# Concerning Scientific Discourse about Heat

## D. Brookes, G. Horton, A. Van Heuvelen, E. Etkina

*Department of Physics and Astronomy, Rutgers University, 136 Frelinghuysen Rd, Piscataway, NJ, 08854*

**Abstract.** We aim to examine communication in physics from a linguistic perspective and suggest a theoretical viewpoint that may enable us to explain and understand many physics students' alternative conceptions. We present evidence, in the context of the concept of heat, that physicists seem to speak and write about physical systems with a set of one or more systematic metaphors that are well understood in their community. We argue that physics students appear to be prone to misinterpreting and overextending the same metaphors and that these misinterpretations exhibit themselves as students' alternative conceptions. We will analyze physicists' discourse about heat and present evidence of a connection between students' alternative conceptions and the possibility that they are misinterpreting the language that they read and hear.

## INTRODUCTION

David Meltzer describes a study in which he gave 32 calculus-based introductory physics students at Iowa State University a closed thermodynamic cycle and were asked whether the net work done by the gas, and the total heat transferred to the gas, were positive, negative, or zero[1]. 69% of the interviewees said (incorrectly) that the total heat transferred to the gas for the entire process was zero. 63% said that the total work done by the gas was zero. Meltzer presents following quotations as a typical student responses.

> "[S1] The net work done by the gas…is equal to zero…The physics definition of work is like force times distance. And basically if you use the same force and you just travel around in a circle and come back to your original spot, technically you did zero work."

> "[S21] The heat transferred to the gas…is equal to zero…The gas was heated up, but it still returned to its equilibrium temperature. So whatever energy was added to it was distributed back to the room."

There are many possible reasons why students thought that the total heat and/or work for the cycle must be zero. Meltzer explains that students believe that work and heat are state functions of the system. We wish to investigate this idea further and attempt to explain why students might view heat as a state function. Terms such as "added to" suggest students are viewing the gas/system as a container of heat, and that they are confusing energy and heat as substances and using temperature as an indicator of the amount of heat *in* the system. In contrast, the argument about work seems to suggest a simpler view

of work as a state function based on the student's prior experience of work done in a conservative field. Thus we hypothesize that students' confusion with work as a state function comes from inappropriate transfer, while their confusion with heat may have linguistic origins. Our interest is with the role of language in students' reasoning and therefore we will focus on heat in this paper.

We will address two research questions. (1) We want to propose a coding scheme to code language used to describe physics ideas. (2) We will use this coding scheme to analyze textbook language about heat and connect this language to students' reasoning about heat in thermodynamic systems.

## THEORETICAL FOUNDATION

There has been considerable theoretical speculation[2, 3, 4, 5, 6, 7] and some practical evidence[7, 8] that language is not just a passive representation of reality. Rather, language also influences what the language user perceives and understands. Physicists and physics education researchers have argued that there is a linguistic component to mastering physics; that part of the difficulty of learning physics may lie in the language used to convey physics concepts. In particular, Arons and Touger have separately suggested that certain common locutions used by physicists may serve to reinforce incorrect ideas[9, 10]. Williams[11] has argued that part of students' difficulty in learning physics may lie in (1) the obscurity of the specialized meanings associated with certain terms, and (2) physicists' sometimes careless and contradictory use of language. Sutton[12, 13] has suggested that part of learning science must involve the reactivation of "dead"

metaphors. For example, to say that "heat flows. . . " suggests a metaphor, "heat is a fluid". Such a metaphor started out as an analogical model of heat as caloric fluid. To simply say "heat flows. . . " hides the applicability and limitations of this model. Itza-Ortiz et. al.[14] have shown a correlation between students' ability to distinguish every-day meanings of the word *force* from its meaning in physics and their performance answering class test questions which included the concept of *force*. Similar correlations were found for the words *impulse* and *momentum*.

When it comes to language about heat, there is consensus that physicists' language can be misleading, but little agreement about why it is misleading or how it can be corrected. Zemansky is content to accept using heat as a noun as long as it is clear that the term refers to the name of a process whereby energy is transferred into or out of a system. He cautions against using the term heat as a verb[15]. Baierlein, on the other hand, says exactly the opposite. To make the process nature of the term heat clear, he argues that one should never use heat as a noun, but rather as a verb[16]. Bauman[17] suggests replacing the term "heat" with "thermal energy" while Zemansky condemns this as a confusing oversimplification[15].

