Click for updates

International Journal of Science Education
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tsed20

The Importance of Language in Students' Reasoning About Heat in Thermodynamic Processes

David T. Brookes[a] & Eugenia Etkina[b]
[a] Department of Physics, Florida International University, Miami, FL, USA
[b] The Graduate School of Education, Rutgers University, New Brunswick, NJ, USA

Published online: 27 Mar 2015.

International Journal of Science Education, 2015
http://dx.doi.org/10.1080/09500693.2015.1025246

The Importance of Language in Students' Reasoning About Heat in Thermodynamic Processes

David T. Brookes[a*] and Eugenia Etkina[b]
[a]*Department of Physics, Florida International University, Miami, FL, USA;*
[b]*The Graduate School of Education, Rutgers University, New Brunswick, NJ, USA*

Researchers believe that the way that students talk, specifically the language that they use, can offer a window into their reasoning processes. Yet the connection between what students are saying and what they are actually thinking can be ambiguous. We present the results of an exploratory interview study with 10 participants, designed to investigate the role of language in university physics students' reasoning about heat in thermodynamic processes. The study revealed two key findings: (1) students' approaches to solving certain heat-related problems are related to the way in which they explicitly define the word 'heat' and (2) students' tendency to reason with heat as a state function in inappropriate contexts appears to be connected to a model of heat implicitly encoded in language. This model represents heat or heat energy/thermal energy as a substance that moves from one location to another. In this model, students talk about thermodynamic systems as 'containers' of heat, and temperature is a measure of the amount of heat 'in' an object.

Keywords: *Heat; Student conceptions; Caloric metaphor; Reasoning; Language*

In this paper we will explore the interplay between how university physics students speak and how they reason about heat in thermodynamics processes. We will focus on one particular area of student reasoning in thermodynamics: several studies in physics and chemistry education have found that there is a recurring pattern in student reasoning about thermodynamics processes. Specifically, a majority of university-level physics and chemistry students conceptualize heat as having the characteristics of a state function (an extensive thermodynamic quantity that is independent of

*Corresponding author. Department of Physics, Florida International University, 11200 SW 8th St., Miami, FL 33199, USA. Email: dbrookes@fiu.edu

thermodynamic path) (Fuchs, 1987; Kaper & Goedhart, 2002; Loverude, Kautz, & Heron, 2002; Meltzer, 2004; Roon, Sprang, & Verdonk, 1994). For example, in an interview study of 32 students enrolled in a calculus-based introductory university physics course, Meltzer (2004) found that 69% of the interviewees said that the total heat transfer for a closed thermodynamic cycle was zero. He observed that students most commonly argued (incorrectly) that the heat transferred into and out of the system during the cycle would be the same because the initial and final temperatures of the system were the same. Students focused on the beginning and end points of the process and ignored the path that was taken. This is the essence of state function-like reasoning.

Possibly related to this reasoning is the way in which we talk about heat in everyday language and even in well-established scientific fields such as physics and chemistry. It is common to talk about heat as a substance (Chi & Slotta, 1993; Chi, Slotta, & de Leeuw, 1994; Reiner, Slotta, Chi, & Resnick, 2000) that flows or is transferred into and out of thermodynamic systems. Thermodynamic systems are seen as containers of heat (Engel Clough & Driver, 1985; Erickson, 1979; Fuchs, 1987; Jasien & Oberem, 2002; Kesidou & Duit, 1993; Warren, 1972) and the temperature as an indicator of the amount of heat in the system (Beall, 1994; Erickson, 1979; Jasien & Oberem, 2002; Kesidou & Duit, 1993; Rozier & Viennot, 1991; Tripp, 1976; Warren, 1972). We will call this way of speaking, and its implicit ontology of heat as a substance and objects as containers of heat, the caloric metaphor. (The word caloric is a historical term from the eighteenth century, coined by Lavoisier, given to a hypothetical fluid that is transferred by contact between objects at different temperatures.) In prior research we found this caloric metaphor used roughly 40–50% of the time in all sentences that contained the word ‘heat’ in popular university-level introductory physics textbooks (Brookes, Horton, Van Heuvelen, & Etkina, 2005). In the view of Jeppsson, Haglund, Amin, and Strömdahl (2013), conceptual metaphors such as the caloric metaphor should be treated as resources that students can recruit in their reasoning. Brewe (2011) has suggested that thinking about kinetic or potential energy as a substance that flows and is stored in systems is a productive resource for students (note that, for example, gravitational potential energy *is* a state function). However, talking about heat this way is frequently blamed for students’ difficulties with heat in thermodynamic processes (Arnold & Millar, 1994; Bauman, 1992; Brown, 1950; Fuchs, 1987; Harris, 1981; Heath, 1974; Hobson, 1995; Leff, 1995; Pushkin, 1996; Tripp, 1976; Zemansky, 1970).

It is likely difficult or impossible to conduct a controlled experimental study to see if there is an unambiguous causal link between language and reasoning. In other words, does the language we use incline reasoners to think about heat as a state function? The challenge stems from the difficulty of expunging or being able to counteract the caloric metaphor in a treatment group. The evidence of a causal connection is only suggestive: Hewson (1984) showed that first language Sotho speakers in South Africa, whose language possesses a dominant cultural metaphor in which ‘heat’ or the state of being hot is associated with emotional agitation or sickness, reasoned about heat in a way that was more closely aligned with kinetic molecular theory and rarely invoked caloric ideas. The authors explicitly shy away from concluding that language is influencing reasoning. Instead, they emphasize that the interaction between language and physical experience is a bi-directional one in which each can change and influence the other. In a more recent study, Kaper and Goedhart (2002) gave two groups of five students two different ways to talk about energy. The first group used the traditional 'forms of energy' language, while the second group was introduced to a new 'exchange value' language. When both groups of students were presented with and asked to interpret some thermodynamic processes, they found that the 'exchange value' group were able to move beyond state function reasoning about heat in those processes while the 'forms of energy' group remained trapped in inappropriate state function reasoning. The authors acknowledge that the scale of their study is too small to draw firm conclusions about the influence of language on students' reasoning.

We share the view, originally formulated by Sapir (1957) and Whorf (1956), that our experience of the physical world can influence our language, but that language can also influence our interpretation and understanding of physical experience. This bi-directional interaction of language and experience serves as a fundamental theoretical assumption in our work.

In this paper, we will adopt a viewpoint in which students are able to recruit various resources (Hammer, 2000) when engaged in reasoning about a physics problem. In the case of thermodynamics, we wish to examine whether state function reasoning is supported by a linguistic resource, namely the caloric metaphor. If this is true, we should see evidence that students who display state function-like reasoning recruit that metaphor more frequently than those who do not. Our prior research suggests additional complexity: physical models encoded in language have both explicit and implicit ontological components (Brookes & Etkina, 2007, 2009). In the case of heat, the explicit ontological component can be found in students' responses to the direct question: 'What is heat, or how do you define heat?' The implicit component may be uncovered by examining the grammatical structure of the metaphors that students use when they talk about heat while explaining their reasoning. These two components should combine together into a locally coherent model of heat encoded in language. In this manuscript we will describe an interview study using Meltzer's (2004) interview questions that set out to examine both the explicit and implicit ontological components of students' language about heat and how these relate to their difficulties with the concept of heat as a state function while solving thermodynamics problems. The study attempts to answer the following question. Is there a relationship between the way students talk and the way they approach physical situations and problems?

