Heat is not a noun

Let's strike a blow for clear thinking by ridding the English language of the word *heat* as a noun. ''What in the world is he driving at?,'' I immediately hear you asking. So let me get right to the point: Heat is not a substance! More formally: Heat is not a thermodynamic function of state.[1,2] Using *heat* as a noun helps to perpetuate erroneous thinking about physics and unnecessarily muddles our attempts to discuss thermodynamics.

Physics is full of words such as *force*, *energy*, and *acceleration* that are used all the time in non-physics talk, words which we have appropriated and to which we have given precise technical meanings, meanings that are often closely related to but not identical to their everyday meanings. In all these cases, it is our responsibility to explain as carefully as possible what we mean by a word and how it differs from its meaning in nonscientific discourse. Without such explanations, we are simply sowing unnecessary confusion in the minds of our students.

Heat presents one of our most serious linguistic problems. Not only is it a common word in the outside world, but in addition its frequent misuse within physics reinforces ancient and erroneous views of the physical world and encourages sloppy thinking.

If Rumford did not quite succeed in putting paid[3] to the caloric theory, then surely the experiments of Joule and the careful thinking of the thermodynamicians of the second half of the nineteenth century should have put it to rest forever. Yet we continue to hear vestiges of caloric theory in common talk. ''Winters are milder near the coast because the ocean holds a lot of heat.'' ''Heat rises.'' ''That brick physics building (or the tub in the apple cellar) holds a lot of heat.'' ''Turn on the Bunsen burner (do they still use them in chemistry classes?) and put some heat in that beaker.'' ''Great insulation in that house—they won't lose much heat this winter.'' ''The Holyoke steam power plant dumps a lot of heat into the Connecticut River.'' ''Close that door! Don't let the heat out.'' And I believe that caloric theory thinking continues to contaminate the minds and sentences of beginning students—and, indeed, those of too many of their professors.[4]

Here is what I find the logically purest way to begin thermodynamics.[5] *Adiabatic work is path independent*. That empirical fact is the first law of thermodynamics.[6,7] It is not, and this is important, a tautology.[8] How simple it is (for us!—over a century later) to state the first law. Note the absence of the word ''heat'' in the preceding statement.

Next, knowledge of the first law allows us to define something that *is* a thermodynamic function of state, the internal energy U:

$$\Delta U = W_{\text{adiabatic}}. \tag{1}$$

And then Q is the discrepancy between ΔU and W in a more general process:[9]

$$\Delta U = W + Q. \tag{2}$$

Once you put energy into a system (and allow it to reach equilibrium), the system does not remember how the energy arrived, whether because it was near something with a different temperature, because someone compressed it or stirred it, because someone immersed in it an electric heater, or whatever. Rid your vocabulary of the noun ''heat.'' If you want a name for Q (but who needs it?), call it ''energy transferred by virtue of a temperature difference'' or something similarly tortuous.

I have found as yet few supporters in my linguistic minicrusade. Baierlein[10] is one; Bohren and Albrecht[11] are also on my side, as is Leff.[12] Is there anyone else out there? All the dictionaries, of course, are solidly against me, including those of Microsoft. With Bill Gates on the other side, it looks like a losing battle. Even Zemansky, such a powerful advocate of clear thinking and writing in thermodynamics, seems to be against me, for in his famous article[13] on the subject he inveighs against the use of *heat* as a *verb!* If neither a noun nor a verb, what use is the word anyway? Let's get rid of it altogether; that would be fine with me. Perhaps that was what was in the mind of the unknown genius who introduced the symbol Q rather than H into this discussion at some point in the distant past.

