Examining students' understanding of the first rule of thermodynamics, heat, and work in an introductory calculus-based general physics course

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Abstract

Students in an introductory university physics course were found to share many substantial difficulties related to learning fundamental topics in thermal physics. Responses to written questions by 653 students in three separate courses were consistent with the results of detailed individual interviews with 32 students in a fourth course. Although most students seemed to acquire a reasonable grasp of the state-function concept, it was found that there was a widespread and persistent tendency to improperly over-generalize this concept to apply to both work and heat. A large majority of interviewed students thought that net work done or net heat absorbed by a system undergoing a cyclic process must be zero, and only 20% or fewer were able to make effective use of the first law of thermodynamics even after instruction. Students' difficulties seemed to stem in part from the fact that heat, work, and internal energy share the same units. The results were consistent with those of previously published studies of students in the U.S. and Europe, but portray a pervasiveness of confusion regarding process-dependent quantities that has been previously unreported. Significant enhancements of current standard instruction may be required for students tomaster basic thermodynamic concepts.

I. INTRODUCTION

Thermodynamics has a wide-ranging impact, as is demon- strated by the number of different fields in which it plays a fundamental role both in practice and in instruction. The broad-based and interdisciplinary nature of the subject has motivated us to engage in a project to develop improved curricular materials that will increase the effectiveness of instruction in thermodynamics. We are initially investigating the effectiveness of current, standard instruction in order to pinpoint student learning difficulties that might potentially beaddressed with alternate instructional approaches.

Given the fundamental importance of thermodynamics, it is surprising that there has been little research into student learning of this subject at the university level. Although there have been hundreds of investigations into student learning of the more elementary foundational concepts of thermodynam- ics (such as heat, heat conduction, temperature, and phase changes) at the secondary and pre-secondary level, the num- ber of published studies that focus on university-level in- struction on the first and second laws of thermodynamics is on the order of ten, of which only one was devoted to phys- ics students at U.S. universities.[1]

Prior work has demonstrated convincingly that pre- university students face enormous obstacles in learning to distinguish among the concepts of heat, temperature, internalenergy, and thermal conductivity. In physics, heat (or heat transfer) is a process-dependent variable and represents a *transfer* of a certain amount of energy between systems due to a temperature difference. By contrast, in the kinetic theoryof a gas, temperature is a measure of the average kinetic energy of the molecules in a system. However, among begin-

ning science students heat is frequently interpreted as amass-independent *property* of an object and temperature isinterpreted as a measure of its intensity. Often, temperatureand heat are thought to be synonymous. Alternatively, heatoften is interpreted as a specific quantity of energy possessedby a body with temperature a measure of that quantity.[2–4]Objects made of materials that are good thermal conductorsare believed by students to be hotter or colder than otherobjects at the same temperature, due to the sensations expe-rienced when the objects are touched.[5] Instructors at the uni-versity level often have noted similar ideas among their ownstudents,[6] and investigations that have probed university stu-dents' thinking about these concepts have recently appeared.[7] A few investigations have been reported that examined pre-university students' understanding of the concept of en-tropy and the second law of thermodynamics.[3,8] Several re-ports have examined student learning of thermodynamicsconcepts in university chemistry courses.[9–15] Some of thesestudies have touched on first- and second-law concepts inaddition to topics more specific to the chemistry context. Among the investigations directed at university-level physicsinstruction, one in France focused on oversimplified reason-ing patterns used by students when thinking about thermo-dynamics, particularly when explaining multivariable phe-nomena with reference to the ideal gas law.[16] A Germanstudy examined the learning of basic thermal physics con-cepts by students preparing to become physics teachers.[17] There also was a very brief report of a survey of entrants toa British university,[18] and a study related to U.S. students' concepts of entropy and the second law of thermo-dynamics.[19]

The first detailed investigation of university physics stu- dents' learning of heat, work, and the first law of thermody- namics was published by Loverude, Kautz, and Heron in 2002.[20] (Additional details are in Loverude's dissertation.[21]) This study incorporated extensive data collected from obser- vations at three major U.S. universities and documented se- rious and numerous learning difficulties related to fundamen-tal concepts in thermodynamics. It was found that many students had a very weak understanding of the work concept and were unable to distinguish among fundamental quantities such as heat, temperature, work, and internal energy. Only a small proportion of students in introductory courses werefound to be able to make use of the first law of thermody- namics to solve simple problems in real-world contexts.