Theoretical Background

Heat and Temperature in Science

As the notions of heat and temperature are the foundational concepts of this paper, we provide a brief overview of expert understanding of these concepts in thermodynamic systems. Examining expert understanding will also give us key insights into the relationship between how experts define heat and the conceptual metaphors that they use to talk about it. There is no definition of what heat is that all physicists and chemists will agree on. However, there is certainly a consensus view about what heat is not. While the physical quantity of heat (Q) is measured in the SI unit of Joules and is therefore a quantity of energy, heat is not a form of energy in the same sense as we think of kinetic energy or potential energy. Additionally, temperature is not a measure of the amount of heat in a thermodynamic system.

A thermodynamic system may be described by either microscopic state variables (e.g. the positions and momenta of all the molecules in the system) or by macroscopic state variables such as volume, pressure, and temperature. State functions such as the internal energy, or molecular kinetic energy of the thermodynamic system, are functions of these state variables. Physically, this means that if one specifies the values of the state variables of a thermodynamic system, a state function will return a unique value associated with that system configuration. For example, given the temperature of a monatomic ideal gas, one can say that the average kinetic energy of a molecule in the gas will be $K = (3/2)\,kT$. Consequently the internal energy of that gas, which is the sum of the kinetic energies of the individual molecules, is a state function as well. Since there is no such function associated with heat, one cannot think of heat as a state function or as a form of energy in the conventional sense. It is meaningless to ask 'what is the heat of the system' for a specified volume, temperature, and/or pressure. Heat represents a quantity of energy added to or taken from a thermodynamic system by a heating process such as placing a sealed metal container of room temperature air on a stove and raising its temperature by heating it, or placing the same metal container of air in a refrigerator, thereby cooling it down.

The role of heat in thermodynamics is better understood if we examine the equation describing the first law of thermodynamics: $\Delta U_{\text{int}} = Q + W$. This equation describes the behavior of a state function, the internal energy of a thermodynamic system (U_{int}). The internal energy can change through the addition or removal of energy from the system through two distinct processes, either heating or doing work. Heating processes are those that involve transfers of energy through 'thermal contact between the system and the surrounding environment'. Work processes involve a collective macroscopic action applied to the system or performed by the system. For example, a work process could involve compressing a gas by squeezing it with a piston. The symbols Q and W represent the quantities of energy (most often called 'heat' and 'work', respectively) that are added to or removed from the system by these two processes. The equation that represents the first law of thermodynamics can be confusing because, while U_{int}, Q, and W are all quantities of energy, U_{int} is a state function of the thermodynamic system. In contrast, Q and W are process variables that quantify additions or subtractions of energy from the system, resulting in changes in the state function U_{int}.

Language Used to Model the Physical World

Humans use language to describe and model their physical experiences (Halliday, 1985). This same modeling function is key to understanding how language works in science, both when scientists talk to each other and when teachers communicate scientific ideas to their students in a science classroom (Lemke, 1990, 2004). To understand the modeling function of language, we have adopted a number of views from different areas of linguistics and cognitive science. In this section we will introduce these different views and show how they fit together to describe language in a physics classroom.

In prior research we have adopted the framework of Lakoff and Johnson (1980) that views much of language and thought as metaphorical. Human language consists of many expressions that do not initially appear to be figurative but on careful analysis reflect underlying conceptual metaphors. For example, consult any English language manual on how to insulate your house and you will find sentences such as 'in hot weather, heat invades from the outdoors' or 'better insulation keeps more heat in during the cold weather'. Sentences such as these suggest that 'heat' is a substance (sometimes a fluid) that moves, flows, or is transferred from one location to another and that objects/locations (such as your house or the outdoors) are 'containers' of heat. Sutton (1993) explains the presence of conceptual metaphors in physics in terms of their analogical origins. For example, the caloric metaphor entered the language of physics after the adoption of the caloric model of heat. Because of the analogical origins of the caloric metaphor (and similar metaphorical language), experts are aware of the limitations and applicability of their language models.

In previous research we have shown that physicists use metaphorical language as a representation of a physical model of the world. For example, physicists use a metaphor of 'tunneling' to describe the process by which a bound quantum mechanical object (e.g. an electron) can 'pass through' a potential 'barrier' without having enough energy to 'pass over' it. While these metaphors may take on subtly different forms, sometimes 'tunneling', sometimes 'leaking', they have systematic grammatical patterns that encode an implicit ontology of *matter* (nouns or noun groups), *processes* (verbs or verb groups), and *physical states* (grammatical 'location': essentially container metaphors denoted by prepositional phrases that begin with prepositions such as 'in', and 'into' and may be supported by prior choice of verb group such as 'is absorbed') (Brookes, 2006; Brookes & Etkina, 2007; Chi & Slotta, 1993; Chi et al., 1994). For example, when writing about α-particles, Feynman, Leighton, and Sands (1965, pp. 7–8) state that '... they start out with the energy E inside the nucleus and "leak" through the potential barrier'. Here the objects or substances in the model are the α-particles (implicitly referred to by 'they'), the nucleus, and the potential barrier; all functioning grammatically as nouns or noun groups. The process is one of 'leaking through' the barrier, and the physical state of the system is denoted by the metaphor of the α-particle contained within the nucleus, identified by 'inside' and 'through'.

With the caloric metaphor, different choices of verb may associate different meanings with heat. 'Flows' may suggest heat is a fluid, while 'is transferred' leaves the exact nature of heat somewhat ambiguous. Yet, underpinning all these sentences is a common grammatical structure: the grammar of the caloric metaphor involves (a) heat functioning as a noun, (b) a verb that implies some sort of movement of heat, followed by (c) one or two grammatical location structures. See Table 1 for examples. This analysis allows us to systematically identify the implicit ontology of heat and its role in thermodynamic systems in students' discourse. A full discussion of the grammar on which this analysis is based is covered in Halliday (1985). The connection between grammar and the ontology of physical models is discussed in Brookes and Etkina (2007).

