom several days before I actually started videotaping (this was not possible in the case of Mrs. Marsters’s class). I installed the equipment ahead of time, and left everything set up in each classroom for the entire duration of my field work. In each class, frequent evidence of camera effects can be found in the video of the first one
or two days of my presence there. After that, the students seem to be rather used
to the additions in the classroom. For my analysis, I only selected video episodes
that are free of camera effects.

5.4 Episode selection and data generation

The process of selecting video for analysis is lengthy and iterative, and it involves
the evolution and progressive refinement of a research focus (e.g., Goldman, Erickson,
Lemke, & Derry, 2007; Roschelle, 2000). In section 5.3.2 I already described the
first stage of video selection (Goldman et al., 2007, p. 17): the physical and temporal
positioning of the recording equipment. As elaborated earlier, only a small subset of
the actual occurrences in a classroom can be recorded. The setup of the recording
equipment places constraints on the video that is collected and therefore on the
data that can be made available for analysis. During six weeks of field work, I
recorded about 142 hours of video from the three cameras in each classroom and I
generated approximately 150 pages of field notes. These field notes were essential
in the selection of episodes for analysis. In this section, I describe this process and
introduce the episodes that are analyzed in Chapter 6.

5.4.1 Finding relevant stretches of video

My goal was to find video that showed students develop and express their ideas
about energy in order to be able to answer the guiding question, “Do Maine middle
school students activate productive resources regarding energy in classrooms using
Project-Based Inquiry Science?” Assuming that instances of rich discourse about
students’ ideas would most likely take place in small group work and in idea collection
phases with the whole class, I turned to my field notes to find examples of such
classroom activities. Table 5.1 shows an excerpt from my field notes in Mrs. Carter’s
first class on the first day of energy instruction that illustrates the utility of field
notes to find relevant episodes. It describes an activity in its context and provides the approximate temporal location of the event that can be synchronized with the video. This particular example was the first episode to be flagged for further analysis while I was in the field.

<table>
<thead>
<tr>
<th>timestamp</th>
<th>notes</th>
</tr>
</thead>
</table>
| 11:38     | Students still want to know who Rube Goldberg is, Mrs. Carter tells them to be patient for a little while longer.  
First activity: Think, Pair, Share: 1) What do you think energy is? 2) What are different forms of energy? 3) When do you use energy? First, think for yourself, then talk to your neighbor and share. [This comes much earlier than in the book. The book asks the question “What do you think energy is” on page EN 8; the class has not been reading or looking at the other pages.]  
*** This will be the first possibly interesting episode |
| 11:40     | Mrs. Carter repeats instructions: Think, pair, share. |

Table 5.1. Excerpt from field notes on the first day of energy instruction in Mrs. Carter’s first class.

*Pseudonym; name altered for the reproduction of this excerpt from my field notes.

Whenever I identified an interesting classroom activity, I tried to find the same activity in field notes from the other classes. I was particularly drawn toward the activities on the first day because students would express their very first, “pre-instructional” ideas about energy. Finding productive resources in students’ ideas that had not yet been influenced by the formal energy instruction of PBIS became my priority. According to my field notes, the activities on the first day in each classroom seemed to provide rich opportunities for idea exchange. Therefore, I decided to limit my search for video to only the first day of using PBIS: Energy, which eliminated video from Mrs. Marsters’s class that had started the energy unit a day before I visited. Eventually, I had a long list of video clips from Mrs. Carter’s and Mrs. MacAvoy’s classes that potentially contained students expressing ideas about energy.
Soon after starting to watch the corresponding video, I decided to eliminate video of Mrs. MacAvoy’s two classrooms. The recorded groups of students in those classes drifted off task very quickly, only superficially engaging with the activities at hand. These activities were also mostly constricted to the creation of lists of descriptors that were publicly compared after the groups had finished their work. In contrast, Mrs. Carter’s three classes seemed very organized, activities were linked to each other and the students seemed mostly on task, sharing and discussing their ideas with each other and with the teacher.

5.4.2 Selecting episodes of students expressing ideas about energy

With the amount of relevant video reduced to less than 12.5 hours, I returned to my field notes to divide the three recorded lessons into activity segments. There were periods of time during which the teacher dealt with organizational issues. At other times, the students would read portions of text in the PBIS: Energy textbook. One class period was divided in half by the lunch break. All of these segments took up considerable amounts of time, so that, in the end, I was left with about 20 minutes of relevant classroom activities in each class.

As a next step, I watched these 20 minutes for each class and every camera angle multiple times. I isolated three events in two of Mrs. Carter’s classes during which several students expressed and discussed their ideas about energy in ways that would allow me to use these ideas as illustrative cases of resource activations. These

6I am using the word *event* in Goldman et al.’s sense: “Events are time-analogs of objects. Like objects they have underlying structures reflecting multiple parts and timescales […] To illustrate, consider a classroom event during which students collaborate on the interpretation of data presented as a histogram. This event could be parsed in terms of various sub-events, for example: the presentation of an idea by a student; the response by another indicating acceptance, confusion, disagreement, or even disengagement; periods of negotiation through which joint understanding emerges; etc. These sub-events might be further analyzed as coordination of even smaller events on smaller timescales: gestures, speech, tool use, mental states, etc. Or, the entire classroom event could be considered to be part of a longer-term macro-event, such as the development of students’ ability to read and interpret a range of data representations from various sources.” (Goldman et al., 2007, p. 16)
events were selected because they contain a wealth of illustrative examples (Goldman et al., 2007) for resource activations in actual classroom environments. Video of these events was of good audiovisual clarity and many of the activated resources were related to the three topics introduced in Chapter 4: conceptual metaphors, indicators for energy, and mechanistic reasoning. In the remainder of this chapter, I introduce and describe these events that I analyze for students’ activated productive resources regarding energy in Chapter 6.

All three events took place on the first day of energy instruction in Mrs. Carter’s classroom. The video recordings from this day containing the three events were edited into three “episodes,” individual video files that only contain a single event. Only one camera had an unobstructed view of the students in the first episode and was able to record clear audio of these students. Therefore only video recorded with this camera was used for the analysis of the first episode. All three camera angles were used for the analysis of the remaining two episodes.

5.5 Introducing episodes for analysis

The three selected events occurred in two different classes, but within the same activity: A Think/Pair/Share about the three questions, “What is energy,” “What are different forms of energy,” and “When do you use energy?” A Think/Pair/Share is a teaching technique that was proposed by Lyman (1981) to allow for individual student thinking time before the students pair up with another student to share their ideas and eventually share their thoughts with the rest of the class. In this section, I narrate how Mrs. Carter introduced PBIS: Energy to her classes in general before

Note that the description in this section does not imply a value statement about the entire video corpus. The process of episode selection is detailed here as a record of the employed methods. No judgment is being made about whether the events in the selected episodes are typical for the classrooms or rare occurrences. As explained in section 5.2, it was not my goal to find events representative of a particular class but instead cases of a particular phenomenon: the activation of productive resources regarding energy.
I briefly describe each episode. The headings of the following subsections are short names for the episodes to allow for easy referencing.

Introducing the PBIS: Energy unit in her three classes, Mrs. Carter told her students that they would spend the next 3-4 months exploring ideas about energy. Following the progression of the curricular materials, she had her classes read the first text page in the PBIS: Energy student book. This introductory section in the book reminds students of various uses of the word “energy” in their everyday experience, encourages them to think about other words with multiple meanings, and finally introduces the “Big Challenge” of the unit: To design Rube-Goldberg machines that turn off a light. The students were already familiar with the concept of a Big Challenge from their previous participation in a different PBIS unit. The Big Challenge in PBIS is the central design project around which engagement with disciplinary content is organized. The questions Mrs. Carter used for the Think/Pair/Share activity are suggested in the PBIS teacher’s guide as a follow-up to the reading of the introductory text about the Big Challenge in the student textbook and the discussion about words that have more than one meaning (Kolodner, Krajcik, Edelson, Reiser & Starr 2010a, p. 18).

Before the students started the activity, Mrs. Carter instructed them to listen to each others’ ideas and add to their lists what they had not thought of. The students were not encouraged to challenge each others’ ideas. Instead, Mrs. Carter told them that no idea could be wrong, but that their partners’ ideas might influence them to erase some of their own ideas in their notebooks and instead write others down. These instructions are slightly conflicting but they are consistent in that they suggest to the students to challenge their own answers but not their neighbors’.
5.5.1 Mark and Madison

Mark and Madison are two of the 15 students (8 boys and 7 girls) in Mrs. Carter’s first class of the day. The students were sitting in five groups of two to four students each (see seating plan in Fig. 5.2; names of persons referred to in the transcript excerpts in Chapter 6 are highlighted using bold, italicized letters).

Figure 5.2. Mrs. Carter’s first class seating plan. All names are pseudonyms. Names of persons referred to in the transcript excerpts in Chapter 6 are highlighted using bold, italicized letters.

In the beginning of the period, Mrs. Carter had wrapped up a previous non-PBIS-related sequence on gravity before she asked the students to open up their new energy notebooks and the PBIS: Energy textbook. After reading the introductory text and a brief discussion about the different meanings of words and their new Big Challenge, Mrs. Carter dismissed her students for the lunch break.
When the students were back from lunch, the teacher briefly reminded them of their discussion before break and started to take notes with them about the results. Although the students were eager to learn more about energy, the Big Challenge, and who Rube Goldberg was, Mrs. Carter postponed their questions by asking them to be patient for a little while longer. Then she introduced the Think/Pair/Share.

Mark and Madison start working on the task individually. Madison seems to finish first and starts doodling in her paper notebook. Mrs. Carter comes by to inquire about their progress and infers that Madison is “waiting patiently” until Mark is finished. When he signals that he is done, the two students start presenting their answers to the three questions to each other.

This first event, Mark and Madison’s sharing of their ideas about energy with each other, was further divided into two episodes. In the first episode, they discuss their answers to the first question, “What is energy?” (Datum 6.1). This episode contains several cases of resources regarding the ontology of energy, which allows me to illustrate what the activation of resources regarding energy’s nature can look like in student discourse. In the second one, Mark and Madison talk about different forms of energy (Datum 6.2). I use this episode to showcase the analysis of productive resources related to energy forms.

The resources I find in these episodes are illustrative examples of productive resource activation in conversations among a small group of students. I do not claim that the episodes show representative behavior of the two students, are typical for the classroom at large or contain representative cases of resources about energy. However, these episodes already allow me to positively answer the guiding research question: I find productively activated resources in actual Maine middle school classroom discourse.
5.5.2 Energy Forms Discussion

After the initial Think/Pair part of the activity, Mrs. Carter pulls her first class together for a whole-class discussion (“Share”) about their individual answers to the three questions. Part of this class conversation is a discussion of answers to the question “What are different forms of energy?” This discussion was chosen as the second event for further analysis because it turns from a list-making activity to a discussion about forms of energy that are associated with specific energy sources. During this class conversation, students’ utterances provide evidence for various resources regarding energy and its forms.

The video of this event is divided into several episodes, as well. Seven segments could naturally be found based on the conversational topics, the flow of the conversation, and units of conversational turn sequences. The first episode (Datum 6.3) contains Jessica’s ideas about energy forms. In the second episode (Datum 6.4), Jeff and Jessica discuss solar energy, aided by the teacher. Jeff contributes “hydro energy” as a new form of energy in the third episode (Datum 6.5). “Heat” is added to the list by Madison in episode four (Datum 6.6). Uli proposes “plasma energy,” which is slightly challenged by Mrs. Carter in the fifth episode (Datum 6.7). A discussion about “human energy” and what the difference might be between “energy” and “energy forms” in episode six (Datum 6.8) causes the teacher to give a brief monologue about her interpretation of Jessica’s idea about energy forms in the final episode (Datum 6.9).

My analysis of these episodes illustrates how resources regarding the ontology and forms of energy are activated productively in an activity that arguably could, on the surface, be classified as pedagogically questionable (see section 6.2.3). In initial viewings of my recorded video, I put aside the entire event as just another—more or less pointless—list-making activity that does not engage students in meaningful
ways. However, like the Mark and Madison episodes, the energy forms discussion was selected not only because of its audiovisual clarity; it allows me to present examples of how students activate productive resources in a context that seems unlikely to foster the expression of rich ideas about energy.

5.5.3 Monkey and Bananas

The third event took place in Mrs. Carter’s third class of the day (for seating plan, see Fig. 5.3). Like in her previous classes, Mrs. Carter engaged the 13 present students (out of 17) in a whole-class conversation about energy forms after the Think/Pair part of the activity described above. During this class discussion, an example was proposed for a scenario involving kinetic energy: a running monkey that eats bananas. The students subsequently engaged in a communal inquiry into this scenario and co-constructed a mechanistic energy story. This conversational sequence was chosen as the third event because it features cases of resources about energy and energy forms in addition to examples of mechanistic reasoning but also cases of irreducible resources that emerged from interactions between students and teachers.