It has not escaped my notice that the word *heat* appears with some frequency as a noun in my own 1976 book.[14] Though I now regret that fact, I believe that in every place where the word appears in that book, I was careful to accompany it with a word such as ''transfer'' or ''flow.'' And that leads me to my fallback linguistic position on *heat*. If you talk about ''transfer of heat'' or ''flow of heat,'' that construction is acceptable because the wording makes it clear that *heat* is a shorthand for energy in transit.[15] (I am not truly happy with phrases like ''transfer of heat;'' they are just too close to the ''heat is a substance'' point of view. Perhaps we could just write ''*toh*'' and think of it as a single word, like ''*emf.*'')[16] Also acceptable are terms such as ''heat flow'' or ''heat transfer'' or ''heat transfer coefficient.''[17] (I am not enthusiastic about turning nouns into adjectives, but of course in my thinking *heat* is not a noun anyhow.) Once in a while I have run across ''heat conductivity;'' the usual ''thermal conductivity'' is far better. ''Heat capacity'' is a dreadfully misleading term, which we are almost surely stuck with for historical reasons. One would think from the name that heat capacity (say at constant V) describes the totally meaningless[18] derivative $(\partial Q/\partial T)_V$. At least the SI units of specific heat capacity are convenient and easy to remember: foot–pounds/pound–Kelvin=feet per Kelvin. Angströms per °F if you prefer.[19]

Some of those who disagree with my objections to *heat* as a noun suggest that I must, logically, make the same demand about *work*.[20] The situation is not the same, because misuses of *work* do not in fact corrupt our thinking in the same way as do those of *heat*.[21,22] I find it difficult to construct a sentence in which the noun *work* does not appear with an appropriate preposition such as *on* or *by* and with an action verb such as *do*.[23] An expanding gas *does work on* something. I do not know of anyone who has been tempted to think of work as a substance or to talk about the ''work content of a system,'' as if work were a function of state. I have never heard the term ''work transfer,'' and Leff's objections (Ref. 17) to ''heat transfer'' do not apply.

I doubt that I will soon gain a great many converts to the particular plea that forms the title of this editorial. What I

work very hard on is to insist on scientific correctness, clarity,[24] and lack of ambiguity. I do hope that perhaps this editorial will contribute a bit to the goal of persuading teachers and authors to consider carefully the words and notation they use in their teaching and in their books and articles. I spend a lot of time and effort with authors, behind the scenes, striving for improvement in these areas, sometimes with alternative choices of words, sometimes with more sweeping suggestions for rewriting. ''Heat is not a noun'' is not a rule but a plea for clear thinking.[25] I believe firmly in striving for the greatest possible clarity in presenting our beautiful subject—and surely the terminology of thermodynamics continues to be one of our most vexing concerns.

[1]Of course, outside of physics, *heat* is often unobjectionable as a noun: ''Frank's Original Red Hot Cayenne Pepper Sauce—Adds Tang & Flavor, Not Just Heat.''

[2]Many thermodynamic quantities qualify as functions of state: *U, S, F, G*, etc. *Q* and *W*, however, most definitely do not—they denote energy in transit.

[3]Put paid to. Chiefly British. To finish off; put to rest. *The American Heritage Dictionary of the English Language* (Houghton Mifflin, Boston, 1992), 3rd ed. To deal finally or effectually with (a person); to terminate (aspiration, hopes, etc.); to eliminate or put an end to (something). ''He and his premises were put paid to by a land mine.'' (E. C. R. Lorac, 1955.) ''The return journey put paid to my only pair of formal trousers.'' (G. Household, 1971.) *Oxford English Dictionary*, 2nd ed. (1992, CD-ROM.) ''I thought I'd put paid to Bob in the first lap, but he caught me at the finish line.'' (Carson Rutherford, private communication, 1992. Delightful words to hear!)

[4]Not, of course, here at Amherst or at my graduate institution, Princeton. Well, hardly ever.

[5]In this sketch I am, of course, omitting the zeroth law, the meaning of ''temperature,'' and a good deal of important discussion.

[6]To elaborate a bit on that, let me quote from p. 14 of the wonderful little book by A. B. Pippard, *Elements of Classical Thermodynamics* (Cambridge U.P., Cambridge, 1957). ''If the state of an otherwise isolated system is changed by the performance of work, the amount of work needed depends solely on the change accomplished, and not on the means by which the work is performed, nor on the intermediate stages through which the system passes between its initial and final states.'' Some may be unfamiliar with this book, a brief 165-page gem which, as the title implies, includes no mention of kinetic theory or statistical mechanics. A few words from the preface may give a bit of the flavor of this too-little-known and unfortunately out of print book: ''It may be objected by some that I have concentrated too much on the dry bones [of thermodynamics], and too little on the flesh which clothes them, but I would ask such critics to concede at least that the bones have an austere beauty of their own.'' As a matter of fact, every one of Pippard's books will repay careful reading.