Dynamic Ontologies and Local Coherence

We have shown in previous research in quantum mechanics that expert physicists change their language model (and ontology) quickly and easily when confronted with anomalous situations (Brookes & Etkina, 2007). Other researchers have observed that physics students' reasoning seems to 'straddle' ontological categories (Gupta, Hammer, & Redish, 2010) and that students are able to use conceptual metaphors with a seemingly 'incorrect' implicit ontology to reason productively about physical situations (Gupta, Elby, & Conlin, 2014). These viewpoints contrast with the work of Chi and Slotta (1993) and Chi et al. (1994) who have argued the case that ontology is more static and that conceptual change in physics (moving from novice to expert) requires that the reasoner recategorize a physics concept into a different ontological category. For example, as they become more expert reasoners in physics, students need to undergo a conceptual shift, moving the concept of heat from the ontological category of substances to the ontological category of processes before they can reason effectively about heat in thermodynamic processes. Similar to Jeppsson et al. (2013) we suggest that there is a middle ground in this debate. Conceptual metaphors and their implicit ontology are resources (Jeppsson et al., 2013). While experts are able to shift easily between different conceptual metaphors, seemingly playing 'fast and loose' with ontology, there is at least some local coherence: for some period of time a coherent model with a consistent set of ontological categories is being activated. Novice physics students, on the other hand, have the challenge of navigating expert ways of speaking that must appear ontologically 'chaotic' at

Table 1. Grammatical structure of the caloric metaphor

Grammatical function	Participant (noun/noun group)	Process (verb/verb group)	Location	Location
Common words	Heat/heat energy/ thermal energy	Flows/moves/is transferred/is rejected/is absorbed	Into/to/from/ out of object A	Into/to/from/ out of object B

first. It is a necessary part of learning physics that students be given time and space to explore how particular models (and their oft-conflicting ontologies) can be used productively in different situations (Brookes & Etkina, 2009).

The local coherence of experts' ontology is sometimes hard to tease apart. This is especially true in thermodynamics and so we will consider the case of 'heat' in detail. In the context of heat in thermodynamics, Slisko and Dykstra (1997) have observed, there is little agreement between experts about what 'heat' means and its role in thermodynamic processes. Many experts say that heat is a form of energy (Brown, 1950; Lewis & Linn, 1996); however most of these researchers and teachers qualify this statement by stating that heat is a 'special' form of energy. Heat is generally either referred to as 'disordered/random' energy (Helsdon, 1976) or as 'moving energy'/ 'energy in transit' (Tripp, 1976; Zemansky, 1970). Doige and Day (2012) call these definitions 'Class II' and 'Class I', respectively. The Class I definition, 'heat is energy in transit', is the definition that dominates most of the university introductory level physics textbooks (Cutnell & Johnson, 2001; Giancoli, 2000; Halliday, Resnick, & Walker, 2003; Tipler, 1999; Walker, 2002). Note that heat cannot be a 'normal' form of energy because it is not a state function. The quantity of heat Q represents how much energy is added to or removed from a thermodynamic system in a heating process. Uniformly these researchers and textbook authors invoke the caloric metaphor, writing about heat as a noun, matching the way in which physicists talk about energy: i.e. 'heat is transferred from A to B' is the same as 'energy is transferred from A to B'. Note that this way of speaking hides the fact that heat is a 'special' form of energy.

While beyond the scope of this paper, we speculate that there are two possible components to this very common choice of language: (a) one historical and (b) one cognitive. (a) As Sutton (1993) has pointed out, historical models seem to live on in modern scientists' language as conceptual metaphors. As we have discussed in earlier work (Brookes & Etkina, 2007) conceptual metaphors can encode productive modes of reasoning. There are many cases when it is productive to think of heat as a state function. (b) There is an inevitable ontological tension between the *process* of heating and the *amount* of energy added by that heating process. Expert reasoners may tend to talk about heat as a substance because there is a practical need to be able to talk about the *physical quantity* Q in the equation of the first law of thermodynamics. This quantity is referred to as 'heat', representing the amount of energy that is transferred in a particular heating process.

Other researchers have, however, suggested that, to avoid confusion, 'heat' should be defined exclusively as a process, a means by which energy is transferred from one place to another (Baierlein, 1994; Bauman, 1992; Heath, 1974, 1976; Hobson, 1995; Pushkin, 1997; Romer, 2001). Without exception, these researchers and teachers have suggested that the only acceptable way to talk about heat grammatically is as a verb (the fire heated the room) or as grammatical manner ('energy flowed into the chamber by heat/heating'). The process definition and matching grammatical usage is found relatively rarely in introductory university physics textbooks (Etkina, Gentile, & Van Huevelen, 2014; Serway & Beichner, 2000).

It is important to note that surveying textbooks and the published recommendations of educators and practitioners likely does not reflect the real-world language usage of experts reasoning about heat in thermodynamic processes. The empirical results of Jeppsson et al. (2013) support a more dynamical view of expert language in action, in contrast with the more rigid view that expert reasoners offer when asked to think and reflect about their language usage in formal publications. Apart from this study, we do not know of any study that examines *in vivo* language usage of *experts* solving thermodynamics problems. This should be a topic for future research.

The goal of this section is to illustrate that, to understand how language models are applied in physical reasoning and the local coherence of their ontology, we need to examine both the explicit ontology of the concept as the reasoner defines it *and* the implicit ontology encoded in the grammatical structure of the conceptual metaphors that the reasoner uses to talk about the concept.

This discussion allows us to clarify the research question we wish to address in this paper: Is there a relationship between the way students talk and the way they approach physical situations and problems in thermodynamics? Specifically, we want to know (1) When students activate state function reasoning, do they talk about heat with an identifiable metaphor? (2) Are students who are able to access more sophisticated expert-like meanings associated with 'heat' reasoning differently about heat in thermodynamic processes as compared to those who can only access more novice-like meanings? In reviewing the literature, there appears to be a consistent pattern between how experts conceptualize heat on the one hand and how they recommend we define it and talk about it on the other. But how does that play out in the real world of student reasoning and problem-solving? As researchers, we would like to believe that listening to what students say can give us insights into their reasoning. If we can find evidence of a clear association between the way students talk and their reasoning, it would give us a deeper insight into the way in which we try to understand student reasoning through language. It would also give teachers fundamental tools to help them understand what their students are thinking as they try to help them diagnose and overcome their difficulties with various physics topics.

Method

Population

We recruited 10 students from a variety of physics courses at a large North Eastern University. They ranged from an introductory algebra-based sequence to honors calculus-based physics, to junior physics majors. The requirement was that students had already covered the thermodynamics section of the syllabus. All except S7 were native English speakers.