The episode containing this event was split into three segments. In the first part, Eaton proposes the running monkey as an example for kinetic energy (Datum 6.10). In the second segment, a mechanistic account is created for the transfer of energy from the banana to the monkey (Datum 6.11). Finally, the students co-construct a mechanistic explanation for how energy ends up from the sun in the banana (Datum 6.12).

Arising from the same activity as the Energy Forms Discussion, the Monkey and Banana episode not only features individual students’ activation of productive resources regarding energy but enables me to show how such resources can emerge from interactions between learners. In addition, I can show how knowledge pieces
Figure 5.3. Mrs. Carter’s third class seating plan. All names are pseudonyms. Names of persons referred to in the transcript excerpts in Chapter 6 are highlighted using bold, italicized letters.

about the nature and forms of energy are productively activated to co-construct a mechanistic account of a chain of energy transfers and transformations.

5.6 Summary

In this chapter, I developed an interpretive framework for the analysis of video recorded classroom discourse for productively activated resources related to energy. I detailed the process by which I recorded the video that comprises the data corpus for this study. The selection of video episodes was described before I introduced the episodes that I analyze in the next chapter. These episodes allow me to illustrate increasingly sophisticated scenarios of resource activation in the context of energy.
Chapter 6
IDENTIFYING MAINE MIDDLE SCHOOL STUDENTS’ PRODUCTIVE RESOURCES FOR DISCIPLINARY ENGAGEMENT WITH ENERGY

In this chapter, I identify productive resources related to the three crucial topics of energy identified in Chapter 4—conceptualizing energy, forms of energy, and mechanistic reasoning with energy—in students’ ideas about energy. The presented evidence comes from three episodes: the case of Mark and Madison’s discussion about the three Think/Pair/Share questions, the case of a whole class discussion about different forms of energy, and the case of a co-constructed mechanistic explanation for how energy from the sun allows a monkey to run around in the jungle (see section 5.5). I conclude the chapter with a discussion about how the identified resources are productive with regard to the Project-Based Inquiry Science: Energy curriculum.

6.1 Energy: Conceptualizing the “imponderable” with metaphors

This section presents a brief review of the historical and philosophical roots of the energy concept in physics to lay the groundwork for an analysis of disciplinary productive resources in students’ ideas about energy. Energy is an abstract, “imponderable” idea that has been proposed as a generalized conserved quantity. This is compatible with the scientific conception of energy that researchers of prior work on students’ ideas about energy proposed and used to compare and evaluate their categories of student ideas (see Chapter 2). However, it is not sufficient to view this notion as the unified scientific conception of energy (Issue 3). Scientists are only able to investigate the multifaceted concept energy by using models that employ certain conceptual metaphors. This allows for the creation of rich narratives to explore phenomena
involving energy. Different areas of physics use different models and metaphors for energy and therefore conceptualize energy in different ways. Quantum physics, for example, uses spatial metaphors for energy: electrons are said to be at different energy levels. In classical mechanics, on the other hand, container metaphors are more typical: a system contains a certain amount of energy. A detailed example of identifying conceptual metaphors in Maine middle school students’ ideas shows that these students bring to the classroom productive resources for a disciplinary engagement with energy.

6.1.1 The “indestructible, imponderable object” energy

The modern concept of energy was introduced into physics not as the result of empirical investigations alone but through careful philosophical considerations. Physicists in the early 19th century attempted to find a unifying connection between the very much established theory of forces and motion, and the still rather new theory of heat. While many agreed that heat was a form of motion\(^1\) and that it was created by mechanical and chemical processes, the quantitative nature of the relationship between heat and motion was not known (Coopersmith, 2010, p. 246). Scientists also knew that objects in motion had a property, called “vis viva”—the “living force.” After a century-long debate, physicists agreed that the quantity of this property was \(mv^2\) (G. E. Smith, 2006). Although generally assumed to be a conserved quantity, empirical results implied that this property of moving objects was not universally conserved. At the time, the word “force” was ambiguously used for both the Newtonian force concept and the developing energy concept. Thomas Young proposed a new name for “vis viva”: “energy” (Planck, 1908, p. III). However, Young’s nomenclature did not catch on for decades: Writings by contemporary

\(^1\)Others—followers of the “caloric” theory—still believed it was a fluid.
scientists still used the word “force” in the ambiguous way that must be interpreted appropriately according to the context in which it appears.

At least twelve scientists were simultaneously working on the problem of energy conservation in the first half of the 19th century (Kuhn, 1969). According to Kuhn, some of them (Carnot, Séguin, Holtzmann, Hirn) were convinced that heat and mechanical work could be transformed into each other. Others (Mohr, Grove, Faraday, Liebig) had already argued that the world could be described in terms of a unified “force,” which is manifested in various forms. In the 1840s, rigorous experiments on the equivalence between these various forms were conducted and formal derivations of a general law of energy conservation were proposed by Joule, Colding, Mayer, and Helmholtz. While Joule and Colding, both inspired by religious beliefs, independently postulated the “conservation of forces” as a way to maintain god-given order in the universe (Kragh, 2009) and performed experiments to investigate quantitative relationships between different kinds of “forces” (heat, motion, etc.), Julius Robert Mayer is commonly seen as the first scientist to formally derive a general law of energy conservation.

In his paper “Bemerkungen über die Kräfte der unbelebten Natur” (“Remarks on the forces of the inanimate nature”) (Mayer, 1874, pp. 1-12), Mayer attempted to clarify the developing energy concept, which he referred to as something “unknown, unsearchable, hypothetical” (p. 3). Using the scholastic principle “causa aequat effectum” (“cause equals effect”), he derived the conservation of energy in a logical, philosophical argument. He argued that a cause and any of its effects are merely different forms of appearance of one and the same “object” and that

\[2\text{He means by “force” what we call “energy” today; he clearly distinguishes between the two concepts, using “force” only to mean energy; for example, he writes “Fallkraft”—“falling force”—to mean potential energy, and “Schwere”—“gravity”—to describe gravitational force.}

\[3\text{...knüpft sich an die Benennung Kraft vorzugsweise der Begriff des unbekannten, unerschöpflichen, hypothetischen.”} \]
“causes are (quantitatively) indestructible and (qualitatively) changeable objects” (p. 4). According to Mayer, there have been only two kinds of causes identified in nature: matter, which has the “property of ponderability and impenetrability” and “forces” (in the sense of “energy”), which don’t have those properties but are instead “indestructible, changeable, imponderable objects” (p. 4). Mayer discusses several examples of “forces” that can be changed (or transformed) into each other. These are what we would call “energy forms” today. For example, he describes the equivalence of potential energy (“Fallkraft,” “falling force,” which he calls the energy representing spatial distance between ponderable—or material—objects, p. 5) as a cause, and kinetic energy (“Fall,” the process of “falling,” or more general “Bewegung,” “motion”) as its effect. These are only two of the manifestations he presents of the same indestructible and imponderable object, energy.

A few years later, Hermann von Helmholtz also derived the modern energy conservation law in his treatise “Über die Erhaltung der Kraft”—“On the conservation of force” (Helmholtz, 1889). Like Mayer, Helmholtz started with principles of cause and effect to develop the argument that the quantitative properties of “forces” were conserved, despite their qualitatively different manifestations (Bevilacqua, 1993). The nature of the conserved “object,” however, eluded Helmholtz, just as it did Mayer. The closest Helmholtz came to a general definition of the transcendent energy was giving it the name “Arbeitskraft”—literally “work force,” or, more adequate to its meaning, “labor power:” the power or ability to perform (mechanical) work (Rabinbach, 1992, p. 55).

4"Ursachen sind (quantitativ) unzerstörliche und (qualitativ) wandelbare Objecte."
5"Eigenschaft der Ponderabilität und Impenetrabilität"
6"Kräfte sind also: unzerstörliche, wandelbare, imponderable Objecte"
7e.g., the spatial separation of objects can result in motion of one or both objects
Even half a century later, physicists were still struggling to define what energy is: Poincaré, for example, wrote in the preface to the first edition of his 1892 textbook on thermodynamics (“Cours de physique mathématique. Thermodynamique”): “In every special instance it is clear what energy is and we can give at least a provisional definition of it; it is impossible however, to give a general definition of it. If one wants to express the law [of energy conservation] in full generality, one sees it dissolve before one’s eyes, so to speak leaving only the words: There is something that remains constant” (Poincaré, 1908, p. IX; translation adapted from Feistel & Ebeling, 2011, p. 55).

Still later, Feynman famously said, “It is important to realize that in physics today, we have no knowledge of what energy is. […] It is an abstract thing in that it does not tell us the mechanism or the reasons for the various formulas” (Feynman et al., 2011, p. 4-2). Even though energy was and is considered an imponderable concept, physicists (and scientists in other disciplines) were still able to develop a sophisticated understanding of it using methods and tools described in the remainder of this section.

6.1.2 Models as allegories: Using metaphors to understand energy

According to Clarke (2001), “Modern physics gained conceptual and technological purchase on the imponderable forms and phenomena of heat, light, gravity, and electromagnetism not by seizing reality bare-handed but, to a significant extent, through scientific allegories, that is, by constructing and investigating as factual fictions increasingly workable models of energy” (p. 18). As a matter of fact, even the name “energy” was not arbitrarily proposed by Young, but rather because of

8Dans chaque cas particulier on voit bien ce que c’est que l’énergie et l’on en peut donner une définition au moins provisoire; mais il est impossible d’en trouver une définition générale. Si l’on veut énoncer le principe dans toute sa généralité et en l’appliquant à l’Univers, on le voit pour ainsi dire s’évanouir et il ne reste plus que ceci: Il y a quelque chose qui demeure constant.”
its connotations in literary use. Energy, according to the Oxford English Dictionary, originally made its way into the English language in the 16th century (in an interpretation of Aristotle’s use of ἐνέργεια) referring to “speech or writing: Force or vigour of expression” \textbf{(energy, n., n.d.)}. At the beginning of the 19th century, the word was also used to mean “Vigour or intensity of action […] The capacity and habit of strenuous exertion,” which explains Young’s proposal to rename the “living or ascending force”: He thought the new term would “[indicate] the tendency of a body to ascend or to penetrate to a certain distance” \textbf{(Young 1807 p. 44)}.

The allegorical character of current energy models becomes apparent, for example, in my previously published descriptions of two particular models that have been proposed in the science education literature.

In [a Forms model, adapted from \textbf{(Kaper & Goedhart 2002)}], energy is described as something that objects with observable and changeable properties can have. It has different forms, each of which is associated with one of those properties. When two properties of the same object change simultaneously, energy is being transformed from one form to another. When one and the same property changes simultaneously for two different objects, it is reasonable to say that energy was transferred from one object to the other. \textbf{(Harrer et al. 2013b p. 163)}

A different model of energy, a Stores and Transfer model, places emphasis on processes of transfer and transformation \textbf{(Jewett 2008)}. The focus in this model is on storage and transfer of energy in a system. The model postulates that energy can only be stored in three stores within a system. These means of storage are associated with motion, position, and intrinsic properties like temperature and phase (for more detail see [Jewett’s] original publication). If there is an internal transfer of energy within
a system *and* from one store to another, an energy transformation has occurred. The three primary mechanisms of energy transformations are work, and chemical and nuclear reactions. Energy transfers across system boundaries may occur by mechanisms that can be categorized into six processes: work, heat, matter transfer, mechanical waves, electromagnetic radiation, and electrical transmission. (Harrer et al., 2013b, p. 164)

Both models allow a physicist (or a learner of physics) to formulate distinct narratives (“factual fiction”) of physical phenomena involving energy, and explore these phenomena within the narrative.

Fundamentally at the heart of a narrative about energy (either using one of the two presented models or an entirely different one) is the use of conceptual metaphors. In particular, the use of substance metaphors has permeated the history of the developing energy concept. Planck (1908), for example, pointed out that drawing analogical parallels between energy and matter was not only helpful in establishing acceptance of the energy concept among scientists of the 19th century; he also strongly suggested that a substance-like conception of energy, in addition to adding clarity to the abstract concept, would inspire progress in the development of energy theory that goes beyond mere quantitative considerations. Even Feynman, who has been cited on numerous occasions for his definition of the energy concept as a purely

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9. "Ohne Zweifel beruht zum großen Teil auf dieser Analogie die verhältnismäßig überraschende Leichtigkeit und die sieghafte Klarheit, mit der sich das Prinzip der Erhaltung der Energie binnen weniger Jahre die allgemeine Anerkennung eroberte und in der Überzeugung eines jeden festsetzte.” (Planck, 1908, p. 116)

abstract and mathematical principle\(^{11}\) (e.g., Arons 1999; Brook & Driver 1984; Trumper et al. 2000; Watts & Gilbert 1983), used a variety of conceptual metaphors for energy throughout his lectures, including ones that indicate the treatment of energy as a substance (Amin 2009 pp. 182-185).