[7]The late Mark Zemansky, whose opinions on thermodynamics we must all take very seriously, states the first law thus: ''If a system is caused to change from an initial state to a final state by adiabatic means only, the work done is the same for all adiabatic paths connecting the two states.'' Mark W. Zemansky, *Heat and Thermodynamics* (McGraw–Hill, New York, 1968), 5th ed., p. 76.

[8]For some of my own thoughts on the ''tautology problem,'' see Robert H. Romer, *Energy—An Introduction to Physics* (W. H. Freeman, San Francisco, 1976, out of print), especially pp. 67–69, 220–224, 418–420, 446–451.

[9]Of course we must make some choice for the zero level for U. We also must be careful about signs; here I will make the logical choice of sign convention, not the choice usually made by physics authors. Like me, Zemansky (Ref. 7, p. 78) defines *Q* (''heat'') thus: ''When a system whose surroundings are at a different temperature and on which work may be done undergoes a process, the energy transferred by nonmechanical means, equal to the difference between the internal-energy change and the work done, is called heat.''

[10]Ralph Baierlein, ''Entropy and the second law: A pedagogical alternative,'' Am. J. Phys. **62** (1), 15–26 (1994), especially p. 22, and Ralph Baierlein, *Thermal Physics* (Cambridge U.P., Cambridge, 1999), especially pp. 16–18 and 21. On p. 18 of his book, however, he writes: ''Energy that is being transferred by conduction or radiation may be called 'heat.' That is a technically correct use of the word and, indeed, a correct use as a noun.'' Daniel Schroeder, author of another recent excellent thermal physics text, [*An Introduction to Thermal Physics* (Addison–Wesley, Reading, MA, 2000)], is not an ally; he does, however, carefully explain the logical issues and cautions against misuses of ''heat,'' and—I believe—does not allow the word to appear except in close proximity to words such as ''flow'' or ''transfer.'' See in particular Sec. 1.4.

[11]Craig F. Bohren and Bruce A. Albrecht, *Atmospheric Thermodynamics* (Oxford U.P., Oxford, 1998), especially pp. 24–28.

[12]Harvey Leff in fact takes an even stronger position than I do on the ''heat is not a noun'' issue. See Ref. 17 below.

[13]Mark W. Zemansky, ''The Use and Misuse of the Word 'Heat' in Physics Teaching,'' Phys. Teach. **8**, 295–300 (1970). But I do not think that Zemansky and I have a truly fundamental disagreement. What we are both advocating is clear thinking and the banishment of caloric theory from even our subconscious thinking. Though I shudder at his reference to ''the heat that has entered or left the system'' (p. 297), I think that if Zemansky were alive today, he and I could reach consensus, probably by agreeing to ban the word *heat* altogether.

[14]See Ref. 8 above. What I wrote then would stand up pretty well under my current line of criticism. See, for instance, p. 214: ''Heat ... is a particular type of energy *transfer*. Heat is not itself a form of energy an object can 'have'; heat is energy in transit. ... Maximum clarity would be achieved if we were to use the word 'heat' only to refer to *flows* of energy (of the type that take place between objects of different temperatures).'' There are more serious crimes in that book, a book of which I continue to hold a rather high overall opinion even though I wish I now had the opportunity to rewrite portions of it and to bring the data up to date. One is the wishy-washy introduction of the term ''thermal energy;'' somehow, I had the peculiar notion in those days that the nonscience students for whom the book was intended were not sophisticated enough to deal with ''internal energy'' or the idea of path independence. Since then I have taught many more nonscience students and have come to realize more explicitly that they may not know how to differentiate and integrate but are just as capable of handling ideas as are physics majors. See Zemansky (Ref. 13) for devastating remarks about *thermal energy*: ''... by all odds the most obscure, the most mysterious, and the most ambiguous term employed by writers of elementary physics and by chemists.'' (Chemists! That one hurts.) Bohren and Albrecht (Ref. 11, p. 23) write: ''With [Zemansky's] words ringing in our ears, how can we do other than toss thermal energy onto the scrap heap?'' One trap that I narrowly avoided in my book was erroneous or misleading talk about the work supposedly done by friction. In retrospect, I think that when I wrote my book, I knew that there were puzzles here that I did not yet know how to resolve and thus would do well not to get into. My thinking about friction and work has changed a great deal in the last quarter century, largely under the influence of some excellent articles (most of them in this journal), by Erlichson, Penchina, Sherwood, Bernard, Arons, Leff, and Mallinckrodt. See also Arons, Ref. 15 below.