Materials and Procedure

We used the same interview questions as in an interview study conducted by Meltzer (2004).[1] Meltzer's interview questions were particularly appropriate for our study

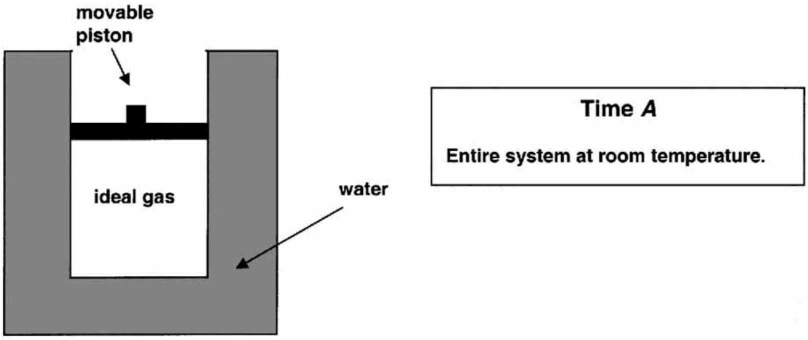

Figure 1. The state of the system at the initial starting time A

because students had to answer questions about heat transfer, for both a closed thermodynamic cycle and in an isothermal step of that cycle. In addition we asked students to define the term 'heat' as best they could.

In the interview, each student was presented with a sheet of paper with a step-by-step description of a thermodynamic cycle performed by an ideal gas, enclosed in a piston and cylinder configuration. For each step of the cycle, students had to answer accompanying questions. The cylinder that enclosed the gas was depicted as having a jacket of water around it. This jacket served, in part, to control the rate of the thermodynamic processes so that the thermodynamic cycle could plausibly occur quasi-statically. Figure 1 shows the system at the starting point of the cycle.

In step 1 of the cycle from time A to time B, the piston was slowly raised by the gas at constant pressure as the gas was heated by the jacket that surrounded it. Figure 2 shows the state of the system after the initial heating step that raised the piston.

Question 1: During the process that occurs from time A to time B, which of the following is true: (a) positive work is done on the gas by the environment, (b) positive work is done by the gas on the environment, (c) no net work is done on or by the gas (correct answer is (b)).

Question 2: During the process that occurs from time A to time B, the gas absorbs x J of energy from the water. Which of the following is true: the total kinetic energy of all of the gas molecules (a) increases by more than x J; (b) increases by x J; (c) increases,

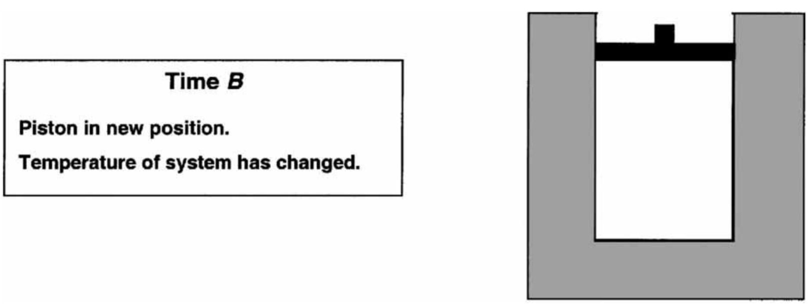

Figure 2. The state of the system at time B after the piston was raised by heating the gas

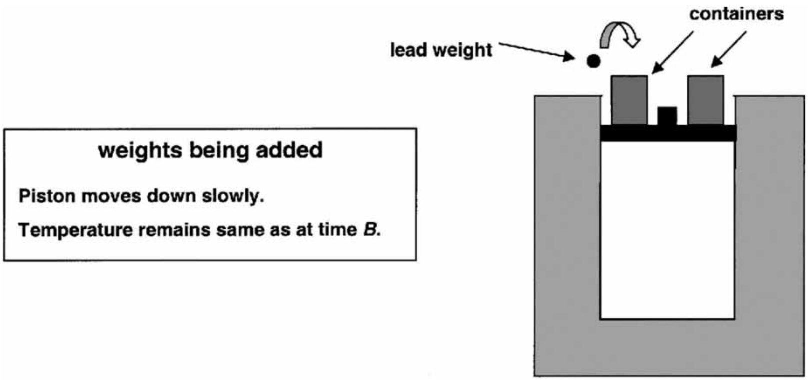

Figure 3. Illustration of the containers placed on top of the piston as the B to C process begins

but by less than x J; (d) remains unchanged; (e) decreases by less than x J; (f) decreases by x J; (g) decreases by more than x J (correct answer is (c)).

In step 2, from time B to time C, the gas was slowly compressed by an external agent (containers were placed on top of the piston and small lead weights were gradually added to the containers). The act of adding lead weights is shown in Figure 3.

From time B to time C, the temperature was maintained at a constant value throughout this step of the process. Figure 4 shows the state of the system at time C.

Question 3: During the process that occurs from time B to time C, does the total kinetic energy of all the gas molecules increase, decrease, or remain unchanged? (Correct answer is 'remains unchanged').

Question 4: During the process that occurs from time B to time C, is there any net energy flow between the gas and the water? If no, explain why not. If yes, is there a net flow of energy from gas to water, or from water to gas?

The correct answer is that there should be energy flowing from the gas to the water (Q gas $\rightarrow$ water) because as the gas is compressed, the total kinetic energy of the gas should increase. To keep the temperature constant, kinetic energy has to be removed from the gas as the compression takes place.

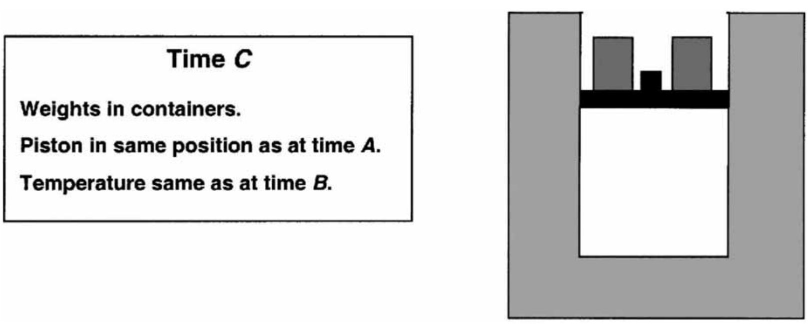

Figure 4. The state of the system at time C

In the final step 3, students were told that the piston was locked in place and the gas was allowed to cool down to room temperature from time C to time D (a constant volume process). The final state of the system is shown in Figure 5. Then they were asked Q5 and Q6.

Question 5: During the process that occurs from time C to time D, the water absorbs y J of energy from the gas. Which of the following is true: the total kinetic energy of all of the gas molecules (a) increases by more than y J; (b) increases by y J; (c) increases, but by less than y J; (d) remains unchanged; (e) decreases, by less than y J; (f) decreases by y J; (g) decreases by more than y J. Because the piston is locked in place there is no work done in this phase of the cycle. Consequently the energy transferred by heating must account for all of the energy that the gas loses. Thus the correct answer is (f).

Question 6: Consider the entire process from time A to time D. (i) Is the net work done by the gas on the environment during that process (a) greater than zero, (b) equal to zero, or (c) less than zero? (ii) Is the total heat transfer to the gas during that process (a) greater than zero, (b) equal to zero, or (c) less than zero? The correct answer to Q6(ii) is that the total heat transfer to the gas is less than zero ($Q < 0$). Physically this means that overall, for the gas to return to its initial pressure, temperature, and volume (a complete cycle), it had to get rid of some excess kinetic energy by heating.