6.1.3 Mark and Madison: Energy is a substance-like entity

In section 4.4.1, I identified the use of a substance metaphor as a resource that was activated by a student during an interview. I argued that the use of multiple ontological metaphors is productive for experts and students alike. According to Lakoff and Johnson (2003), “Understanding our experiences in terms of objects and substances allows us to [...] refer to them, categorize them, group them, and quantify them—and, by this means, reason about them” (p. 25). In this view, conceptualizing energy as a substance or entity enables us to treat it as a physical quantity that we can study. Lakoff and Johnson further argue that ontological metaphors can be elaborated, using so-called “structural metaphors” (p. 61) to describe a phenomenon in more detail. For example, the abstract concept “mind,” seen as an entity—as a bounded object—can be further described as a machine or as a brittle object (pp. 27-28). In the former example, “The mind is a machine” then is the metaphor that provides structure to the concept of mind using the well-structured (and more readily understood) concept “machine.”\(^{12}\) In this section, I present a detailed analysis of two students’ use of metaphors for energy. In particular,

\(^{11}\)“There is a fact, or if you wish, a law, governing all natural phenomena that are known to date. There is no known exception to this law—it is exact so far as we know. The law is called the conservation of energy. It states that there is a certain quantity, which we call energy, that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity which does not change when something happens.” (Feynman et al. 2011 p. 4-1)

\(^{12}\)This metaphor can be found, for example, in sentences like “We’re still trying to grind out the solution to this equation.” (Lakoff & Johnson 2003 p. 27)
I highlight the structural metaphors that elaborate and help us make sense of the students’ current understanding of energy.

The transcript in Datum 6.1 features Mark and Madison (see section 5.5.1), two students in Mrs. Carter’s first class, who are sitting at one of the videotaped tables (see Fig. 5.2). After several minutes of silent writing in their notebooks, they have the following conversation during the “share” phase in their Think/Pair/Share.

<table>
<thead>
<tr>
<th>line</th>
<th>speaker</th>
<th>transcript</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mark:</td>
<td>I’m done.</td>
</tr>
<tr>
<td>3</td>
<td>Madison:</td>
<td>What did you write for the first one.</td>
</tr>
<tr>
<td>4</td>
<td>Mark:</td>
<td>Uh I think energy is something that keeps something going?</td>
</tr>
<tr>
<td>5</td>
<td>Madison:</td>
<td>I think energy is like. something you need to be able to move and do things you do. and like. something that you use for electricity (and other type of) ( )</td>
</tr>
</tbody>
</table>

Datum 6.1. Mark and Madison: Entity metaphors for energy

Madison takes Mark’s utterance as a sign that he is finished with the “Think” part and asks him what he wrote for the first question, “What is energy?” The students express two similar-sounding ideas: “Energy is something that keeps something going” (Mark, line 4 in Datum 6.1) and “Energy is something you need to be able to move and do the things you do” (Madison, line 5). Madison’s addition to her idea is difficult to hear, she seems to be saying that energy is something that has to do with electricity.

Following Goodwin (1995, footnote 3), I am using transcript conventions adapted from (Sacks et al., 1974, pp. 731-733): “Talk receiving some form of emphasis is underlined. Punctuation is used to transcribe intonation: a period indicates falling pitch, a question mark rising pitch, and comma a falling rising contour, as would be found for example after a non-terminal item in a list. Comments (e.g. descriptions of relevant nonvocal behavior) are printed in italics.” In addition, overlapping speech is denoted by square brackets connecting the overlapping utterances; equal signs are used to indicate that there is no interval between the end of a prior and start of a next piece of talk; a single dash indicates that the word or syllable was cut off; a small circle before an utterance indicates that this utterance is spoken in low volume; utterances in parentheses denote uncertainty in the transcription of the utterances; empty parentheses are used to indicate that the utterance was incomprehensible and could therefore not be transcribed; omissions in the transcript are indicated by ellipses in parentheses. For increased readability and clarity, some lines were omitted from the transcript excerpts because they are not relevant to the analysis presented in this chapter. Complete transcripts can be found in the appendix.
Both students’ use of the pronoun “something” suggests an ontological view of energy as having real existence; energy to the students has the qualities of a substance or entity. Treating energy as a bounded object by using an entity-metaphor, Mark ascribes agency to it: energy “keeps something going” (Datum 6.1, line 4). The structural metaphor Mark uses is “Energy is an agent.” A metaphor that describes energy as an entity, able to act on objects or processes, was identified by Scherr et al. (2012) as a “stimulus metaphor.” Scherr et al. write about the usefulness of a stimulus metaphor in learning about energy:

The stimulus metaphor is a conceptualization that supports features valued in sociopolitical discourse, specifically the necessity of energy for sustaining activity. It also supports the idea that energy is the ‘ability to do work,’ and to some extent the causal mechanistic relationship between energy and forces. It is also problematic for this relationship in that it does not clearly differentiate energy from forces. Further, the stimulus metaphor does not support conservation: forces (or more general trigger or impetus mechanisms) can appear and disappear without constraint and do not transfer from one object to another. More generally, defining energy as the ‘ability (or capacity) to do work’ does not promote conservation, as ‘ability’ and ‘capacity’ are not easily understood as conserved quantities. (Scherr et al., 2012, p. 4)

The stimulus metaphor is remarkable in its similarity to the predominant conceptualization of “force” at the beginning of the 19th century. As history shows, thinking of energy as a cause that has an effect can be a productive starting point for the development of an understanding of energy conservation. Several curricula have been developed that use a conceptualization of energy as a cause of changes (e.g., Nordine et al., 2011; Papadouris, Constantinou, & Kyratsi, 2008).
Madison’s statement that energy is “something you need to be able to move and do things you do” (Datum 6.1 line 5) suggests that she sees the entity energy as a requirement for motion and doing in general. Madison’s use of the pronoun “you” suggests that she might be referring to energy sources that we as humans need in order to function, like food. The notion of energy as a requirement for action and Madison’s assertion that energy can be used “for electricity” (Datum 6.1 line 5) are compatible with the structural metaphor “Energy is a resource” (cf. Lakoff & Johnson, 2003, p. 65). According to Lakoff and Johnson, “A material resource is a kind of substance, can be quantified fairly precisely, can be assigned a value per unit quantity, serves a purposeful end, [and] is used up progressively as it serves its purpose” (Lakoff & Johnson, 2003, p. 65, emphases in the original). A metaphor that provides similar structure, “Energy is fuel” is described by Scherr et al. as follows:

Fuel is not energy; rather, it is a (literal) material substance that contains energy and (taken together with oxygen) can transfer that energy to other objects at a selected time. In physics, any object can possess and transfer energy. Fuel is distinctive in that the energy of interest is often chemical energy; the transfer often takes place by combustion; and the desired effect of the energy transfer is to result in mechanical work, so that the energy of interest is the ‘useful’ energy and the objects of interest are those we use as ‘power sources’ (wind, gasoline, batteries, food). The fuel metaphor is also apparent when expert physicists talk about energy being used, stored, and extracted:

We spend a tremendous amount of money to acquire and use energy.

...the elastic potential energy stored in the spring is $\frac{1}{2}kx^2$. 

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... all we would have done would be to extract energy from the reservoir at T2!

Fuel is unlike energy in that it is used up (transformed into a nonfuel substance). Nonetheless, the strong everyday association between energy and fuel may be a resource for instruction if learners can be persuaded to think of fuel as having (and giving) energy rather than being energy. The burning of fuel may also support understanding the second law of thermodynamics in that it is a compelling everyday example of an irreversible process. (Scherr et al., 2012, p. 3, citations omitted)

Conceptualizing energy as a resource or fuel is of particular value in physics because it brings with it certain productive connotations. Energy in this view is seen as measurable and therefore quantifiable, and can be assigned a numerical or qualitative value (for example usefulness, cf. Daane, Vokos, & Scherr, 2013b).

Many more examples can be found of students in Mrs. Carter's classes using various metaphors for energy. Jessica, for example, uses substance and fuel metaphors when she states that the “sun is giving us the solar energy to live off from” (Datum 6.4 line 15). Tabitha also uses these metaphors: “[when] you eat [a] banana […] your body […] turns it into […] fuel and […] energy for you […] and then […] your body uses the energies to make you move” (Datum 6.11 line 26). Later, she observes that “the tree […] absorbs energy,” again using a substance metaphor (Datum 6.12 line 51).

I maintain that the use of multiple metaphors is a disciplinary productive resource that students bring to the classroom. Energy is a phenomenon so complex that multiple, coherent but not necessarily consistent, metaphors are necessary to characterize and describe it (Lancor, 2012, p. 4). Mark and Madison’s conceptualization of energy as an entity prepares them to classify energy into different forms (see
section 6.2.2) and see energy as quantifiable. In addition, both students’ elaborations on the entity metaphor are aligned with features of the sociopolitical energy concept: “the energy used to operate electrical grids, run automobiles, etc.” (Daane, Vokos, & Scherr, 2013a).

6.2 Forms of energy: Making energy ponderable

In light of the historical-philosophical review of the energy concept in physics, I briefly review how the concept of energy forms helps physicists in their investigation of phenomena involving energy. My analysis of Maine middle school students’ classroom discourse reveals that these students activate a variety of resources that are compatible with the ways in which physicists use energy forms and can therefore be called disciplinarily productive. I illustrate this by presenting the example of Mark and Madison discussing their list of energy forms, and by analyzing a whole class list-making activity about forms of energy, during which several students activate various disciplinary productive resources regarding the nature of energy and its forms.

6.2.1 The study of energy as the study of its forms

A hallmark of common conceptualizations of energy in physics is the idea of metamorphosis (Clarke, 2001). “Energy assumed its modern scientific meaning in order to encompass the broad phenomenology of physical forms unified by the principle of the conservation of energy, also known as the first law of thermodynamics. Numerous energies are constantly being converted from one form to another, altering quality without loss of absolute quantity” (p. 20). Energy is a conserved quantity that cannot be directly perceived. We can only describe energy’s effects on our senses or measurement instruments and infer about its existence and involvement in physical
phenomena through the ways in which it manifests itself. These manifestations are “the essential determinant principles,” or “forms” (form, n. [Def. 4.a] n.d.) of energy.

The concept of energy was developed as a consequence of experimental observations, as well as scientists’ determination to find conserved quantities and to reduce their observations and findings to general principles. From the early days of energy theories, physicists have sought to identify the various manifestations of energy. While Mayer identified individual forms like “motion,” “gravity,” “heat,” “electricity,” etc., Helmholtz categorized the phenomena associated with Mayer’s forms into the two main energy forms “lebendige Kraft” (“living force”—which we call kinetic energy today) and “Spannkraft” (“tension”—potential energy) (Planck, 1908). This distinction into two basic forms of energy is still accepted in physics, today: one that is manifest in an object’s motion and another one which depends on the configuration of the constituents of a system and can manifest itself in various ways (Coopersmith, 2010, pp. 330-332).

The investigation of energy in physical systems is, to this day, an inquiry into its forms. Maxwell (1877) wrote, “in the study of any new phenomenon our first inquiry must be, How can this phenomenon be explained as a transformation of energy? What is the original form of the energy? What is its final form? and What are the conditions of the transformation?” (p. 390). McKagan et al. (2012) have proposed a definition of energy forms as “categories of mechanism by which energy acts and/or evidence for the presence of energy” (p. 280). While the latter part of this definition is aligned with the previously described view of energy forms as different perceivable manifestations, energy is typically not conceptualized as an acting entity in physics. Rephrasing the first half of the definition to “mechanisms by which energy is transformed” would make the statement compatible with Maxwell’s question “What are the conditions of transformation?”
The inquiry into energy forms is a powerful way of analyzing systems according to the fundamental law of energy conservation. Physicists propose new forms of energy when the principle of energy conservation seems violated while using only the currently agreed upon energy forms. For example, Einstein proposed the existence of rest energy in his development of the theory of special relativity. This energy form is inherent to systems for which a frame of reference exists in which the momentum of the system vanishes, and only depends on the total mass of a system, \( E = mc^2 \). In this case, energy is manifested in the mass (or inertia) of an object (Einstein, 1905).