The present investigation includes an independent exami- nation of some of the same research questions analyzed in Ref. 20 and other, related questions. A preliminary report of the work described here appeared in 2001.[22]

Our findings include several previously unreported aspects of students' reasoning about introductory thermodynamics. In contrast to at least one previous report,[11] it was found that students have a reasonably good grasp of the state-function concept. However, students' understanding of process- dependent quantities was seriously flawed, as sizeable num- bers of students persistently ascribe state-function properties to both work *and* heat. This confusion regarding work and heat is associated with a strong tendency to believe that the net work done and the net heat absorbed by a system under- going a cyclic process are both zero. Interview data disclosedunanticipated levels of confusion regarding the definition of thermodynamic work and heretofore unreported difficulties with the concept of heat transfer during isothermal processes. Consistent results over several years of observations enabled us to make a high-confidence estimate of the prevalence of difficulties with the first law of thermodynamics among stu-dents in the calculus-based general physics course. Our find- ings should help provide instructors of introductory physics with a solid basis on which to plan future instruction in ther- modynamics.

II. CONTEXT OF THE INVESTIGATION

Our data were collected during 1999–2002 and were in three forms: (1) a written free-response quiz that was admin-istered to a total of 653 students in three separate offerings (Fall 1999, Fall 2000, Spring 2001) of the calculus-based introductory physics course at Iowa State University (ISU);
(2) a multiple-choice question that was administered to 407 students on the final exam during the 2001 course offering; and (3) one-on-one interviews that were conducted with 32 student volunteers who were enrolled in a fourth offering of the same course in Spring 2002.

A. Written diagnostic

Thermodynamics is studied at ISU during the second se- mester of the two-semester sequence in calculus-based intro- ductory general physics, which is offered during both the fall and spring semesters. Most students taking this course are engineering majors. The course is taught in a traditional manner, with large lecture classes (up to 250 students), weekly recitation sections (about 25 students), and weekly labs taught predominantly by graduate students. Homework is assigned and graded every week. Thermal physics com- prises 18 –25% of the course coverage, and includes a wide

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Variety of topics such as calorimetry, heat conduction, kinetic theory, laws of thermodynamics, heat engines, and entropy.

The 1999 and 2000 classes were taught by the same in- structor, using a different textbook in each course. The 2001 course was taught by a different instructor, using the same text (later edition) that was employed in the 1999 course.[23] Both instructors are very experienced and have taught intro- ductory physics at ISU for many years. (The author was not involved in the instruction in any of the courses that servedas a basis for this study.)

A written diagnostic quiz (described in Sec. IV) was ad- ministered in two different ways: in 1999 and 2001, it was given as a practice quiz in the final recitation session (last week of class). In nearly all cases it was ungraded, although one recitation instructor used it as a graded quiz. In 2000 the quiz was administered as an ungraded practice quiz in the last lecture class of the semester. In addition, a multiple- choice problem similar to those on the diagnostic quiz was administered on the final exam of the 2001 course.

B. Interviews

During the Spring 2002 offering of this course, instead of administering a written diagnostic quiz, student volunteers were solicited to participate in one-on-one problem-solving interviews in which their reasoning processes were probed in depth. This course was taught by the same instructor as the Spring 2001 course. Thermal physics topics occupied 25% of the class lectures, and a different text[24] was used than in the previous courses. Due to travel obligations, two different fac- ulty members (the professor in charge of the course, plus another very experienced instructor) were responsible for presenting the thermodynamics lectures.