After the thermodynamic cycle portion of the interview, we asked each student to discuss the meaning of the term 'heat'.

We recorded students with an mp3 recorder and an analog back-up recorder after one student's interview (S8) disappeared from the mp3 recorder before it could be saved. We only analyzed students' responses to Q4–Q6 since these questions (especially Q4 and Q6) required reasoners to go beyond state function reasoning with heat in order to answer correctly.

Coding

In our analysis, students' responses to Q4, Q5, and Q6(ii) were first coded for correctness and then examined for any patterns in their reasoning. We especially asked

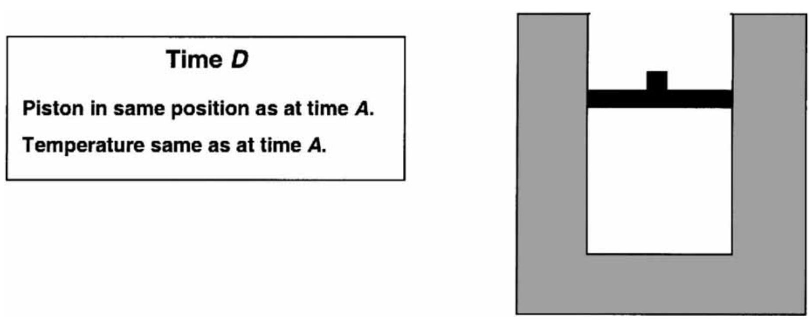

Figure 5. The state of the system at time D

students to explain their reasoning in more detail when they came to Q6(ii). We rated students' level of understanding displayed in transcripts of their responses and justifications to Q6(ii) over and above their ability to get the right answer. This rating was done by a process of grouping responses with similar justifications and then ranking the different responses or groups of responses from weaker to better understanding of the problem. We also gave the student responses to a second rater who independently grouped students' responses and ranked students' understanding of the problem. There was 100% agreement between the two raters after discussion. A second analysis was then performed on Q6(ii) in which we counted the number of times the full caloric metaphor was invoked in each student's response and justification. For the full caloric metaphor to be identified we needed to identify (a) heat functioning as a noun, (b) a verb that described movement of heat, and (c) a grammatical location that heat was moving to or from. This coding was unequivocal, so we did not use a second coder for inter-rater reliability.

Finally, students' heat definitions were coded independently by two coders. Students' definitions were grouped into categories according to common features. Hundred percent agreement was achieved. Both coders participated in the creation of the coding scheme and thus were deeply familiar with it.

Results and Analysis

Through the whole interview, we found a pattern of responses that was remarkably similar to those found by Meltzer (given the variability and small size of our population: algebra-based introductory physics students through to junior physics majors). In addition, many of the typical justifications were of a similar form (Meltzer, 2004).

Students' Definitions of Heat

We were able to identify three different categories of heat definition. The first group consisted of those students who defined heat either as a substance on its own or as a form of energy without further elaboration. We classified their definitions together as a 'caloric/form of energy' definition. We grouped these definitions together because they possess a common trait: they do not identify subtleties of meaning that experts associate with the term 'heat'. (Physicists and chemists either treat heat as a 'special' form of energy, or as a 'process', a means of transferring energy from one location to another.) The second group consisted of those students who defined heat as 'energy in transit' or 'the quantity in the equation', similar to the operational definition given by Serway and Beichner (2000). We classified their definition as 'operational'. As mentioned above, this category of definition is similar to definitions put forth in most modern introductory college level physics textbooks. The third group consisted of those students who said that 'heat is a transfer of energy', rather than 'heat is energy that is transferred'. We classified their definitions as a 'process' definition. The three categories of definition with examples from the interviews are provided in Table 2.

Table 2. All students' heat definitions from interview study

Category	Student's definition
Caloric definition: Heat is a substance, or heat is a form of energy	S1: 'Temperature ... is a measure of the heat ... of the system' S2: 'Heat is actual energy that gives the molecules the kinetic energy S5: 'They [heat and temperature] are directly proportional. If you add heat, you increase temperature ... ' S6: 'Heat is ... the average kinetic energy, so it would be the total kinetic energy of the gas Interviewer: 'Are you saying that the temperature is an indicator of the amount of heat in the system?' S9: 'Yeah, of course!'
Operational definition	S4: 'I'm not exactly sure what it means ... for heat, all I know there is a specific quantity in the equation, I don't really understand what it is ... ' S3: '[Heat is] just the energy that's transferred ... '
Process definition	S7: '[Heat is] ... not even a type of energy. A way of transferring energy from one system to another by thermal contact S10: ' ... it's a transfer, heat is a process, transferring energy ... ' S8: [Process definition; reconstructed from interview notes]

Table 3 shows all students' responses to Q4, Q5 and Q6(ii) of the interview study. These responses are tabulated with students' heat definitions.

In Q4, of the five students who defined heat as either a caloric substance or a form of energy, four said incorrectly that heat transfer was zero, while one student answered Q4 correctly. A typical justification for $Q = 0$ comes from S4:

> S4: There is no net flow of energy from the gas to the water because, um, the temperature remained the same and I guess that means there's no heat transferred.

Some of the other responses in this category included more convoluted reasoning, invoking the ideal gas law, but in each case, students used the ideal gas law to help them reason about the temperature of the system from B to C, rather than thinking about the two competing processes (heating and doing work) that would cause the average kinetic energy (and consequently the temperature) of the gas to change.

Of the five students who defined heat as a 'special' form of energy (operational definition) or a process of energy transfer, one student said $Q = 0$ while four did

Table 3. Summary of students' heat definitions and their responses to Q4, Q5, and Q6(ii) of the interview study

	Heat definition	Q4 (Q gas → water)	Q5 (y J)	Q6(ii) ($Q < 0$)
S1	Caloric/energy	$Q = 0$	y J	$Q = 0$
S2	Caloric/energy	$Q = 0$	y J	$Q = 0$
S3	Operational	Q water → gas	y J	$Q > 0$
S4	Operational	$Q = 0$	y J	Unsure
S5	Caloric/energy	$Q = 0$	y J	$Q = 0$
S6	Caloric/energy	$Q = 0$	y J	$Q < 0$
S7	Process	Q gas → water	y J	$Q < 0$
S8	Process	Q gas → water	y J	$Q < 0$
S9	Caloric/energy	Q gas → water	y J	$Q = 0$
S10	Process	Q gas → water	y J	Unsure

Note: Correct responses are shown in parentheses in the column headings.

not: $p = .103$, one-tailed Fisher exact test. An example of the most clear and succinct reasoning from this group comes from S7:

> S7: And in this process the internal energy doesn't change for the particles and there is some work performed to the system, so the system has to release energy through heating to the water.