### 6.2.2 Mark and Madison: Forms of energy are ways of using energy

In section [4.4.2](#), I characterized energy as an abstract concept that cannot be measured directly, and concluded that a students’ identification of movement as an indicator for energy involvement was a productively activated resource. After the brief review of the importance of energy forms as the perceivable manifestations of energy in physics, it is easy to see this resource as a step toward the systematic identification of energy forms and transformations in a system of interest. In this section, I present the example of Mark and Madison who productively activate resources regarding energy forms.

<table>
<thead>
<tr>
<th>line</th>
<th>speaker</th>
<th>transcript</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>Mark:</td>
<td>What are different forms of energy.</td>
</tr>
<tr>
<td>8</td>
<td>Madison:</td>
<td>I don’t know like. moving? like you know, just moving is using energy. and then um. like lights and electricity use energy.</td>
</tr>
<tr>
<td>9</td>
<td>Mark:</td>
<td>I put lights heat. but-</td>
</tr>
<tr>
<td>10</td>
<td>Madison:</td>
<td>Oh yeah. heat too.</td>
</tr>
<tr>
<td>11</td>
<td>Madison:</td>
<td>And friction.</td>
</tr>
</tbody>
</table>

Datum 6.2. Mark and Madison: Forms of energy

This episode is a continuation of the transcript presented in Datum [6.1](#). After a long pause, Mark initiates the next round of dialog by stating the second question, “What are different forms of energy” (Datum 6.2 line 7). Madison seems to express
uncertainty about her idea that “moving” is a form of energy when she starts her reply with “I don’t know” (line 8). However, she quickly gains confidence as she explains that she thinks so because “moving is using energy” (line 8). With the same reasoning, she adds “lights” and “electricity” to her list of energy forms: they both “use energy.” Mark says that he wrote “lights” and “heat” on his list and starts modifying his statement but interrupts himself before he can elaborate and starts writing in his notebook (line 9). Madison agrees that “heat” is a form of energy (line 10), and a little later adds “friction” (line 11).

The list of energy forms produced by the two students is quite impressive. “Moving,” or motion, was one of the first agreed upon (if not the first) manifestations of energy. “Light,” as a manifestation of energy, also dates back to at least the early 19th century, as do “electricity” and “heat” (e.g., cf. Mohr, 1837, reproduced in Mohr, 1869, p. 84-106). Although many documents containing learning standards for science state the identification of different forms of energy as a learning goal (e.g., Maine Department of Education, 2007; Washington Office of Superintendent of Public Instruction, 2010), the ability to list the names of certain energy forms does not show mastery of this topic. However, the familiarity with these terms—which are part of the scientific language students are expected to learn—and their use in the context of identifying energy forms can be considered a disciplinary productive resource that instructors can tap into to foster their students’ mastery of a scientific understanding of energy.

While Mark’s statement is too brief for a detailed analysis of his view on energy forms, we can infer that he might be thinking of energy forms in terms of indicators: things he can see/feel that he associates with energy. Both light and heat are phenomena that are readily perceivable, and we can assume that Mark has ample experience with them. Even though this interpretation stands on shaky grounds, the use of indicators to describe energy is productive, as I established in section 4.4.2.
Madison seems to view phenomena that “use energy” as forms of energy. She justifies “moving” as a form of energy by saying “moving is using energy.” Since according to her, “lights” and “electricity” use energy, too, both of them are then also valid forms of energy. After Mark brings up heat, she agrees that it should be on her list. I am speculating when I say that she might see “friction” as a process of heating something (the class had talked about heating due to friction in a previous PBIS unit on “vehicles in motion”). If heating something is seen as using energy, it suggests itself to describe friction as a phenomenon that uses energy, too.

The phrase “using energy” indicates a fuel metaphor: Madison seems to view energy as a fuel-like (abstract) substance that allows phenomena like motion, light, and electricity to exist and be perceived. This is compatible with the original notions of energy forms as outlined above: energy forms, like movement, light, or electricity, are manifestations of energy. Or, in other words, these phenomena could not exist without energy.\(^{13}\)

This interpretation also allows for “using energy” to mean “converting one form of energy into another” (see Stead’s characterization of the “scientists’ view” of energy, tenet (c) in section 2.3.1.1). Planck (1908), for example, wrote about “using” the motion of an object to produce a certain effect.\(^{15}\) “Moving,” in this sense, “uses energy” through the conversion of, for example, chemical energy in food into the kinetic energy of a moving body. The language “using energy” can be found in contemporary scientific publications, as well. For example, Pratt (1993) describes how the energy released by annihilating Pions can be used to raise the temperature of

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14 These considerations are based on a meaning of “use” as “to take (something) from a supply in order to function” (use, v. n.d.).

15 “Wir haben hier schon einen der oben erwähnten Fälle vor uns, wo es sich weniger um die Anerkennung der Unveränderlichkeit der Kraft handelt, als um den Äquivalenzwert dieser von beiden Parteien als unveränderlich anerkannten Größe, nämlich um das Maß der Kompensation, welche in der Geschwindigkeit eines Körpers eintritt, wenn seine Bewegung dazu benutzt wird, um eine bestimmte Wirkung hervorzubringen” (p. 10, emphasis added).
a pion condensate. van den Heuvel and Dekker (2007) observed that motor proteins can use chemical energy to perform mechanical work. In both examples, the word “use” indicates a transformation of one energy form to another.

Madison’s classification of energy forms by their use of energy is consistent with the notion of energy transformation. For example, we can describe a conversion from chemical to kinetic energy as “chemical energy was used to create the kinetic energy of a moving object.” We can also say that “electrical energy was used to create light energy” to describe the transformation from electrical to electromagnetic energy. Therefore, Madison’s way of describing energy forms can be seen as disciplinarily productive.

6.2.3 Class discussion: What are different forms of energy?

In the following, I show how students activate disciplinary productive resources while engaged in a classroom activity that asks them to create a list of energy forms. The whole class discussion was video recorded in Mrs. Carter’s first class (see section 5.5.2). After the students had finished their Think/Pair/Share in small groups, the teacher intended to collect examples for forms of energy. However, the conversation developed into a discussion about certain types of energy that can be associated with specific sources, and ended with a discussion about human energy and the difference between what energy is and what a type of energy is. Although the whole class of 15 was encouraged to participate, only four students are the main protagonists in this 3-minute episode: Jessica, Jeff, Madison, and Uli. To increase the clarity of the analysis, I divided the episode into seven topically distinct parts that each are discussed in their own subsections.

16Note, that while the abstract quantity energy is conserved and cannot be created or destroyed, a specific energy form (or manifestation) is created while another is destroyed in every energy conversion.
6.2.3.1 Jessica and Jeff: Forms of energy are sources of energy

Mrs. Carter starts her collection for answers to her second question (“What are different forms of energy?”) by asking, “How is [this question] different than our first question [what is energy]?” (Datum 6.3, line 1). Jessica offers two forms of energy that had already been mentioned in the preceding conversation as answers to the first question: electricity and movement (line 2-4). Mrs. Carter writes both down into her class notebook before Jessica adds another form of energy—“The sun”—and explains that the sun is a source—“the main source”—of energy (line 9-11).

<table>
<thead>
<tr>
<th>line</th>
<th>speaker</th>
<th>transcript</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Teacher:</td>
<td>And so now as we start to talk about different forms of energy what does that now-, how is that different than our first question. Yeah.</td>
</tr>
<tr>
<td>2</td>
<td>Jessica:</td>
<td>Umm- Oh hold on. do you want me to explain why it’s different or do you want like, different forms-</td>
</tr>
<tr>
<td>3</td>
<td>Teacher:</td>
<td>Either one. I’ll take either one.</td>
</tr>
<tr>
<td>4</td>
<td>Jessica:</td>
<td>Alright. I’m gonna do different forms. like electricity is a form,</td>
</tr>
<tr>
<td>5</td>
<td>Teacher:</td>
<td>OK? can I-</td>
</tr>
<tr>
<td>6</td>
<td>Jessica:</td>
<td>movement,</td>
</tr>
<tr>
<td>7</td>
<td>Teacher:</td>
<td>I wanna make sure I write this down OK? electricity. movement. (...)</td>
</tr>
<tr>
<td>9</td>
<td>Jessica:</td>
<td>Um. and then. the sun. sun is the main. for-. or the main. source.</td>
</tr>
<tr>
<td>10</td>
<td>Teacher:</td>
<td>Sun?</td>
</tr>
<tr>
<td>11</td>
<td>Jessica:</td>
<td>Energy source.</td>
</tr>
<tr>
<td>12</td>
<td>Teacher:</td>
<td>OK?</td>
</tr>
</tbody>
</table>

Datum 6.3. Jessica: Energy forms

Like Mark and Madison in the episode discussed above, Jessica lists electricity and movement, both accepted forms of energy, but both only mentioned by name without explanation for why they are considered energy forms. It is well established in previous literature on teenage students’ ideas about energy that electricity is often associated with energy (for a review, see Duit [1986]), possibly because of the students’ familiarity with their parents having to pay the “electricity,” “power,” or “energy bill.” “Movement” on Jessica’s list might be associated with her past experience with energy
(e.g. fuel, food) as a requirement for (a car’s or her own) movement. While she tells us herself that she thinks both electricity and movement are forms of energy, the considerations about why she might consider them to be forms has to remain speculation.

The last form of energy on Jessica’s list is “the sun.” However, instead of listing the sun as a form of energy (she seems to stumble over the word “form” as she is expressing her idea, line 9), Jessica says that the sun is an energy source, if not “the main source” of energy. The phrase “energy source” suggests the use of a substance metaphor for energy (cf. section 4.4.1) with a fuel metaphor providing structure (see section 6.1.2): Energy is not spontaneously created but can be traced back to a provider or a cause. This is compatible with the historical view of energy forms as causes that have effects (see section 6.1.1).

When Jeff proposes a name for the energy form that is associated with the sun, “solar” (Datum 6.4 line 13), Mrs. Carter announces an attempt to consolidate the two students’ ideas (line 14). Jessica elaborates briefly on what she meant by her previous statement. Although maintaining that sun and solar are the same thing, she explains that the “sun is giving us the solar energy to live off from” (line 15). Mrs. Carter’s suggests to write “Sun (Solar Energy)” in her projected class notebook, and Jessica nods in agreement (line 16).

<table>
<thead>
<tr>
<th>line</th>
<th>speaker</th>
<th>transcript</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Jeff:</td>
<td>Solar. sun is so lar.</td>
</tr>
<tr>
<td>14</td>
<td>Teacher:</td>
<td>So hold on. so we’re gonna piggy-back. we’re gonna kinda connect thoughts here. it- it felt like. so Jessica was talking about sun. Jeff throws in solar?</td>
</tr>
<tr>
<td>15</td>
<td>Jessica:</td>
<td>Cuz it’s the same thing. cuz sun is giving us the solar energy to live off from.</td>
</tr>
<tr>
<td>16</td>
<td>Teacher:</td>
<td>OK so, can I put solar energy in parentheses? or either one does that still fit? OK? Jessica nods</td>
</tr>
</tbody>
</table>

Datum 6.4. Jeff and Jessica: Solar energy
With Jeff’s suggested name for the energy form, Jessica is able to express her idea that the sun is the source of solar energy. The phrase “sun is giving us the solar energy” again uses a substance metaphor: It describes the sun as an energy giver and “us” (humans) as energy receivers. In addition, Jessica’s expression “sun is giving us the solar energy to live off from” suggests a fuel metaphor that, together with her earlier statement that the sun is the “main source” of energy, indicates that she views “solar energy” as a necessity for life on earth.

Jessica’s statement suggests that she conceptualizes energy as something that can be transported. Understanding the principle of energy conservation requires an appreciation of energy as a transferable quantity that cannot be destroyed, i.e. has to have a source. The notion of energy as something substance-like that can be transported and has a source is therefore disciplinarily productive.

After Mrs. Carter is done writing into the class notebook, Jeff offers “hydro” and “water” (Datum 6.5 line 17). Mrs. Carter tries to clarify how he thinks the two are related by asking him if she should do a similar thing as she had done for sun/solar (line 18). Jeff tells her to write “water (hydro).”