Exam questions and assigned homework problems in- cluded calculations of work done, heat transferred, and changes in internal energy during various processes (some represented on P-V diagrams), including adiabatic, isother- mal, isobaric, and numerous cyclic processes. Other ques- tions related to the temperature/kinetic energy/internal en- ergy relationship, and to the efficiency of heat engines and refrigerators. (There also were many problems related to the other thermal physics topics covered during the course.)

All lectures and homework assignments related to thermal physics were completed before the second midterm exam. This exam included questions related to the role of the ther- mal reservoir in an isothermal expansion, changes in internal energy during a cyclic process, and many questions related to entropy, engines, and the second law of thermodynamics.

Interviews began five weeks after the second midterm exam, and continued over a three-week period through the week of final exams. A new set of questions was developed for the interviews. (These are the Interview Questions shown in the Appendix and discussed in Sec. IV.) The average du- ration of each interview was over 1 h, including time for the students to work by themselves. Many interviews extended longer than that period, and a few were shorter. All were recorded on audiotape. Students were asked to explain as best they could how they obtained their answers to the ques- tions. When inconsistencies appeared in their responses, theywere urged to address them. This often led to changes in responses, often from incorrect to correct, sometimes from one incorrect answer to a different one, but only very rarely from a correct response to one that was incorrect. Substantial efforts were exerted to ensure that students very clearly un- derstood the meaning of the questions, diagrams, and spe-

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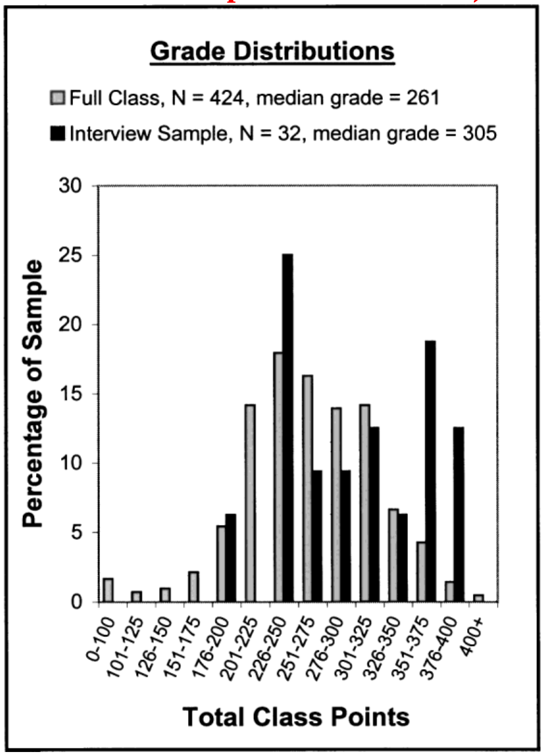

Fig. 1. Grade distributions for the interview sample (N=32) and for the full class from which the interview sample was drawn (N=424). Grades based on total class points (nominal maximum=400). The interview sample mean score (300) and median score (305) are well above the corresponding scores for the full class (mean score=261, standard deviation=59; median score =261).

cific terminology employed. Any apparent ambiguities in the students' interpretations of the questions were explicitly addressed by the interviewer (the author).

III. CHARACTERIZATION OF THE INTERVIEW SAMPLE

There were 32 students in the interview sample. They were drawn from 13 different recitation sections (out of a total of 20), taught by seven different recitation instructors (out of a total of nine), and 66% were engineering majors. Other majors with at least two representatives were computer science, chemistry, and meteorology; there was one physics major. All but one had studied physics while in high school, and many had taken Advanced Placement physics or a com- munity college physics course while in high school.