In Q6(ii), of the five students who defined heat as either a substance or a form of energy, four said incorrectly that heat transfer was zero, while one student did not answer $Q = 0$. Of the five students who defined heat as a 'special' form of energy (operational definition) or a process of energy transfer, none of the students answered that $Q = 0$ for the complete thermodynamic cycle: $p = .024$, one-tailed Fisher exact test.

Interestingly, this association between heat definition and reasoning completely disappeared in Q5 where heating is the sole energy transfer process. However, we found an additional pattern of reasoning: students who could define heat as 'energy in transit or as a 'process' produced qualitatively different reasoning when justifying their answer to Q5. Students S3, S4, S7, and S10 explicitly mentioned that there was no work being done when answering Q5. A typical response was:

> S7: Well, the gas heats the water by y Joules, but there is no work done so the kinetic energy decreases by y Joules.

In contrast, none of the students who defined heat as a substance or a form of energy explicitly mentioned this fact (no work done). A typical response from this group was:

> S2: … okay. Decreases by y Joules.
> Interviewer: Why do you say that?
> S2: Um, because the net energy flow is to the water since the heat flow is to there as well and that's the only energy that's being transferred, so it's equivocal [sic].

This association between heat definition and justification on Q5 is also significant ($p = .024$, one-tailed Fisher exact test). Thus we see some evidence of distinct ideas being recruited when we examine the students' language.

Student Responses to Q6(ii) and the Caloric Metaphor

As mentioned in section 'Method', we both ranked students' responses to Q6(ii) from poorer to better understanding, and counted the total number of occurrences of the caloric metaphor in their justification. The results of this coding are shown in Table 4.

Table 4 reveals a significant correlation between the quality of students' reasoning on Q6(ii) and the number of times they invoked the caloric metaphor in their explanation: $R_s = 0.85$, $p < .05$ (non-directional test).

Two examples of student responses are shown below. These are not the full responses (since they are too long). Students' responses to this question ranged from 780 words (S5) to 150 words (S10). In the following excerpt from S1, categorized as reflecting 'poor understanding' of Q6(ii), note the frequent use of the caloric metaphor (shown in italics):

> S1: And for part (ii) . . . If it returns back to the same temperature, I would have to say, once again, its equal to zero. Well, the temperature increased, and then it decreased so now, so the net heat, like the net heat transfer I guess would be zero, and I guess, because it goes up then it goes down back to the same thing . . .

Table 4. Students' recruitment of the caloric metaphor compared with their ability to understand Q6(ii)

	Caloric metaphor count	Rank	Categories of student responses to Q6(ii)	Rank	Heat definition
S5	21	9	Poor understanding ($Q = 0$)	7.5	Caloric/energy
S9	17	8	Poor understanding ($Q = 0$)	7.5	Caloric/energy
S2	8	7	Poor understanding ($Q = 0$)	7.5	Caloric/energy
S1	6	6	Poor understanding ($Q = 0$)	7.5	Caloric/energy
S6	4	5	Some idea	5	Caloric/energy
S4	3	3.5	Good ideas	3.5	Operational
S10	0	1	Good ideas	3.5	Process
S3	1	2	Good understanding, just got signs mixed up	2	Operational
S7	3	3.5	Best (correct, clear understanding)	1	Process
S8	N/A	N/A	N/A	N/A	Process

Note: These are shown with ranks used for Spearman's rank order correlation coefficient.

> [Later] ... And that's what I would be thinking. Like because I think *it [heat] goes out as much as in* because if it returns back to the same temperature as it was at A, if *[heat] goes in* ... let's say it [the system] went up 10 degrees Kelvin, if it was up 10 degrees Kelvin and that's how the system changed. And then it loses that 10 degrees Kelvin, it's as though nothing ever happened. So I would say the total heat transfer is zero.

The following excerpt from S3 shows reasoning that was categorized as 'good understanding' of Q6(ii).

S3:	[The total energy transfer] is also zero because it returns to the same temperature as it was at time A. If it returns to the same temperature, any energy it absorbed went back to the ... actually some of it went into work, but that also ... because the net work was zero ... So, if there was some energy that got transferred to the gas that was used in work and therefore ... there was positive energy flow to the gas. Does that make sense? ... some of the energy was used up so all the energy that was transferred into the gas by the water cannot possibly go back to the water.
Interviewer:	Okay. Where was it used up?
S3:	In moving the piston.
Interviewer:	So what would your answer be for the heat transfer.
S3:	I wanna say zero because it's the same temperature [laughs] [After a long pause] The *total heat transferred to the gas* is greater than zero. Because the gas does this work in that time and it needs energy to do that because it returns to the same temperature and position as it was at the beginning. In order to do that work it needs energy from the water.

Discussion

In this paper we set out to answer two research questions: (1) When students activate state function reasoning, do they talk about heat with an identifiable metaphor? (2) Are students who are able to access more sophisticated expert-like meanings associated with 'heat' reasoning differently about heat in thermodynamic processes as compared to those who can only access more novice-like meanings? While our sample size is small, we can see clear relationships between metaphors that students use, their understanding of the term 'heat', and their reasoning. (1) Students who incorrectly reasoned that $Q = 0$ in Q6(ii) invoked the caloric metaphor far more frequently in their justification than students who do not suggest $Q = 0$. (2) Students who defined heat as substance or a 'normal' form of energy were more likely to answer $Q = 0$ for Q4 and Q6(ii) as compared to students who were able to access more expert-like definitions of heat. On Q5 all students were able to get this question correct, independently of the model they were able to access. This is not so surprising since no work is done during this stage of the cycle. In this step of the thermodynamic cycle, thinking of heat as a state function would be a productive resource. More remarkably, students who could access an expert-like definition of heat all spontaneously mentioned that no work was done in this step. This suggests that their expert-like understanding of heat is accompanied by an overall more sophisticated understanding of thermodynamic processes, being able to recognize that there are two competing processes (work and heating) that add or subtract energy from the system.

With our data and methodology, it is not possible for us to make causal assertions about the impact of the caloric metaphor on students' reasoning, whether reasoning is being driven by language choices or if students' underlying conceptions of heat are influencing their choice of language. What we observe from our data is that the caloric metaphor is connected to reasoning about heat that appears as state function-like reasoning. For example, students who are applying the caloric metaphor are saying that if the thermodynamic system returns to its initial starting point (same temperature as before), the amount of heat/heat energy in the system should be the same as it was initially and thus the net heat transfer for a closed thermodynamic cycle should be zero. Likewise, if temperature stays constant (as in an isothermal process) there should be no heat transfer during the process.

There are a number of possible interpretations of these results that we would like to consider:

(1) It could appear to the reader that learning and the development of expertise is a progression from a substance-based conception of heat to a process conception of heat (Chi et al., 1994). However, we believe a more nuanced view is necessary. It is likely that the more expert reasoners who explicitly defined heat as a process still find it productive to access other conceptions of heat as a substance. Gupta et al. (2010) provide some empirical evidence in support of this interpretation. We suggest that experts simply have more linguistic resources to draw from than novices do.