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<thead>
<tr>
<th>line</th>
<th>speaker</th>
<th>transcript</th>
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</thead>
<tbody>
<tr>
<td>17</td>
<td>Jeff:</td>
<td>Hydro. water. and hydro.</td>
</tr>
<tr>
<td>18</td>
<td>Teacher:</td>
<td>Hydro. K? hydro and you just said water. Jeff. do I do the same thing? hydro s- uh-</td>
</tr>
<tr>
<td>19</td>
<td>Jeff:</td>
<td>Water, and then-</td>
</tr>
<tr>
<td>20</td>
<td>Teacher:</td>
<td>Water and then hydro. gotcha. K. types</td>
</tr>
</tbody>
</table>

Datum 6.5. Jeff: Hydro energy

The pattern matches the one above where solar was the form of energy with the sun as the source. In this case, hydro seems to be the form of energy, and water the source. Unlike the previously mentioned forms electricity and movement, the newly recorded forms solar and hydro are explicitly associated with specific objects that have been identified as sources for the respective form. While Jessica sees solar
energy as the requirement for life on earth, we can speculate that Jeff might view solar and hydro energy from a perspective of power generation. After all, the terms solar and hydro are most often associated with so-called alternative energy sources (sun and water).

The interaction between Jeff and Jessica, moderated by Mrs. Carter, seems to have established, if only for a brief moment, a pattern for answers to the question “What are different forms of energy?” Answers that match this pattern include not only a name for the form but also an associated object, the energy source. In contrast to Madison’s categorization of energy forms as ways of using energy, Jessica and Jeff seem to think of energy forms as energy sources or at least as being associated with certain objects that act as energy sources. The two forms Jessica mentioned before fit into this way of categorizing energy forms: electricity is a source of energy for almost any modern technological device. Movement, in turn, can be a source of (i.e. can be transformed to) electricity.

Up until now, Mrs. Carter has acknowledged and written down “electricity” and “movement” as forms of energy, and a little discussion about “sun” vs. “solar” has resulted in her writing “sun (solar)” into the notebook. Another result of this discussion was the contribution “water (hydro)” to their list. The discussion about the connection between the sun and solar energy, though facilitated by Mrs. Carter’s question about the connection between the two thoughts, has been negotiated and elaborated mostly by the two students, Jessica and Jeff. The teacher only writes down a shorthand for the result of the discussion. Jeff’s contribution of water and hydro is not explicitly investigated. Mrs. Carter’s question about how she should write the two words down, seemingly in an attempt to make the notation of the energy forms solar and hydro parallel, implicitly asks for clarification about the relationship between water and hydro. However, it is never made explicit in the class dialog whether Jeff sees water as a source for hydro energy as implied above.
6.2.3.2 What about Heat and Plasma?

Madison then proposes “heat” as another form of energy, at first very quietly (Datum 6.6, line 22); then, after the teacher’s bid for clarification (line 23) louder, with a question-like prosody. While Mrs. Carter types this energy form into her projected class notebook (line 25), Jessica mutters that heat “is also made out of a couple of things” (line 26).

<table>
<thead>
<tr>
<th>line</th>
<th>speaker</th>
<th>transcript</th>
</tr>
</thead>
<tbody>
<tr>
<td>22</td>
<td>Madison:</td>
<td>um heat?</td>
</tr>
<tr>
<td>23</td>
<td>Teacher:</td>
<td>Say that again, I’m sorry.</td>
</tr>
<tr>
<td>24</td>
<td>Madison:</td>
<td>Heat?</td>
</tr>
<tr>
<td>25</td>
<td>Teacher:</td>
<td>Heat. types</td>
</tr>
<tr>
<td>26</td>
<td>Jessica:</td>
<td>Heat is also made out of a couple of things</td>
</tr>
<tr>
<td>27</td>
<td>Teacher:</td>
<td>Heat. OK.</td>
</tr>
</tbody>
</table>

Datum 6.6. Jessica: Heat is made up of “things”

I already presented my analysis of Madison’s ideas about energy forms, including heat, above (see section 6.2.2). Here, I focus on Jessica’s comment: “Heat is also made out of a couple of things.” It seems like Jessica is concerned that heat might, just like solar and hydro, need some more explanation, maybe an associated object as a source. She seems to think that there are several “things” associated with heat. The phrase “made out of” further suggests a substance and entity metaphor: heat as a compound object. Since Jessica’s statement is not followed up on during the discussion, we do not have any further information about her understanding of heat.

Jeff tries to add “human energy” to the list of energy forms (Datum 6.7, line 28) but Uli had raised his hand and caught Mrs. Carter’s attention first (line 29). Uli’s contribution of “plasma” (line 30) is greeted by the teacher with the question whether he thinks “plasma” is a form of energy (line 31). Uli affirms that (line 32) and Mrs. Carter types it into her class notebook (line 33). While Jessica interjects something, almost to herself and barely audible (line 34), the teacher seems to be uncertain.
how to respond to Uli’s “plasma.” She is silent for several seconds, looking into Uli’s general direction, and eventually asks again if he thinks plasma is a form of energy (line 35). When Uli answers again affirmatively (line 36), Mrs. Carter accepts his answer and goes on to call on another student (line 37). Jessica’s comment went unnoticed.

<table>
<thead>
<tr>
<th>line</th>
<th>speaker</th>
<th>transcript</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>Jeff:</td>
<td>°Human energy.</td>
</tr>
<tr>
<td>29</td>
<td>Teacher:</td>
<td>Uli.</td>
</tr>
<tr>
<td>30</td>
<td>Uli:</td>
<td>Plasma?</td>
</tr>
<tr>
<td>31</td>
<td>Teacher:</td>
<td>Plasma. So Uli’s throwing out- is that a type of energy?</td>
</tr>
<tr>
<td>32</td>
<td>Uli:</td>
<td>Si. Yes.</td>
</tr>
<tr>
<td>33</td>
<td>Teacher:</td>
<td>So Uli’s thinking of plasma as type of energy? OK? types</td>
</tr>
<tr>
<td>34</td>
<td>Jessica:</td>
<td>°But the difference between ( ) is what we can ( )</td>
</tr>
<tr>
<td>35</td>
<td>Teacher:</td>
<td>As a different form Uli. plasma is a form of energy?</td>
</tr>
<tr>
<td>36</td>
<td>Uli:</td>
<td>Yeah. I think so.</td>
</tr>
<tr>
<td>37</td>
<td>Teacher:</td>
<td>You think so. OK. points at Jeff</td>
</tr>
</tbody>
</table>

Datum 6.7. Uli: Plasma energy

Plasma, in a scientific sense, describes a state of matter, not a form of energy. It seems as if Mrs. Carter is encouraging Uli to reconsider his answer by repeatedly asking him if he thinks plasma is a form or type of energy. Uli remains firm in his answer that he thinks plasma is a form of energy. Instead of asking Uli about why he thinks plasma is a form of energy, Mrs. Carter eventually accepts it as an answer and writes it down. This is consistent with her statement at the beginning of the activity that any answer is valid in this setting and that there won’t be any “wrong” answers. However, from a disciplinary perspective, “plasma” was inappropriately activated in this context. This particular resource (“plasma is a form of energy”) can therefore not be seen as disciplinarily productive.

6.2.3.3 Human Energy: Energy Forms vs. Energy

Jeff had already mentioned “human energy” before, but Mrs. Carter apparently had not noticed that. When called upon by the teacher, he brings it up again
The ensuing discussion seems to follow up on the teacher’s initial question of this episode: “And so now, as we start to talk about different forms of energy, what does that now—how is that different than our first question?”

Mrs. Carter’s question “What do you mean by [human energy]?” marks the first time she explicitly inquires into a students’ idea in this episode. Jeff replies, “the energy in humans” (line 40), which suggests that he thinks of energy as something that can be contained in objects. Jeff is not the only student who answers to the teacher’s request for more information: Jessica replies, too, although her answer is not completely audible to me (line 41). Based on an earlier comment by her (not part of this episode) and her fanning herself with her hands while speaking, I infer that her response might have to do with thermal energy, and the heat humans give off. Mrs. Carter seems satisfied with the response(s) to her question, and observes “we’re going back to energy within humans” (line 42). “Back” seems to refer to conversations she has overheard during the think/pair/share since human energy did not come up during the class conversation, so far. Mrs. Carter follows up by asking whether Jeff thinks “human energy” is a form of energy or an answer to the question of what energy is (line 42). Jeff responds, “A form” (line 43) but Jessica does not seem satisfied: To her, “human energy” could be filed under both questions (lines 45, 47, 51). Jeff, however, thinks of “human energy” as a form and points out that they’re trying to answer the question about energy forms (lines 46 & 49).

“Human energy” in the vitalistic sense of a “life force” has been criticized since the early 19th century and was debunked using the theories developed by pioneers like Mayer and Helmholtz (e.g., cf. Mayer [1874] pp. 53-59). However, in the sense of “energy in humans,” and especially in the form of heat (as Jessica’s gesture seems to suggest), Jeff’s proposal has disciplinary value. While humans are not manifestations of energy and “human energy” therefore is not compatible with the definition of energy
forms proposed above, human energy could be seen as a summary term for the many forms of energy that can occur within the human physiology. The term “human energy,” then, becomes similar to the scientific term “mechanical energy,” which encompasses kinetic and potential energy in a system.

The phrases “energy in humans” (Mark, line 40), “energy within humans” (Mrs. Carter, line 42), and “energy within us” (Jessica, line 45) suggest a container metaphor for energy. Energy as a substance that can be contained in objects has been described as a conceptualization of energy that physicists make use of for contemplating “isolated or very well defined systems” (Lancor, 2012, p. 11). In these situations, the substance and container metaphors provide tools for reasoning about energy quantitatively. Conceptualizing energy as a localized quantity using a container metaphor is part of a powerful energy model that allows a scientist to apply the principle of energy conservation in order to identify transfers and transformations of energy within and across systems (Scherr et al., 2012, pp. 4-5).
Jessica’s statements that human energy is a form of energy, but that “energy within us can also [. . .] be energy” (line 45) suggests that she makes an ontological distinction between forms of energy and energy. She seems to be thinking of ‘energy’ and ‘forms of energy’ as different things, as evidenced by her apparent difficulty to reconcile ‘human energy is a form of energy’ with ‘human energy is energy.’ As I elaborated above, there is an important ontological difference: energy forms are perceivable manifestations of the abstract but conserved quantity energy. Historically, only a long debate about empirical results and philosophical considerations allowed physicists to articulate this distinction. Jessica’s struggle with the classification of human energy therefore can be seen as a productive way of scientific engagement with energy.

6.2.3.4 Energy silos

This class discourse shows signs of struggle with a deep philosophical question about energy that could be used for a productive discussion about the nature of energy. Mrs. Carter concludes the dispute between Jessica and Jeff by giving her own interpretation of what Jessica is trying to say (Datum 6.9, line 52). After several false starts, she says that Jessica maybe was thinking of “What is energy?” as a very broad question that asks about “all energy.” Forms of energy, then, are essentially different silos in which energy can be put. This suggests a substance and a container metaphor: Energy can be put into (transferred to) and stored in containers. The next sentence “you probably would have it within this big definition, it just would be in a different category” also uses a container metaphor. With this metaphor, human energy on the one hand is energy, but on the other hand also is a container in which energy can be stored.

Throughout Mrs. Carter’s interpretation of Jessica’s utterances, Jessica is slightly nodding, seemingly agreeing with what her teacher is saying about her thinking. The
Datum 6.9. Mrs. Carter: Energy silos

Teacher: OK I hear- I think I hear what you’re saying Jessica, so what I’m- I think I hear you saying, is that Jessica is basically saying that this is such a broad question? that by asking what is energy, you’re gonna talk about all energy? and then what types is kinda like putting them in silos. So you probably would have it within this big definition. it just would be in a different category. Is that what I’m hearing you say. OK. So what Jessica is saying is that there is some broad understanding, forms are trying to get it into categories.

nod seems not entirely convincing to me (possibly because it is only a slight head movement and not a vehement agreement). However, Jessica starts nodding before Mrs. Carter looks back at her and explicitly asks her if what she had inferred is indeed correct. This suggests that Jessica at least agrees with the contents of what her teacher says about energy.

6.2.3.5 Review: Disciplinary productive resources in a list-making activity

Although the activity was largely framed as creating a list of names for energy forms, the students participating in the discussion activated a variety of disciplinary productive resources related to energy. Some of these resources concerned the ontology of energy. Students saw energy as a substance-like quantity that can be contained in objects. Some of these objects were considered energy sources, which implies a view of energy as a transferable quantity. The students categorized energy forms according to the source-objects they associated these forms with, activating a different set of productive resources for disciplinary engagement with energy. Finally, students struggled with the ontological distinction between energy and its forms, which led to a working definition of energy forms that was proposed by the teacher.

Resources, just like energy, are manifested in various ways. The analysis in this section showed a variety of examples for manifestations of similar resources, for example the use of a substance metaphor, in students’ discourse. In the remainder of
this chapter, I present another detailed analysis of a classroom discussion in which I find more instances of productive resources for disciplinary engagement with energy.