The grading in the course was based on exam scores (three midterm exams and a final) plus a recitation-laboratory grade; the nominal maximum total points available was 400. The distributions of total class points (out of 400) both for the full class (N=424) and the interview sample (N=32) are plotted in Fig. 1 as a percentage of each population. It can be seen that the scores of the students in the interview sample are strongly skewed toward the top end of the class. More than one third of the interview sample scored above the 91st percentile of the class, and half scored above the 81st percentile; only two students in the interview sample fell below the 25th percentile. It is evident that the average level of knowledge demonstrated by the interview sample is very unlikely to be lower than that of the class population as a whole.

or ***equal to*** that for Process #2? Explain.

2. Is Q for Process #1 ***greater than***, ***less than***, or ***equal to*** that for Process #2? Please explain your answer.

3. Which would produce the largest change in the total energy of all the atoms in the system: ***Process #1***, ***Process #2***, or ***both processes produce the same change?***

Fig. 2. Written quiz used in investigation, referred to as ‘‘Diagnostic Ques- tions.’’ This version was administered in Spring 2001. Responses to this quizare shown in Tables I and II.

IV. DIAGNOSTIC QUESTIONS AND INTERVIEWQUESTIONS

The written diagnostic quiz is shown in Fig. 2; it was administered in four separate courses. The version shown here was administered in Spring 2001, and it was also used (with minor wording changes to match the terminology ofthe course textbook) during the interviews conducted in Spring 2002. The Fall 1999 and Fall 2000 versions had very minor variations from the one shown in Fig. 2 with respect to Questions #1 and #2. A different version of Question #3 was used in 1999, and it was omitted entirely in 2000.

For the interviews, an additional separate set of questions was developed consisting of eight sequential questions re- lated to two cyclic processes. (Before being presented with the questions, interview subjects were first asked to respond to the written diagnostic quiz.) The questions are shown in the Appendix. A *P*-*V* diagram corresponding to the pro- cesses described in these questions is shown in Fig. 3; this diagram was not given to the students. (Note that this processis the same as depicted in Fig. 4 of Ref. 20, although tra- versed in the opposite direction.) Students were asked to

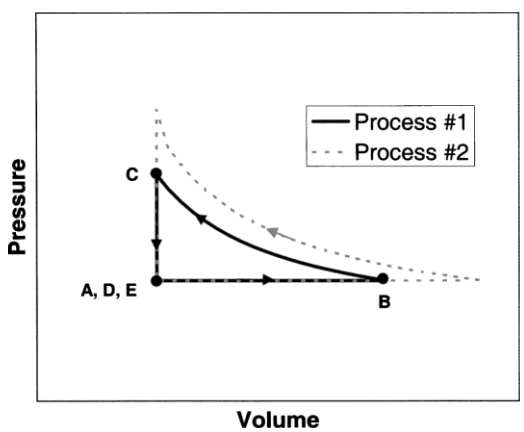

Fig. 3. A *P*-*V* diagram corresponding to processes described in the Inter- view Questions. (This diagram was not shown to the students.)

circle their answers to these questions and verbally explain the reasoning they used to obtain their answers. (Several mi- nor changes in wording to the questions were made to im- prove clarity during the course of the series of interviews.)

The multiple-choice question administered on the 2001 final exam will be described in Sec. VI.

V. THERMAL PHYSICS CONCEPTS: PREDOMINANT THEMES OF STUDENTS’ REASONING

The students’ responses to items #1 and #2 of the diagnos- tic questions are shown in Tables I and II, respectively. The responses in the 1999, 2000, and 2001 samples were very consistent from one year to the next. They also are consistentwith the verbal and written responses given to the samequestions by students in the interview sample. In Table III, the responses of students in the interview sample to the ques-tions in the Appendix are tabulated.

In the following, I will examine in detail the most preva- lent concepts in students' thinking. In each case the subhead-ing refers to a reasoning pattern common to a minimum of 20–25% of all students in the respective samples.