To resolve this confusion and to understand students' reasoning, we will consider language to be a representation of a physicist's model in the same way as a picture, or an equation. Inside any representation is a basic ontology of objects/substances, processes and states[18]. In the basic thermodynamics model the objects are point particles, processes are heating and work (processes of energy transfer) and the system possesses states (energy, pressure and temperature etc. . . ). One of the functions of language is to encode this ontology. Consider (1) "heat flows" versus (2) "energy is added to the system by heating". In the first case heat is functioning as a substance that is moving from one place to another. In the second, "heating" is functioning in the phrase as a process by which energy moves. The key to uncovering the implicit ontology in a linguistic representation lies in grammar of the phrases. This will be explained in the method section below.

## METHOD

To study the language physicists use to talk about heat, we analyzed three popular college level introductory physics textbooks[19, 20, 21]. Williams has argued that such textbooks represent a higher standard of linguistic rigor than the regular talk of physicists[11]. Thus a study of textbooks can at least give us an upper bound on the quality of language used to refer to the concept of heat. The goal of the analysis is to present a scheme

that can be used to understand the types of meanings that may be construed from the language of physics. To this end, we used an ergative/nonergative model of grammar. The detail of this approach may be found in Ref. [22]. In brief, the model identifies two core constituents of any clause in English, namely a *process* (verb or verb group) and *medium* (noun or noun group) which participates in the process. For example, "heat [*medium*] flows [*process*]". We used this scheme to classify the function of heat in each sentence (that contained the word "heat") in the textbooks, covering the chapters on temperature and thermodynamics. Compound sentences in which heat occurred twice were broken into two clauses and coded separately. This grammatical scheme was then mapped to a basic ontology coding scheme (substances, processes and states) in the following way. If heat functioned as the *medium* of the clause, or as a descriptor of the medium (grammatical *role*) it was classified ontologically as a *substance*. Cases where heat functioned as a grammatical process, descriptor of that process (grammatical *manner*), or as a nominalization (naming) of a process of energy transfer, were coded ontologically as a *process*. In a few cases where the word heat functioned grammatically as a *modifier* (adjective or adverb), it was classified ontologically as a *state*. The full mapping is shown in table 1. Using this mapping from grammar to ontology ensured the reliability and reproducibility of the coding.

**TABLE 1.** Table of grammar-ontology mapping

| Substance | Process | State |
|---|---|---|
| medium, agent, beneficiary, range, role | process, nominalizations of process, manner | any modifier |

## RESULTS

The results of the ontological analysis described above, are presented in figure 1.

We include six definitions of heat from six popular textbooks to serve as examples of the coding scheme. The first four are essentially substance based definitions, the last two are process definitions of heat:

- "Heat is energy that flows from a higher-temperature object to a lower-temperature object because of the difference in temperatures."[23]
- "Heat is the energy that is transferred between a system and its environment because of a temperature difference that exists between them."[24]
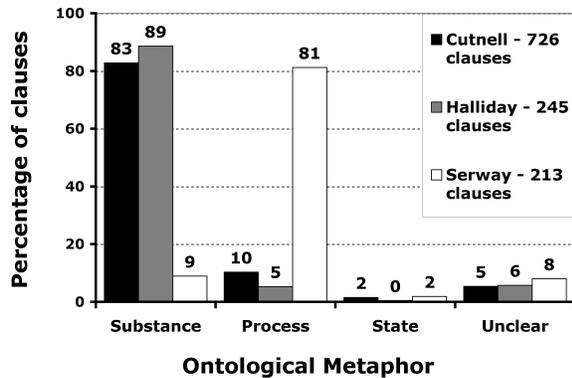
**FIGURE 1.** Classification of heat clauses into ontological categories.