[15]Like me in my 1976 book (Ref. 8, above), Zemansky (see Ref. 7) does not seem to use the noun without at least the implicit appearance of an accompanying word such as ''flow'' or ''transfer,'' and the same can be said of Schroeder, as noted above (Ref. 10). Although Arons is no ally of mine on the ''heat is not a noun'' front, he too seems never to use the word without a similar word in the immediate vicinity. See Arnold B. Arons, (A) *A Guide to Introductory Physics Teaching* (Wiley, New York, 1990). This wonderful book contains a wealth of valuable insights into physics and how to teach it. This book is reprinted as Part I of a composite book (B), *Teaching Introductory Physics* (Wiley, New York, 1997). Part II of (B) is also a reprint of a previously published book, *Homework and Test Questions for Introductory Physics Teaching* (Wiley, New York, 1994); Part III of (B) (which has not, as far as I know, been published separately) is an *Introduction to the Classical Conservation Laws*. In (A) and in Part III of (B), there is much thoughtful discussion of heat and work and how to present thermodynamics and how to deal with friction. As Arons points out, a lot of troublesome issues can be swept under the rug (and quite properly) by judicious choice of the boundaries of the ''system'' under consideration; I too (Ref. 8, especially in Sec. 4.1.A) tried to point out how important it is to specify the system under consideration and how different choices lead to different energy descriptions. Arons, on p. 125 of Part III of (B), *defines Q* with the three-word phrase ''transfer of heat,'' which is in accord with my fallback position. So much in our teaching, and in our chosen profession of physics, depends on the wise choice of words and of notation. Some attempt to deal with the issue of heat by means of notation,

and some of their contortions are wonderful to behold. δQ or ∂q, or perhaps dq instead of dQ, or all that discussion, pretty mysterious to me as an undergraduate, about ''inexact'' or ''imperfect'' differentials: $đQ + đW = dU$. Somehow those two bars on the left annihilate each other to produce a bar-free right-hand side. Some authors, such as Kittel and Kroemer [Charles Kittel and Herbert Kroemer, *Thermal Physics* (Freeman, San Francisco, 1980), p. 228], deal with the issue of defining ''heat'' by first defining entropy, and then defining heat by $đQ \equiv TdS$ (or $\tau d\sigma$, in their notation) in a reversible process. This approach I do not find congenial, at least not as a way to begin.

[16]An ''electromotive force'' is of course not a force and is best thought of as simply the composite symbol *emf*.

[17]But not to Leff. In a recent email, he writes ''I go a bit further than you'' and reminds me of the concluding remarks in his 1995 paper: ''Transfer of an entity implies movement of that entity from one storage region to another. ... We conclude that because heat cannot be stored, the term *heat transfer* is an oxymoron.'' See Harvey S. Leff, ''Entropy and heat along reversible paths for fluids and magnets,'' Am. J. Phys. **63** (9), 814–817 (1995).

[18]A mathematical expression that is, of course, meaningless because you cannot differentiate a nonexistent function. The same point often crops up in discussions of dc circuits, with (by coincidence) the same odd symbol, Q. (''Q is for heat,'' ''Q is for charge''?) Too many textbook authors ''define'' current by $I \equiv dQ/dt$, without bothering to notice that they have not defined a function $Q(t)$. At least in that case, one *can* (with some effort) define a function $Q(t)$ to be differentiated.

[19]In the hopes of forestalling more letters and messages about my tolerant attitude toward various systems of units, that was supposed to be a joke. (Intended, perhaps, to annoy the SI Police.) Not exactly a side-splitter, but how much can you expect in an editorial about thermodynamics?

[20]This point was made by one of my friendly but linguistically unenlightened critics, Daniel Schroeder. Schroeder of course understands completely the logical issues, but does not accept my linguistic remedy. The immediate provocation for this editorial was a challenge issued by Schroeder during a recent collegial email conversation: ''I dare you to write an editorial on this subject.''