(2) Controlled studies introducing students to alternative ways of talking about thermodynamic phenomena show that we can have an impact on students' understanding and reasoning in that domain (Kaper & Goedhart, 2002). This result supports the idea that instructional linguistic choices can influence how a physical phenomenon is conceptualized. Alternatively, studies show that students activate different linguistic resources depending on the phenomenon they are trying to explain (Gupta et al., 2010, 2014). This result suggests to us that particular thought processes are influencing the language that students use to describe the phenomenon. The fact that both of these perspectives are supported by empirical evidence suggests to us that, as we claimed earlier in the introduction, the connection between language and thought is a bi-directional one. This in turn leads directly to our third and final point.

(3) Lemke (2004) has suggested that understanding is simply the ability to coordinate multiple representations of a phenomenon (including language) in productive and effective ways. He suggests that concepts do not exist independently from their representations, and it is the representations themselves (graphs, equations, spoken/written language, etc.) that constitute the concept itself.

In the context of point 3 above, what we see as the significance of our research is that it deepens our understanding of the role of language as a semiotic resource in students' reasoning. We have shown how (a) implicit ontological metaphors (encoded in grammatical structures) and (b) explicit ontology as expressed in how physical terms such as 'heat' are defined by the reasoner play a role in the case of reasoning about heat in a thermodynamic process.

Instructional Implications

Many physics textbooks explicitly tell students that heat is not like other forms of energy (rather, it is energy in transit) and is not a state function. And yet, any differentiation between heat as a regular form of energy and a 'special' form of energy ('disordered energy'/'energy in transit'), and/or heat as a process of energy transfer, is very subtle. It is therefore plausible that students entirely miss the subtle nuances of the experts' definition of heat (Roon et al., 1994) and simply stick to the idea that heat is a form of energy. This is especially complicated by the fact that most textbooks continue on talking about heat being transferred into or out of a thermodynamic system, entirely consistent with the 'energy in transit' definition. In this type of language, heat functions grammatically identically to any other form of energy. (In other words, the distinction between normal and special forms of energy cannot be made at a grammatical level.) We believe that the ubiquity of the caloric metaphor only encourages students to think of heat as a form of energy and suppress the nuances that are doubtless very difficult to understand on a single viewing of the definition.

While not directly related to the empirical findings in our paper, we would like to conclude by examining the tension that the bi-directional interaction of language and thought introduces into classroom discourse, and discuss a possible way to resolve that tension. To highlight this tension we observe that some researchers recommend that instructors be more precise in their language usage in the classroom (Williams, 1999), while others prefer to point out the value of students' innovative language usage even when that language is imprecise (Gupta et al., 2014). How can an instructor get students be more precise in their language usage without suppressing a classroom culture that values authentic sense-making? If we continue to follow the idea that available semiotic resources are what constitute a concept, learning physics is fundamentally an act of meaning-making (Lemke, 2004). From the observation of physical phenomena, we the instructors alongside with students develop semiotic resources (including language) to describe, make sense of, and then explain these observed phenomena. What that translates to in the classrooms of the authors is that we spend a great deal of effort as instructors, trying to create a classroom culture that adheres to certain linguistic norms. Specifically, students are not allowed to introduce technical terms before they establish an agreed meaning in the classroom learning community. The default expectation is that phenomena are described and explained in strictly non-technical terms. Introducing technical terms only happens later when the underlying mechanisms, the how and why of the phenomenon, is familiar to the members of the learning community. This approach is similar to what Arons (1997) has suggested, namely that technical nominalizing (e.g. calling a complex thermodynamic process 'heating') is one of the last stages of the learning process. Allowing language to naturally develop in this way, in our experience, helps students avoid many of the pitfalls that may arise from (a) linguistic resources that students bring into the classroom and whose meanings are not well established and (b) trying to explicitly define technical terms and encourage students to use the 'right' language from the get-go.

Disclosure Statement

No potential conflict of interest was reported by the authors.

Note

1. The interview questions and accompanying figures are reproduced with permission from Meltzer (2004), © 2004, American Association of Physics Teachers.

References

Arnold, M., & Millar, R. (1994). Children's and lay adults' views about thermal equilibrium. *International Journal of Science Education*, *16*(4), 405–419.
Arons, A. B. (1997). *Teaching introductory physics*. New York, NY: John Wiley and Sons, Inc.
Baierlein, R. (1994). Entropy and the second law: A pedagogical alternative. *American Journal of Physics*, *62*(1), 15–26.
Bauman, R. P. (1992). Physics that textbook writers usually get wrong: II. Heat and energy. *The Physics Teacher*, *30*(6), 353–356.
Beall, H. (1994). Probing student misconceptions in thermodynamics with in-class writing. *Journal of Chemical Education*, *71*(12), 1056–1057.
Brewe, E. (2011). Energy as a substance like quantity that flows: Theoretical considerations and pedagogical consequences. *Physical Review Special Topics—Physics Education Research*, *7*(2), 020106.
Brookes, D. T. (2006). *The role of language in learning physics* (Unpublished doctoral dissertation, Rutgers). The State University of New Jersey, New Brunswick.
Brookes, D. T., & Etkina, E. (2007). Using conceptual metaphor and functional grammar to explore how language used in physics affects student learning. *Physical Review Special Topics—Physics Education Research*, *3*(1), 010105.
Brookes, D. T., & Etkina, E. (2009). "Force," ontology, and language. *Physical Review Special Topics—Physics Education Research*, *5*(1), 010110.
Brookes, D. T., Horton, G. K., Van Heuvelen, A., & Etkina, E. (2005). Concerning scientific discourse about heat. In J. Marx, P. Heron, & S. Franklin (Eds.), *Proceedings of the 2004 physics education research conference* (Vol. 790, pp. 149–152). Melville, NY: American Institute of Physics.
Brown, S. C. (1950). The caloric theory of heat. *American Journal of Physics*, *18*(6), 367–373.
Chi, M. T. H., & Slotta, J. D. (1993). The ontological coherence of intuitive physics. *Cognition and Instruction*, *10*(2 & 3), 249–260.
Chi, M. T. H., Slotta, J. D., & de Leeuw, N. (1994). From things to processes: A theory of conceptual change for learning science concepts. *Learning and Instruction*, *4*(1), 27–43.
Cutnell, J. D., & Johnson, K. W. (2001). *Physics* (5th ed.). New York, NY: John Wiley & Sons.
Doige, C. A., & Day, T. (2012). A typology of undergraduate textbook definitions of 'heat' across science disciplines. *International Journal of Science Education*, *34*(5), 677–700.
Engel Clough, E., & Driver, R. (1985). Secondary students' conceptions of the conduction of heat: Bringing together scientific and personal views. *Physics Education*, *20*(4), 176–182.