### 6.3 Mechanistic reasoning with energy: From kinetic to solar with monkeys and bananas

The importance of mechanistic reasoning in science, especially in physics, was already discussed in section [4.4.3](#). In the context of energy specifically, physicists seek mechanisms of energy transfers and transformations within and across system boundaries, as has already been alluded to above. Jewett ([2008](#)), for example, identified five different mechanisms of energy transfer—work, heat, matter transfer, mechanical waves, electromagnetic radiation, and electrical transmission—and three different mechanisms of energy transformation (which he defines as a transfer of energy between objects within a system): internal work (done by one component of a system on another), chemical reactions, and nuclear reactions.

According to Craver ([2002](#)), mechanisms are hierarchically nested. Jewett’s mechanisms, for example, can be considered “higher-level” mechanisms of energy transfers and transformations, which can be described by “lower-level” mechanisms (pp. 69-70). Much research in physics is devoted to identifying and describing these lower-level mechanisms of energy transfers (e.g., the specific mechanisms of excitation energy transfer; [Kasha](#) [1963](#) and transformations (e.g., mechanisms of energy transformation in molecular motors; [Vologodskii](#) [2006](#)).

Russ et al.’s ([2008](#)) coding scheme (see section [4.4.3](#)) does not account for levels of hierarchy. Since I am using their characteristics of mechanistic reasoning in my evaluation of disciplinary productive resources, I do not attend to hierarchy, either. However, as will become apparent in my analysis below, the students’ mechanistic accounts of energy transfers and transformations are at a lower level than Jewett’s
proposed mechanisms; i.e., students describe transfers and transformations in more specific terms than “heat,” “work,” etc.

In this section, I present the analysis of a classroom discussion about energy forms in Mrs. Carter’s third class (see section 5.5.3). During this whole class conversation, the students used productive resources regarding the ontology of energy and forms of energy to co-construct a mechanistic explanation for how energy from the sun allows a monkey to run around in the jungle. My analysis shows that some of these resources can not be attributed to individual students, but instead are manifested in and span across the interactions of multiple interlocutors. I also argue that the resources were activated in the pursuit of a shared goal, which makes them not only disciplinarily but also situatedly productive.

6.3.1 A running monkey as an example for kinetic energy

Similar to the previous episode from class 1, this whole class conversation takes place during class 3’s discussion about the question “What are different forms of energy?” A student, Tabitha, had suggested “magnetic and kinetic” as two different forms of energy. Mrs. Carter had asked for clarification about “magnetic,” when several students responded to “kinetic.” Eaton said he “remember[s] kinetic from sixth grade” and Liz said that “kinetic is movement.” Nobody seemed to respond to Eaton’s or Liz’s statements. Liz’s gestures after her initial utterance suggest that she had engaged with the teacher’s question for clarification. Eaton started to tell his story (“In sixth grade, we did-”) but interrupted himself just when the teacher started to respond to Liz’s gestures. When Mrs. Carter is finished typing on her laptop, she asks for clarification about “kinetic,” a type of energy that has been suggested by Tabitha.

Eaton responds to the teacher’s bid for clarification (in Datum 6.10, line 1) and continues to tell his story that he had started before. He brings up the example
of a monkey that is “running around” (Datum 6.10, line 2). Liz classifies “running around” as “movement” (lines 5-6) and Eaton agrees with Liz’ classification (line 8).

Datum 6.10. A running monkey as an example for kinetic energy

Eaton suggests a particular scenario involving kinetic energy, a running monkey who eats bananas. The monkey and its actions running and eating are observable physical phenomena within a physical scenario. As shown in section 4.4.2 physicists seek to connect abstract, theoretical constructs like energy to observable phenomena or indicators. Therefore, this is a valuable/desirable resource, especially in the context of PBIS, which emphasizes reasoning about energy using indicators (see section 6.4).

When the students were discussing the question “What is energy,” “movement” was identified as an indicator for energy. Just before this episode, Liz directly made the connection between “movement” and “kinetic energy.” These previous attempts of identifying movement with kinetic energy paved the way for the current discussion. In addition, a term for the form of energy associated with movement was suggested.

Liz classifies the monkey’s “running around” as movement, a more general concept that has already been established as connected with energy. Classifying phenomena according to certain characteristics is another practice among physicists (for example the classification of energy in terms of its manifestations or forms). It enables us to connect these phenomena to physical quantities, as has been done in this case by the students. In addition, the negotiation of a common language that includes specific
terms for physical quantities and phenomena is an important part of scientific model building.

The agreement that the “monkey […] running around” (line 2) is a particular case of the phenomenon movement, which has been linked to energy and the possibility of naming this particular kind of energy “kinetic” can be taken as the outcome of this part of the conversation. The collaborative achievement of this outcome makes the identified resources situatively productive (see section 3.3).

6.3.2 Something is transformed and transported from the banana to the monkey: Energy

Without hesitation, Mrs. Carter takes up Liz and Eaton’s suggestion of movement as a type of energy and starts taking notes on her laptop (Datum 6.11, line 9). Brighton’s reminder that the monkey is also eating bananas (line 10) causes the teacher to initiate a new conversational sequence with a request to elaborate on bananas in the context of the conversation, energy (lines 12 & 14). Eaton and Liz respond to this request simultaneously. They both seem to classify “banana” as food (lines 15-16).

Since all microphones were closer to Liz at that moment, it is hard to understand Eaton’s utterance. Negotiations with fellow researchers have resulted in the parenthetical wording of line 15 in the transcript. Eaton seems to be referring to a transfer (of energy?) from the banana to the monkey, evidenced by his left hand’s gesture that indicates directed movement from left to right and the teacher’s response in line 19. She refers to the idea of “transfer” as a new thought that she intends to associate with the first question, “What is energy?”

Tabitha responds to these connections between food, transfer, and energy by placing a bid to enter the conversation: she raises her hand and utters that she “know[s] the energy cycle” (lines 18 & 20). She lowers her hand after Mrs. Carter
tells her (and her neighbor) to wait with their contributions. After the teacher has placed another bid for clarification on the topic “banana,” Tabitha requests to be heard again by raising her hand. When the teacher signals her readiness to hear Tabitha’s contribution, the student offers a description of the relationship between eating a banana and movement (line 26).  

Mrs. Carter suggests an inference from Tabitha’s explanation: a banana contains energy. Eaton agrees with this interpretation, which causes the teacher to ask if she can write this new insight down in her projected lab notebook. She summarizes the previous part of the conversation as having “identified a form” (Datum 6.11 line 36). Bruce seems to want to clarify by asking if a form has to do with where the energy gets used. Mrs. Carter starts speaking before she can hear Bruce out and steers the conversation away, joking about a “banana phone” (omitted from the transcript). While still joking, she starts typing on her laptop, rendering her question about where to write in her notebook rhetorical. She then acknowledges that the class seems yet unsure about how to categorize “energy in the form of a banana” (line 42). This phrasing is different from her question whether a banana has energy: the banana as an object that can contain energy became the banana as a form of energy, reflecting the general unsureness of how to classify “banana.”

During this segment, the connection between a banana and movement is explored in an act of communal inquiry. First, a banana is classified as food by several students (lines 15 & 16). With this generalization from a concrete instance—the banana—to the more abstract concept of food, the students seem to propose a connection between food and energy, similar to Liz’ earlier classification of “running.”

17 This utterance is interrupted several times by the teacher who is asking if the ideas in the conversation so far originated in an earlier life sciences class (the question is answered positively by several students) and praising these ideas by telling them their former teacher would be proud if she could witness the conversation (interruptions omitted in Datum 6.11). Tabitha’s explanation seems to be attended to and non-contested by her classmates. She seems eager to finish her account despite the frequent interruptions, which suggests high confidence in her idea.
<table>
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<tr>
<th>line</th>
<th>speaker</th>
<th>transcript</th>
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<tbody>
<tr>
<td>9</td>
<td>Teacher:</td>
<td>So some movement? the monkey is moving? starts typing</td>
</tr>
<tr>
<td>10</td>
<td>Brighton:</td>
<td>And eating the bananas.</td>
</tr>
<tr>
<td>11</td>
<td>Teacher is still typing</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Teacher:</td>
<td>Um bananas.</td>
</tr>
<tr>
<td>13</td>
<td>Teacher:</td>
<td>students laugh midway through this pause</td>
</tr>
<tr>
<td>14</td>
<td>Teacher:</td>
<td>Some thoughts on that?</td>
</tr>
<tr>
<td>15</td>
<td>Eaton:</td>
<td>(It’s food. it gives it to the monkey) left hand gesture</td>
</tr>
<tr>
<td>16</td>
<td>Liz:</td>
<td>It’s food. it’s food.</td>
</tr>
<tr>
<td>17</td>
<td>Teacher:</td>
<td>OK? so we’re s- can I can I go back up to what is energy=</td>
</tr>
<tr>
<td>18</td>
<td>Tabitha raises hand, gasps</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Teacher:</td>
<td>=and now I’m gonna.put the word transfer? cuz it sounds like you’ve just=</td>
</tr>
<tr>
<td>20</td>
<td>Tabitha:</td>
<td>Oh, I know the energy cycle.</td>
</tr>
<tr>
<td>21</td>
<td>Teacher:</td>
<td>=added a new thought. can y- ladies hold on.</td>
</tr>
<tr>
<td>22</td>
<td>Tabitha lowers her hand</td>
<td></td>
</tr>
<tr>
<td>23</td>
<td>Teacher:</td>
<td>So? um some transfer of this energy? types and I'm still stuck on my banana.</td>
</tr>
<tr>
<td>24</td>
<td>Tabitha raises hand; Teacher points at her</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>Tabitha</td>
<td>OK, what happens is? like you eat the banana and then (...) like your body like turns it into like fuel and like energy for you? and then (...) then you u- your body uses the energies to make you move and stuff.</td>
</tr>
<tr>
<td>26</td>
<td>Teacher:</td>
<td>Okay, so it- so it sounds like a banana has energy?</td>
</tr>
<tr>
<td>27</td>
<td>Eaton:</td>
<td>Yes.</td>
</tr>
<tr>
<td>28</td>
<td>Teacher:</td>
<td>Can I put that somewhere? cuz w- we’ve kind of identified a form</td>
</tr>
<tr>
<td>29</td>
<td>Bruce:</td>
<td>Where you use it?</td>
</tr>
<tr>
<td>30</td>
<td>Teacher:</td>
<td>It sounds like- anyway, a banana? (...) types</td>
</tr>
<tr>
<td>31</td>
<td>Teacher:</td>
<td>Something about energy in the form of a banana? may- we don’t exactly know how to categorize a- b- boy so it sounds like some- something that we could=</td>
</tr>
</tbody>
</table>

Datum 6.11. Energy transfer from the banana to the monkey as movement. Eaton’s statement “It gives it to the monkey” (line 15) suggests he means something that is contained in food and can be transferred (or given to) the monkey from the food.

Prompted by the considerations about a transfer of sorts, Tabitha describes how a banana is “turned” into “fuel” and “energy” by the human (“your”) body after it is eaten so that the energy can be used for movement (and other things). This explanation of how a banana is related to movement is mechanistic ([Russ et al. 2008](#)): it is non-teleological (not defined by the outcome of the process), causal (it describes “the process of how a cause [eating a banana] brings about an effect [movement]” [Schauble 1996](#), p. 112; emphasis in the original), seems built from experience (“you
eat the banana,” “your body,” etc.; emphases added), and describes an underlying structure (metabolism).

Mrs. Carter eventually summarizes that “a banana has energy” (line 34). The phrase “has energy” suggests that energy is something that can be possessed or contained, but also can be given (transferred), for example, to the monkey. The teacher’s suggestion is a culmination of the discussion so far, with the participants agreeing that a banana has something to do with energy. Whether or not a banana is a valid energy form has not been decided, yet.

Notably, no individual conversation participant expresses the idea that energy is a substance-like quantity that is contained in the banana and can be transferred and transformed into movement by a human body (e.g., Tabitha’s mechanistic account does not contain the idea of energy transfer or the idea that a banana contains energy). Instead, this idea spans across several utterances by different students and the teacher. While aspects of this idea were contributed by individuals who activated disciplinary (and situated) productive resources, the resulting resource “food as an energy source for movement” emerges from the interactions of the entire group.