[21]Except for the appalling though historically sanctified phrase, ''converting heat into work.'' That's not just impossible (at 100% efficiency), it's meaningless. Easier to convert lead into gold, because at least Pb and Au are substances. Michael Flanders and Donald Swann certainly distort and oversimplify thermodynamics, but in a musical version that is so much fun that it is hard to criticize: ''Heat is work and work is heat; Very good—Now, the *second* law of thermodynamics. ...''

[22]Hilborn has recently suggested (though not in a thermodynamic discussion) banning the word *work* from the language of physics. This may be a bandwagon; by the time we get through, few if any words will be left. See Robert C. Hilborn, ''Let's Ban *Work* from Physics!,'' Phys. Teach. **38** (7), 447 (2000).

[23]But easy enough if we broaden the context: ''Editing AJP is a lot of work.'' And it's just fine as a verb: ''I work my students very, very hard''; ''I worked all the problems in that #@!*X* book by Jackson (or perhaps by Schroeder).'' And then there is the delightfully ambiguous letter of reference: ''You will be fortunate indeed if you can get this person to work for you.''

[24]Here's another of my reform efforts, which so far has met with no success, as far as I know. You all know that dreadful diagram purporting to show the electric and magnetic fields of a plane wave, as a function of position (and/or of time?) that besmirch the pages of almost every introductory book. Two mutually perpendicular sinusoids, one for **E** and one for **B**, both firmly attached to the x axis and apparently in a ''perspective'' view, are supposed to represent a plane monochromatic linearly polarized wave. Arrows are all over the place, some denoting x, y, and z axes, some **E**, and some **B**. Physicists have trouble enough trying to show three quantities on a two-dimensional piece of paper, let alone nine or more. For examples of this sort of diagram, from two current and widely used texts, see Paul A. Tipler, *Physics For Scientists and Engineers* (Worth, New York, 1991), 3rd ed., Extended Version, p. 951, or David Halliday, Robert Resnick, and Kenneth S. Krane, *Physics* (Wiley, New York, 1992), 4th ed., Extended Version, Vol. 2, p. 877. When I was a child, trying to understand stuff about radio waves, that diagram nearly convinced me that I was a hopeless idiot. It was only much later that I realized that my problems largely stemmed from the fact that it is a horrible diagram. ''Misleading'' would be too kind a word; ''wrong'' is more accurate. Who knows what *space* things are being plotted in. Is it x, y, z space? Or B_x, B_y, B_z space? Or perhaps E_x, E_y, E_z space? (The figure in the first of the two texts referred to just above is extraordinarily odd. The three mutually perpendicular axes are labeled ''E,'' ''B,'' and ''Direction of propagation.'' What space is *that*?) Any halfway intelligent student should indeed be confused by that diagram—too many things being plotted on the same graph. It's as bad as trying to plot x, v, and a all on the same graph, something we enthusiastically criticize students for doing. (Sometimes the students are asked in which direction the wave is propagating. With all those arrows, including an emphatic one denoting the $+x$ direction, it seems quite unfair to choose an example in which careful inspection reveals that $\mathbf{E}\times\mathbf{B}$ is pointing in the $-x$ direction—as was done in one test I have seen. I wonder how many professors would give the correct answer for the direction of propagation, under pressure and amid all that clutter—and I wonder whether those who use such a test take care to read the testees their Miranda rights.) We should not be bothering to find out why students don't understand that silly diagram; we should congratulate them for their confusion, get rid of that diagram, and create new and intellectually acceptable ways of telling our students about electromagnetic waves—and perhaps then, for historical interest, find out how that diagram came to contaminate our literature in the first place. In the case of one manuscript submitted to this journal, I did try to get the authors to acknowledge how awful that diagram is. All I got for my trouble was the grudging insertion of words to the effect that some instructors blame the difficulties that students have with understanding electromagnetic waves on that diagram. ''Some [inadequate] instructors''—that surely includes me—find it difficult to talk students into comprehending an incomprehensible diagram.

[25]It is not an (unenforceable) ''AJP rule.'' But if you can avoid using *heat* as a noun, you have my blessing. If you want to think up a good noun for ''energy transferred by virtue of a temperature difference,'' that would be fine with me. Call it *Harry*, call it *Quincy*, anything except *heat*. Try it out on me next time you have occasion to submit a thermodynamic AJP paper. What AJP's next editor will think of your neologism I do not want to predict.

Robert H. Romer, *Editor*