Erickson, G. L. (1979). Children's conceptions of heat and temperature. *Science Education*, *63*(2), 221–230.
Etkina, E., Gentile, M., & Van Huevelen, A. (2014). *College physics*. Boston, MA: Pearson.
Feynman, R. P., Leighton, R. B., & Sands, M. (1965). *The Feynman lectures on physics: Quantum mechanics*. Reading, MA: Addison-Wesley.
Fuchs, H. U. (1987). Thermodynamics: A "misconceived" theory. In J. D. Novak (Ed.), *Proceedings of the second international seminar on misconceptions and educational strategies in science and mathematics* (Vol. 3, pp. 160–167). Ithaca, NY: Cornell University.
Giancoli, D. C. (2000). *Physics for scientists & engineers* (3rd ed.). Upper Saddle River, NJ: Prentice Hall.
Gupta, A., Elby, A., & Conlin, L. D. (2014). How substance-based ontologies for gravity can be productive: A case study. *Physical Review Special Topics—Physics Education Research*, *10*(1), 010113.
Gupta, A., Hammer, D., & Redish, E. F. (2010). The case for dynamic models of learners' ontologies in physics. *Journal of the Learning Sciences*, *19*(3), 285–321.
Halliday, D., Resnick, R., & Walker, J. (2003). *Fundamentals of physics* (6th ed.). New York, NY: John Wiley & Sons.
Halliday, M. A. K. (1985). *An introduction to functional grammar*. London: Edward Arnold.
Hammer, D. (2000). Student resources for learning introductory physics. *American Journal of Physics*, *68*(S1), S52–S59.
Harris, W. F. (1981). Heat in undergraduate education, or isn't it time we abandoned the theory of caloric? *International Journal of Mechanical Engineering Education*, *9*(4), 317–325.
Heath, N. E. (1974). Heating. *Physics Education*, *9*(7), 490–491.
Heath, N. E. (1976). Heating. *Physics Education*, *11*(6), 389–390.
Helsdon, R. M. (1976). Teaching thermodynamics. *Physics Education*, *11*(4), 261–262.
Hewson, M. G. (1984). The influence of intellectual environment on conceptions of heat. *European Journal of Science Education*, *6*(3), 245–262.
Hobson, A. (1995). Heat is not a noun. *The Physics Teacher*, *33*(9), 325–326.
Jasien, P. G., & Oberem, G. E. (2002). Understanding of elementary concepts in heat and temperature among college students and K-12 teachers. *Journal of Chemical Education*, *79*(7), 889–895.
Jeppsson, F., Haglund, J., Amin, T. G., & Strömdahl, H. (2013). Exploring the use of conceptual metaphors in solving problems on entropy. *Journal of the Learning Sciences*, *22*(1), 70–120.
Kaper, W. H., & Goedhart, M. J. (2002). 'Forms of energy', an intermediary language on the road to thermodynamics? Part II. *International Journal of Science Education*, *24*(2), 119–137.
Kesidou, S., & Duit, R. (1993). Students' conceptions of the second law of thermodynamics—An interpretive study. *Journal of Research in Science Teaching*, *30*(1), 85–106.
Lakoff, G., & Johnson, M. (1980). *Metaphors we live by*. Chicago, IL: The University of Chicago Press.
Leff, H. S. (1995). Entropy and heat along reversible paths for fluids and magnets. *American Journal of Physics*, *63*(9), 814–817.
Lemke, J. L. (1990). *Talking science: Language, learning, and values*. Norwood, NJ: Ablex Publishing Corporation.
Lemke, J. L. (2004). *Teaching all the languages of science: Words, symbols, images, and actions*. Presentation given at a conference, Barcelona. Retrieved from http://academic.brooklyn.cuny.edu/education/jlemke/sci-ed.htm
Lewis, E. L., & Linn, M. C. (1996). Where is the heat?: A response to David Pushkin. *Journal of Research in Science Teaching*, *33*(3), 335–337.
Loverude, M. E., Kautz, C. H., & Heron, P. R. L. (2002). Student understanding of the first law of thermodynamics: Relating work to the adiabatic compression of an ideal gas. *American Journal of Physics*, *70*(2), 137–148.

Meltzer, D. E. (2004). Investigation of students reasoning regarding heat, work, and the first law of thermodynamics in an introductory calculus-based general physics course. *American Journal of Physics*, *72*(11), 1432–1446.

Pushkin, D. B. (1996). A comment on the need to use scientific terminology appropriately in conception studies. *Journal of Research in Science Teaching*, *33*(2), 223–224.

Pushkin, D. B. (1997). Scientific terminology and context: How broad or narrow are our meanings? *Journal of Research in Science Teaching*, *34*(6), 661–668.

Reiner, M., Slotta, J. D., Chi, M. T. H., & Resnick, L. B. (2000). Naive physics reasoning: A commitment to substance-based conceptions. *Cognition and Instruction*, *18*(1), 1–34.

Romer, R. H. (2001). Heat is not a noun. *American Journal of Physics*, *69*(2), 107–109.

van Roon, P. H., van Sprang, H. F., & Verdonk, A. H. (1994). 'Work' and 'heat': On a road towards thermodynamics. *International Journal of Science Education*, *16*(2), 131–144.

Rozier, S., & Viennot, L. (1991). Students' reasonings in thermodynamics. *International Journal of Science Education*, *13*(2), 159–170.

Sapir, E. (1957). The status of linguistics as a science. In D. B. Mandelbaum (Ed.), *Culture, language and personality* (pp. 65–77). Berkeley, CA: University of California Press.

Serway, R. A., & Beichner, R. J. (2000). *Physics for scientists and engineers* (5th ed., Vol. 1). Orlando, FL: Saunders College Publishing.

Slisko, J., & Dykstra, D. I. (1997). The role of scientific terminology in research and teaching: Is something important missing? *Journal of Research in Science Teaching*, *34*(6), 655–660.

Sutton, C. R. (1993). Figuring out a scientific understanding. *Journal of Research in Science Teaching*, *30*(10), 1215–1227.

Tipler, P. A. (1999). *Physics for scientists and engineers* (4th ed., Vol. 1). New York, NY: W. H. Freeman and Company/Worth Publishers.

Tripp, T. B. (1976). The definition of heat. *Journal of Chemical Education*, *53*(12), 782–784.

Walker, J. S. (2002). *Physics*. Upper Saddle River, NJ: Prentice Hall.

Warren, J. W. (1972). The teaching of the concept of heat. *Physics Education*, *7*(1), 41–44.

Whorf, B. L. (1956). The relation of habitual thought and behavior to language. In J. B. Carroll (Ed.), *Language, thought, and reality. Selected writings of Benjamin Lee Whorf* (pp. 134–159). Cambridge, MA: The MIT Press.

Williams, H. T. (1999). Semantics in teaching introductory physics. *American Journal of Physics*, *67*(8), 670–680.

Zemansky, M. W. (1970). The use and misuse of the word "heat" in physics teaching. *The Physics Teacher*, *8*(6), 295–300.