6.3.3 From the sun: Tracing banana energy back to its origin

Cutting into Mrs. Carter’s last utterance (Datum 6.11, line 42), Buffy starts a line of reasoning about a connection between energy and bananas (Datum 6.12 line 43). Her question if bananas come from trees is taken seriously by the teacher and positively answered. Buffy continues her inquiry by reaffirming that bananas do come from trees and adds “something from (...) the ground” (line 46). She tries to pursue that idea but cuts herself off before she states that “trees make their own f-,” (line 48) seemingly referring to the metabolism of a tree. Her speech pattern and the utterance “I’m so confused” at the end of line 48 indicate an invitation to other participants of the conversation to join her in her inquiry. Bruce responds
by suggesting “the seed” as the “something from ( . . . ) the ground” (line 47) but is ignored by Buffy. Tabitha signals her readiness to contribute to Buffy’s inquiry by raising her hand but before she is allowed to speak, the teacher responds.

Mrs. Carter launches into a pep talk that acknowledges the students’ attempt to make sense of phenomena related to their lives as good, but reminds her students that they’re currently seeking connections to physical science and energy in particular (line 50).

After being invited to speak again by Mrs. Carter, Tabitha adds a new detail to Buffy’s description and proposes a mechanism: a tree “absorbs energy” (line 51). Liz starts to elaborate this idea but gets cut off by the teacher who starts to summarize the new idea. She gets in turn cut off by Liz and Eaton who compete to add details to the mechanistic explanation and say that the energy that the tree absorbs originated from the sun (lines 54 & 55). Eaton repeats Liz’ “From the sun” (line 56) and adds that the tree “makes the sugar and then it makes the banana” (line 56), adding another detail to the mechanistic description, the process in which the tree absorbs energy from the sun. At the same time, Eaton refers back to the banana, completing the story about how energy originates in the sun and ends up in the banana.

Bruce classifies the form of energy as “solar” (line 57), referring back to the original question about different forms of energy, while Buffy terms the process whose mechanistic description had just been communally constructed “Photosynthesis” (line 58).

An outcome of the second part of the analyzed episode is the shared understanding that a banana contains (“has,” Datum 6.11, line 34) energy. The class engages in an inquiry about how it is that a banana has energy. In the process of negotiating a mechanistic explanation for this, the students show valuable conceptual resources about energy involved in plant metabolism. Trees absorb energy that originated from the sun (energy source) and use it together with something from the ground
Datum 6.12. Energy transfer and transformation chain: From the sun to the banana to make sugar and bananas. Energy is recognized as originating from a source, the sun. It is also recognized as a crucial ingredient in the creation of sugar, a chemical process (photosynthesis).

Energy is again seen as something that can be transferred from one object to another (given off by one object and absorbed by another), as well as something that can be used to make something happen (ability to do work/cause change). In addition to the outcome of a communally negotiated understanding of the mechanism of storing energy in a banana, another outcome is the negotiation of a technical term (“solar”) for the energy that originated from the sun (this subsequent negotiation is not part of this analysis).

The pursuit of a mechanistic explanation for how energy from the sun is stored in a banana, and subsequently transformed by the body of a monkey to make the monkey run is not the effort of an individual interlocutor. Instead, all participants
in the conversation contribute to the developing idea about the energy flow from the sun to the monkey. The resource “mechanistic reasoning,” therefore, can not be attributed to an individual in this case but emerges from the interactions between all the participating class members.

6.3.4 A mechanistic account for how energy from the sun makes a monkey run

In this episode, the class negotiated the following semi-mechanistic energy story. Solar energy is a type of energy that originates with the sun. Here on earth, trees absorb this energy and use it, together with something from the ground to make sugar and then bananas in a process called Photosynthesis. Because of this, we can say that there is energy contained in a banana. When a monkey eats a banana, its body turns the banana into fuel and energy, which can be used by the monkey’s body to make it move. This movement is an indicator for the monkey’s kinetic energy.

Using the previously described coding scheme (Russ et al., 2008, see also section 4.4.3), the explanation is mechanistic because the students

- describe the target phenomenon: the running monkey;
- identify setup conditions: energy has to come from the sun;
- identify entities: sun, trees, bananas, monkey;
- identify activities: trees absorb energy, and make sugar and bananas, the monkey eats the banana, its body turns it into fuel and energy, and uses this energy to move; and
- identify properties: the banana has energy, energy can be used for movement.

Note that the conversation began with kinetic energy and ended with solar energy. The sequence of the students’ inquiry happened in the reverse order of the story that they create.
While the organization of entities is not specifically addressed (although implicit: the sun is in outer space, the tree on earth, the banana on the tree), there is implicit chaining of the events: the solar energy has to be absorbed by the trees and transformed into energy that can be stored in a banana before the monkey can eat the banana and use the energy that was stored in the banana to run around.

This story contains some inaccuracies and may be missing some details. However, it is a remarkable account of an energy transfer/transformation chain that contains many valuable insights about energy that can be seen as productive resources for the learning of energy.

Even though many of the identified resources could be attributed to individual students, some resources emerged from the interactions between these individuals and therefore “belong to the group.” In particular, I highlighted the declarative knowledge piece “food as an energy source for movement” and the procedural resource “mechanistic reasoning” as resources that were activated by the group.

All the resources identified in this analysis were activated in the pursuit of the mechanistic explanation summarized above. The sequence of resources that were activated by individuals and by the group as a whole allowed for significant disciplinary progress toward this mechanistic explanation. Therefore, the resources identified in this section can be considered to have been situatedly productive.

6.4 Productive resources for PBIS: Energy

In a recent publication (Harrer et al., 2013b, pp. 162 & 163), I have analyzed the language used in the textbook Project-Based Inquriy Science: Energy (Kolodner et al., 2010b, pp. 3-18), to present the conceptualization of energy that PBIS pursues as a learning goal:
**Objects have energy.** The phrasing of questions like “Do you think the soccer players have enough energy to play harder?” or “How can you know if the oven has enough energy to finish baking the cupcakes?” (pg. 3, emphases added) suggests to students that objects can have energy. The teachers’ guide reinforces this notion by stating that the students “will learn to observe items that have energy” (Kolodner et al., 2010a) (pg. 22, emphasis added).

**Energy has different types.** Emphasis is placed on the idea that energy has many different types (“In this Unit, you will learn how to identify […] many different types of energy”, pg. 3). For example, there are the energy a child has, energy that is released by light bulbs, energy a battery has, or energy that makes a car move (pg. 5).

**Energy can be transformed and transferred.** One of the most important aspects of energy in PBIS is that it can be transformed from one of these types into another. For example, “In a flashlight, a battery’s energy is transformed into the energy released by a light bulb” (pg. 5). Questions like “Where does this energy come from, and where does it go?” (pg. 3) suggest that energy can also be transferred from one place to another.

**Energy involves change.** In the beginning of the energy unit, students are encouraged to think of energy as “the ability to cause change” (pg. 4). Changes in objects are to be considered indicators for energy transformations (pg. 8).

This conceptualization is similar to Kaper & Goedhart’s (2002) proposed “Forms” language (see section 6.1.2). In particular, energy in PBIS is described as something that objects can have. Energy and especially its various forms are related to changes
in objects. Certain changes are indicators for energy transformations. Others are indicators for energy transfers. Mechanisms of energy transfers and transformations are not part of the description of energy presented in the PBIS: Energy textbook.

While some of the resources I identified in Maine middle school students’ discourse about energy are very much aligned with PBIS’s conceptualization of energy, others go beyond this purposefully simplistic energy model. I have found students to conceptualize energy as a substance-like quantity that can be contained in objects, can be categorized into various types (manifestations—forms—but also categories of energy, for example, “human energy”), and that can be transformed and transferred. Energy is sometimes considered to be the cause of phenomena—it involves change. Students readily identify indicators for energy involvement, sometimes without specifically articulating what changed about an object (e.g., movement is an indicator for energy involvement, even if it is not explicitly mentioned that an object changes its position through this movement).

In addition to resources that can be productive for an understanding of the PBIS model of energy, students also brought disciplinary productive resources for mechanistic reasoning to the classroom. These resources will become useful in later units of the PBIS: Energy curriculum, in which the students are asked to explain the energy transfers and transformations that occur in experiments conducted by the students. Besides these features of a scientific conceptualization of energy, students’ ideas about energy contained notions about a socio-political energy concept, especially when describing energy in terms of something that can be used (fuel metaphor).
In Chapter 3, I defined disciplinary productive resources as appropriately activated pieces of declarative and procedural knowledge in certain contexts. It is the responsibility of the researcher (or teacher) to judge the appropriateness of the activation in lieu of the scientific community. To this end, I gave a historical-philosophical review of the development of the energy concept in physics. I showed how this concept is abstract in that it is impossible to define it operationally without regard to its manifestations, or forms (Scherr et al., 2013, p. 1). However, I was also able to show that the energy concept in physics is multi-faceted and conceptualizations of energy are context-dependent. By comparing elements of students’ ideas expressed in naturally occurring classroom activities with the considerations, practices, and achievements of physicists developing the energy concept throughout history, I was able to identify disciplinary productive resources that were activated by students. In particular, I found that students use similar metaphors to describe energy (e.g., substance and entity metaphors), categorize energy forms according to certain rules (e.g., energy forms as ways of using energy), struggle with the ontological distinction between energy and its forms, and reason mechanistically about energy in physical scenarios.

Besides disciplinary productive resources that were activated by individual students, I also found evidence for resources that were irreducible to individuals. These disciplinary productive resources were activated in the interactions of groups of interlocutors. For example, the declarative resource “food (for example a banana) contains the substance-like quantity energy that can be transferred to a living body and transformed into movement” emerged from the interactions of several students and the teacher while co-constructing an explanation for how a banana allows a monkey to run around.
In section 6.3 I particularly highlighted how the identified disciplinary productive resources were activated (whether by individuals or groups) in the pursuit of a common goal: to find an explanation for what role energy plays in the scenario of a running monkey. The class made significant disciplinary progress during the episode. Initially, a student merely mentioned that a running monkey might have to do with kinetic energy. In the end, the class had co-constructed a mechanistic account for how energy originates from the sun and undergoes a chain of transfers and transformations to enable the monkey to run. Every activated resource contributed to the progress toward this outcome and can therefore be seen as situatedly productive.

Lastly, I presented an analysis of the language PBIS: Energy uses to introduce the concept of energy and compared the identified student-activated resources with the results of this analysis. I found that many of the resources were aligned with the conceptualization of energy in PBIS: Energy and therefore provide a productive basis for the students’ achievement of the curriculum’s learning goals about energy. This basis is strengthened by resources that go beyond the basic energy model and will help students productively reason about energy in future activities involving empirical investigations to further explore the concept of energy.
Chapter 7
CONCLUDING REMARKS

7.1 Introduction

For over thirty years, there have been efforts to improve science education on the topic of energy to effectively prepare future generations of responsible, energy-conscious citizens. Much of the recent work in this area has been based on thirty-year-old basic research on students’ ideas and pre-instructional conceptions about energy. However, newer findings about conceptual change and modern models of knowing and learning are challenging the theoretical commitments underlying this prior research. These challenges render questionable the results of prior studies and therefore the basis of much contemporary work on the teaching and learning of energy.

To alleviate this concern, more basic research on the teaching and learning of energy is necessary. The careful study of students’ ideas about energy using a contemporary theory of knowledge and learning, like the work reported on in this dissertation, is one important area of such research.

This dissertation contributes in manifold ways to the research efforts aimed at improving the teaching and learning of energy. However, there are still questions that could not be addressed with this work. In this concluding chapter, I synthesize my findings to highlight my contributions to the systematic research on students’ ideas about science, particularly energy. In addition, I provide an overview of educational implications of this research and propose future directions for research on the teaching and learning of energy.
7.2 Synthesis of the work presented in this thesis

Prior studies on students’ ideas about energy used a theory of knowledge that assumed stable and coherent conceptual structures. Similar to and compatible with this theoretical perspective, scientific knowledge was viewed, rather positivistically, as unified, accepted truths. Each of the studies I reviewed in Chapter 2 assumed a singular scientific conception of energy and considered most students’ conceptions of energy deficient in comparison.

The prevalent theory of learning in this prior research was a radical form of conceptual change (e.g., Driver & Easley, 1978). Researchers thought that for learning to occur, a student’s initial, wrong everyday conceptions of energy needed to first be elicited and brought into internal conflict for the student. It was believed that only if the student was ready to leave a faulty conception behind and choose to accept a new (more scientific) one, conceptual change could occur.

For my work, I adopted a more recently developed theory of conceptual change that views students’ knowledge as well as scientific knowledge as fragmented and context-dependent (diSessa, 1993; Hammer, 1996a). With this perspective, conceptual change does not occur suddenly and does not require the replacement of prior knowledge. Instead, learning is seen as a gradual process of rearranging and fortifying connections between knowledge pieces that is evident in learners’ increasingly sophisticated disciplinary practice.