- "Heat is energy that is transferred from one system to another because of a difference in temperature."[25]
- "…we will define heat as follows: Heat is the energy transferred between objects because of a temperature difference."[26]
- "…scientists came to interpret heat not as a substance, and not even as a form of energy. Rather, heat refers to a *transfer of energy*: when heat flows from a hot object to a cooler one, it is energy that is being transferred from the hot to the cold object."[27]

- "Heat is the transfer of energy from one object to another object as a result of a difference in temperature between the two."[28]

Compare statements, "heat is energy that flows/is transferred…" against "heat is the transfer of energy". In statements that suggest heat is synonymous with energy, the term "heat" is functioning as the grammatical medium and were classified ontologically as a *substance*. In statements that suggest that heat refers to a transfer of energy, "heat" is still functioning as the grammatical medium, but also as a nominalization, making the *process* nature of the term explicit. Giancoli's definition of heat[27] as the name of a process is not upheld by subsequent language in the same textbook. A cursory examination of the remainder of the text reveals a predominantly substance based language when referring to heat. Serway and Beicher[28] are the only authors of the group who use a consistent process-based language and who suggest the possibility of dual meanings associated with heat when they warn the reader: "We shall also use the term *heat* to represent the amount of energy transferred by this method."[29]

In order to further understand student's reasoning about heat, we added a another layer of analysis to this primary coding. Within the category of heat as a substance, heat is described as undergoing processes and the system serving as a receptacle of heat. From a survey of the data (textbook sentences), we identified a scheme of six metaphors (See table 2). Certain words that cue instances of the metaphor were identified. Words like "flow" and "transfer" imply movement of heat. Words like "absorbs", "into", "out" and "reservoir" imply that the system or the gas is a heat container[6]. A typical example of a sentence which would be classified as metaphor 3 is: "Determine whether the heat flows into or out of the gas."[30] The results of this coding are presented in table 2.

## DISCUSSION AND CONCLUSION

Although physicists are quite aware that heat should be thought of as a *process* rather than a *substance*[15, 16, 17], our coding shows that their language does not reflect this understanding. Our coding scheme also enables us to decide systematically what language more closely reflects the correct underlying ontology of modern thermodynamics.

Students' arguments in support of zero net heat transfer for a closed cycle seem to include mentioning the volume and temperature of the system, which may reflect the particular aspect of metaphor 3 where the system is viewed as a container of heat. We hypothesize that the fact that students seem to draw on qualities of the linguistic model indicates that their reasoning may, in some cases, be primarily based in the linguistic representation of the model. Or students' misconceptions about heat as a substance come primarily from the manner in which heat is spoken about in every-day language. If so, physicists' language seems to be reinforcing this idea rather than disabusing students of the notion.

Additional evidence for these ideas comes from two students interviewed by D.B., using Meltzer's questions[1]. They confidently argued that temperature was an indicator of how much heat was in the system and that the system was a container of heat.

> [S2] "…[total heat for the cycle is] zero as well since its come back to the same temperature. That means the same amount [of heat] has been subtracted out as was initially added in." He later confirmed: "Temperature's the same, pressure's the same, so I'm saying it started and ended with the same amount of heat."

Interestingly S3 started out with essentially the same reasoning, but later hesitated:

> [S3] "Well, its the term heat…I think I am confusing the term somehow…I think I'm just

**TABLE 2.** Metaphorical classification of heat clauses

| | Metaphor | % Cutnell | % Halliday | % Serway |
|---|---|---|---|---|
| 1 | Heat is a substance | 13 | 13 | 6 |
| 2 | Heat is a substance that moves from place to place | 17 | 18 | 1 |
| 3 | Heat is a substance that moves from system to system and the system/gas is a container of heat | 53 | 58 | 2 |
| 4 | Heat is a process | 10 | 5 | 26 |
| 5 | Heat is a process which involves the movement of a substance (energy) from place to place | 0 | 0 | 16 |
| 6 | Heat is a process in which a substance(energy) moves from one system to another and the system/gas is a container of that substance | 0 | 0 | 39 |
| 7 | Unclassified | 7 | 6 | 10 |

making it equivalent to temperature... Because its a transfer. Heat is a process, a transfer of energy..."

S3 had previously taken her introductory physics courses from one of the authors. In this course, A.V.H. had modified his language about heat to reflect its status in physics as a *process*.

Using systematic tools of discourse analysis from linguistics, we have shown that physicists talk about heat predominantly as if it were a substance. Thus it is possible that physicists' language may be misleading students, causing them to confuse processes with objects in thermodynamics. This can explain Meltzer's conclusion that students think that heat is state function because students see the system as a container of heat. To test this hypothesis it would be necessary to modify the language used for instruction to reflect the true status of heat as a process rather than a substance and pose the same questions to the students. More investigation is obviously needed.

# REFERENCES

1. D. E. Meltzer, *Am. J. Phys.* **72** (11), 1432-1446 (2004).
2. B. L. Whorf, "The Relation of Habitual Thought and Behavior to Language," in *Language, Thought, and Reality. Selected writings of Benjamin Lee Whorf*, edited by John B. Carroll, The M.I.T. Press, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1956, pp. 134-159.
3. B. L. Whorf, "Science and Linguistics," in *Language, Thought, and Reality. Selected writings of Benjamin Lee Whorf*, edited by John B. Carroll, The M.I.T. Press, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1956, pp. 207-219.
4. E. Sapir, "The Status of Linguistics as a Science," in *Culture, Language and Personality*, Selected essays edited by David B. Mandelbaum, University of California Press, Berkeley and Los Angeles, 1957, pp. 65-77.
5. M. J. Reddy, "The conduit metaphor: A case of frame conflict in our language about language," in *Metaphor and Thought*, edited by Andrew Ortony, Cambridge University Press, Cambridge, England, 1979, 2nd ed., pp. 164-201.
6. G. Lakoff and M. Johnson, *Metaphors We Live By*, The University of Chicago Press, Chicago and London, 1980.
7. J. L. Lemke, *Talking Science: Language, Learning, and Values*, Ablex Publishing Corporation, Norwood, NJ, 1990.
8. W-M. Roth and R. Duit, *J. Res. Sci. Teach.* **40** (9), 869-897 (2003).
9. A. B. Arons, *Teaching Introductory Physics*, John Wiley & Sons, Inc., New York, 1997.
10. J. R. Touger, *Phys. Teach.* **29**, 90-95 (1991).
11. H. T. Williams, *Am. J. Phys.* **67** (8), 670-680 (1999).
12. C. R. Sutton, *Leicester University School of Education Occasional Papers* (1978).
13. C. R. Sutton, *J. Res. Sci. Teach.* **30** (10), 1215-1227 (1993).
14. S. F. Itza-Ortiz, N. Sanjay Rebello, D. A. Zollman and M. Rodriguez-Achach, *Phys. Teach.* **41** (6), 330-336 (2003).
15. M. W. Zemansky, *Phys. Teach.* **8** (6), 295-300 (1970).
16. R. Baierlein, *Am. J. Phys.* **62** (1), 15-26 (1994).
17. R. P. Bauman, *Phys. Teach.* **30** (6), 353-356 (1992).
18. M. T. H. Chi, J. D. Slotta and N. de Leeuw, *Learn. & Ins.* **4**, 27-43 (1994).
19. J. D. Cutnell and K. W. Johnson, *Physics*, 5th ed., John Wiley & Sons, New York, 2001.
20. R. A. Serway and R. J. Beichner, *Physics For Scientists and Engineers*, 5th ed. Vol. 1, Saunders College Publishing, Orlando Fl, 2000.
21. D. Halliday, R. Resnick and J. Walker, *Fundamentals of Physics*, 6th ed., John Wiley & Sons, USA, 2003.
22. M.A.K. Halliday, *An Introduction to Functional Grammar*, Edward Arnold, London, 1985.
23. See Ref [19], p.358.
24. See Ref. [21], p.434.
25. P. A. Tipler, *Physics for scientists and engineers*, 4th Ed. Vol. 1, W.H. Freeman and company/Worth Publishers, New York, NY, 1999, p.566.
26. J. S. Walker, *Physics*, Prentice Hall, Upper Saddle River, NJ, 2002, p.499.
27. D. C. Giancoli, *Physics for scientists & engineers*, 3rd ed. Prentice Hall, Upper Saddle River, New Jersey, 2000, p.486.
28. See Ref. [20], p.580.
29. See Ref. [20], p.603.
30. See Ref. [19], p. 452.