In particular, I developed a theoretical framework that is based on Hammer et. al.’s resources perspective (Hammer et al., 2005, see Chapter 3). This perspective values students’ disciplinary productive ideas as resources for learning. In order to evaluate the productiveness of learners’ ideas, comparisons have to be made with scientific knowledge about energy. In contrast to prior approaches, however, I did not compare students’ conceptions to a unified scientific conception (e.g., energy is “a
construct—numbers calculated in a certain prescribed way, that are found by theory and experiment to preserve a remarkably simple relationship in very diverse physical phenomena,” (Arons, 1965; cited in Watts, 1983a, p. 216). Instead, I identified aspects of the multi-faceted body of context-dependent scientific knowledge about energy in students’ ideas (e.g., energy can be conceptualized as a quantity with substance-like properties that is manifested in various forms associated with different observable properties of objects).

To establish theoretical validity (see Chapter 5), I developed operational definitions of the core constructs of the resources framework: resources, their activation, and productiveness (see Chapter 3). I furthermore extended the existing framework from a perspective of individual cognition to allow for the identification of resources that emerge from interactions between multiple learners. In addition to providing readers of my dissertation with the means to evaluate my work, these definitions will also enable other researchers to transparently apply the resources framework to future studies of knowing and learning.

As a proof of concept, I applied the resources framework to my analysis of a subset of Watts’ (Watts, 1983b) transcripts from interviews with students about the energy involved in certain scenarios (see Chapter 4). I found that these students’ ideas contained valuable disciplinary substance that Watts did not attend to. Older theories of conceptual change do not expect elements of experts’ knowledge to be found in beginning learners’ ideas. Therefore, these theories do not account for how to use disciplinarily appropriate knowledge pieces in learning (J. P. Smith et al., 1994). My findings of productive resources in students’ ideas—expressed in interviews conducted to find students’ naive conceptions—fuels the critique of the theoretical assertions and therefore the value of the findings of prior research on students’ ideas about energy.
My analyses in Chapters 4 and 6 not only allowed me to positively answer the overall guiding question “Do secondary students activate productive resources when reasoning about energy?” in two general contexts: Watts’ Interviews about Instances conducted in Great Britain over 30 years ago, and contemporary Maine middle school classrooms using Project-Based Inquiry Science. I could find disciplinary productive resources in specific contexts that—on the surface—did not appear to provide opportunities for rich ideas to be expressed (e.g., list making activities). In addition, I presented detailed accounts for what these resources were, how they were activated, and what makes them productive. These detailed accounts contribute to the systematic research on students’ productive resources (Brown & Hammer, 2008) and allow me to draw conclusions about resources that inform the resources framework.

Many resources could be identified in students’ use of multiple metaphors to reason about energy. These resources were activated by students in many different contexts: for example, in the explicit ontological description of energy in response to a question like “What is energy?” or implicit in a narrative about the involvement of energy in a particular scenario. In any case, the use of metaphors can inform a researcher or teacher about a student’s ontological understanding of energy in a particular context. Flexible use of multiple ontologies for physical concepts has been shown to be characteristic for the disciplinary practice of physicists (e.g., Gupta et al., 2010). The development of a sophisticated understanding of energy can therefore be fostered by tapping corresponding resources.

I also found resources in students’ declarative statements. An utterance like “moving is using energy” not only contains an ontological metaphor (see section 6.2.2). From the context in which it was expressed, I inferred that “moving” is seen as a form of energy by the student. Other examples of such declarative resources are the scientific names of energy forms, e.g. “kinetic” or “potential.” The activation
of these resources evidences the existence of a productive basis for the development of disciplinary declarative knowledge.

A third group of identified resources involved procedural knowledge. Procedural knowledge, especially about mechanistic reasoning, is of particular importance for disciplinary practice. Attending to students’ mechanistic reasoning, for example, has been found to be crucial in the effort of making classroom assessment relevant to scientific practice (Russ, Coffey, Hammer, & Hutchison, 2009).

My work shows that resources, particularly ones involving mechanistic reasoning, can be activated by individuals but also by groups of learners engaged in collaborative problem solving. This has consequences for both research and instruction (see section 7.3). Researchers and teachers should not only focus on individual students’ utterances to identify productive resources. With my proposed methodology, resources can be found that emerge from interactions in conversations.

Like energy, resources are manifested in various ways. How a certain resource is activated depends on the specific manifestation, just like mechanisms for energy transfer or transformation depend on the specific energy forms involved. For example, a resource regarding the ontology of energy is activated through the particular use of a substance metaphor; the key words in which this metaphor is manifested in the utterance “sun is giving us the solar energy to live off from” (see section 6.2.3.1) are “giving us the [...] energy.”

In the development of my theoretical framework, I proposed a general definition of resource activation: “The conscious or unconscious recognition of applicability, as judged by the learner, and application of a resource to a certain situation” (see Chapter 3). This definition was developed in an effort to synthesize prior literature using the resources framework. However, it does not specify the particular mechanisms by which certain resources are activated. Further research could find universal
characteristics of activating specific resources and inform the development of new definitions for resource activation.

7.3 Pedagogical implications

The findings in this study have implications for both classroom teaching and teacher professional development. In this dissertation, I have shown ways of recognizing disciplinary productive resources about energy in student discourse. The rich descriptions of various manifestations of different resources in students’ utterances may be of help for classroom teachers in their development of heuristics for identifying such resources in their own classrooms. In order to recognize productive resources, however, a teacher must first turn his/her attention toward students’ ideas and be convinced that it is necessary to inquire into these ideas and use them productively to foster learning.

Conjecturing from the analytical work in this dissertation, teachers will only be able to recognize productive disciplinary elements in students’ ideas with sophisticated knowledge of the discipline. However, disciplinary training alone is not sufficient. Teachers need to develop an appreciation for the complexity of students’ ideas as well as—and in regard to—the complexity of scientific ideas about energy. This can only be accomplished with the help of research-based pre-service and in-service professional development.

Being able to recognize and address students’ difficulties in learning physics has previously been argued to be an important part of pedagogical content knowledge (e.g., Etkina, 2010; Maries & Singh, 2013; Thompson, Christensen, & Wittmann, 2011). My work contributes to more recent efforts in physics education research that attempt to identify content knowledge for teaching (CKT; see Ball, Thames, & Phelps, 2008)—particularly the knowledge necessary to recognize productive beginnings of scientific
understanding—in the topic energy (Scherr, Robertson, Seeley, & Vokos, in press). A similar research program has been established in mathematics education research. This field has made great progress toward identifying the knowledge a teacher needs to successfully help students structure their mathematical ideas (“analytic scaffolding;” see Williams & Baxter, 1996). For example, Speer and Wagner (2009) found that considerable mathematical content knowledge is not enough to recognize valuable student contributions and productively use them in an undergraduate mathematics classroom discussion. Instead, they found elements of specialized content knowledge (SCK, “the mathematical knowledge that allows teachers to engage in particular teaching tasks,” p. 533) that might have enabled the studied teacher to recognize students’ contributions as relevant to the topic at hand and use them productively in instruction.

7.4 Directions for future research

While this research focused on identifying productive resources in students’ ideas about energy, questions remain about how instructors can and do use these resources productively in the classroom. New detailed and longitudinal studies of in-the-moment interactions between teachers and students are necessary to determine how teachers’ responsiveness to students’ ideas about energy affect learning.

A possible avenue to pursue such research agenda would be to select experienced master teachers with a record of successful student-centered teaching for analysis. These teachers’ classrooms could be video-recorded for several weeks. Detailed analysis of teacher-student interactions using ethnographic methods would reveal the microstructure of these teachers’ responsiveness to their students’ ideas about energy and how this responsiveness affects students’ conceptual development over a certain time period. Inferences could be made about the content knowledge for teaching
energy that is necessary to recognize productive elements of students’ thinking (see Scherr et al., in press).

In addition to studying how students of successful teachers develop increasingly sophisticated understandings of energy, further research could and should be conducted on the ways physicists conceive of the energy concept in their daily practice. Prior investigations of the energy concept in physics have relied on the analysis and review of historical and contemporary literature, including textbooks (e.g., Brookes & Etkina, 2006; Duit, 1986; Gupta et al., 2010, or Chapter 6 of this thesis). Ethnographic studies of practicing physicists would supplement systematic analyses of contemporary literature from a wide array of sub-disciplines. Such research would be more revealing about how physicists use the energy concept in their practice than a look into various textbooks.

I identified productively activated resources in activities that seemed—on the surface—not conducive to students’ expression of rich ideas about energy. Future research could and should investigate the kinds of circumstances and participation structures that foster students’ exchange of their ideas about energy. If teachers can create environments that mediate the expression of ideas, they will have rich opportunities to find resources that can be productively used in instruction.

Results from this proposed research could inform the design of professional development for pre- and in-service teachers surrounding the topic energy. Through iterative design, the eventual goal of this professional development would be to help teachers become sensitive to students’ disciplinarily valuable ideas about energy and respond to them productively in the moment.
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concerning students’ representation of physics and chemistry knowledge” (pp. 268–319).


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APPENDIX

FULL TRANSCRIPTS

This appendix contains transcripts of the episodes analyzed in Chapter 6. While certain information was stripped from the transcripts in Chapter 6, the original transcripts are reproduced here in their entirety. The transcripts appear in the same order as they do in the chapter.

The transcript conventions from Chapter 6 are extended as follows: “Talk receiving some form of emphasis is underlined. Punctuation is used to transcribe intonation: a period indicates falling pitch, a question mark rising pitch, and comma a falling rising contour, as would be found for example after a non-terminal item in a list. Comments (e.g. descriptions of relevant nonvocal behavior) are printed in italics. Numbers in parentheses mark silences in seconds and tenths of a second” (Goodwin, 1995, footnote 3). In addition, overlapping speech is denoted by square brackets connecting the overlapping utterances; equal signs are used to indicate that there is no interval between the end of a prior and start of a next piece of talk; a single dash indicates that the word or syllable was cut off; colons indicate that the prior syllable is prolonged; a small circle before an utterance indicates that this utterance is spoken in low volume; single dots in parentheses indicate brief, untimed pauses; numbers in parentheses indicate timed pauses in the formats (seconds) or (seconds.tenths); utterances in parentheses denote uncertainty in the transcription of the utterances; empty parentheses are used to indicate that the utterance was incomprehensible and could therefore not be transcribed.

Most notably, time stamps are included here to establish a temporal sense of the events. The time stamps are in the format mm:ss-tenths for the original video files in which the episodes are contained.
Datum A.1. Mark and Madison: Entity metaphors for energy

Datum A.2. Mark and Madison: Forms of energy

Datum A.3. Jessica: Energy forms
Datum A.4. Jeff and Jessica: Solar energy

Datum A.5. Jeff: Hydro energy

Datum A.6. Jessica: Heat is made up of “things”

Datum A.7. Uli: Plasma energy
Datum A.8. Human energy: Energy form or ‘just’ energy?


Datum A.10. A running monkey as an example for kinetic energy
Datum A.11. Energy transfer from the banana to the monkey
Datum A.12. Energy transfer and transformation chain: From the sun to the banana
BIOGRAPHY OF THE AUTHOR

Benedikt Walter Harrer was born in Eichstätt, Germany. He graduated from Gabrieli Gymnasium Eichstätt in 2002. After a year of civilian service, he attended the Ludwig-Maximilians University (LMU) in Munich, Germany, and graduated in 2009 with a graduate degree in Mathematics and Physics Education (Lehramt Gymnasium Mathematik und Physik). The title of his thesis was “Kontextorientierter Physikunterricht – Physik in der Kriminalistik. Empirische Erhebung und Anwendungsbeispiel” (“Contextual physics instruction – Physics in forensics. An empirical investigation and application example”). During his time in Munich, Benedikt worked as a teaching and research assistant with the physics education research group at LMU and taught 7th grade physics at Josef Effner Gymnasium in Dachau. In the U.S., he has been a graduate teaching assistant at the University of Maine and a graduate research assistant with the Energy Project at Seattle Pacific University as well as the Maine Physical Sciences Partnership and the Content Knowledge for Teaching Energy project at the University of Maine. Benedikt’s latest publication is Harrer, B.W., Flood, V.J., Wittmann, M.C. (2013) “Productive resources in students’ ideas about energy: An alternative analysis of Watts’ original interview transcripts,” Phys. Rev. ST Phys. Educ. Res. 9, 023101. He is a member of the Deutsche Physikalische Gesellschaft (DPG), the American Association of Physics Teachers (AAPT), and the National Association for Research in Science Teaching (NARST).

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