A. Relation between temperature and molecular kineticenergy

A fundamental link between the macroscopic and micro- scopic models of thermodynamics lies in the proportionality between temperature and the average molecular kinetic en- ergy of a gas. Almost all introductory texts use the kinetic

theory of gases to provide a derivation of the relation $KE_{tot}=(3/2)nRT$ for the total molecular kinetic energy contained within n moles of a monatomic ideal gas. Interview Question#3 asks students about possible changes in the total kinetic energy of the molecules of the system during the isothermal compression occurring from time B to time C. No deep un- derstanding is required to respond that this energy remains unchanged during the process. Although a slim majority (56%) of students give this answer, nearly one third assert that the total molecular kinetic energy will increase. This difficulty in matching an isothermal ideal-gas process with no change in molecular kinetic energy has not been previ- ously reported.

During the interviews, students who asserted that the mo- lecular kinetic energy would change during the isothermal process were usually asked to explain what role, if any, the temperature had played in their reasoning. The most com- mon line of reasoning is typified by these responses:

(The designation ''S11'' refers to student #11, using an arbitrary numbering system for students in the interview sample.)

> ''[S11] There's a higher pressure; the molecules are moving faster, hitting the sides faster, which creates a larger pressure. And so since they're moving faster, they have a higher kinetic energy.''
> ''[S21] When the volume decreases, something has to make up for it. In this case the pressure's going to increase. If you add more pressure you're going to increase the collisions of the particles, and so ... the kinetic energy will increase because of that. They're moving faster; kinetic energy is related to the speed of the particles ... *Interviewer: Did the temperature play any part of this, any con-sideration here*? Yes ... If you're going to increase the pressure, the temperature also increases ... *In- terviewer: I should point out that ... the tempera- ture is the same as at time B* ... In that case then, the temperature would not have a factor on kinetic energy ... The kinetic energy varies with the tem- perature, but the temperature doesn't change; it won't affect the kinetic energy. In this case, the pressure's the only part of the $PV=nRT$ equation that's going to affect the kinetic energy.''

Reference 20 pointed out that students frequently invoked a ''collision'' argument similar to that used by these two students, to account for temperature increases during adia- batic compression. The same observation was made by Ro-

Table I. Responses to diagnostic Question #1 (work question).

	1999 (N=186)	2000 (N=188)	2001 (N=279)	2002 Interview Sample (N=32)
$W_1>W_2$	**73%**	**70%**	**61%**	**69%**
Correct or partially correct explanation	a	56%	48%	66%
Incorrect or missing explanation	a	14%	13%	3%
$W_1=W_2$	**25%**	**26%**	**35%**	**22%**
Because work is independent of path	a	14%	23%	22%
Other reason, or none	a	12%	13%	0%

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$W_1<W_2$	**2%**	**4%**	**4%**	**9%**

[a]Explanations not required in 1999.

Table II. Responses to diagnostic Question #2 (heat question).

	1999 (*N*=186)	**2000** (*N*=188)	**2001** (*N*=279)	**2002 Interview Sample** (*N*=32)
$Q_1>Q_2$	**56%**	**40%**	**40%**	**34%**
Correct or partially correct explanation	14%	10%	10%	19%
Q is higher because pressure is higher	12%	7%	8%	9%
Other incorrect, or missing explanation	31%	24%	22%	6%
$Q_1=Q_2$	**31%**	**43%**	**41%**	**47%**
Because heat is independent of path	21%	23%	20%	44%
Other explanation, or none	10%	18%	20%	3%
$Q_1<Q_2$	**13%**	**12%**	**17%**	**13%**
Nearly correct, sign error only	4%	4%	4%	3%
Other explanation, or none	10%	8%	13%	9%
No response	**0%**	**4%**	**3%**	**6%**

zier and Viennot in their study of French universitystudents.[25] In the present study, it is seen for the first time that the argument that molecular collisions produce a net increase in molecular kinetic energy is so compelling for many students that they apply it even in the case of an iso- thermal process, persisting even after acknowledging the ex- istence of a relation between temperature and kinetic energy. For many students, the relationship between temperature and the molecular kinetic energy of an ideal gas—considered vir-tually axiomatic by many instructors—is one that is only vaguely understood.

B. The concept of state function in the context of energy

The concepts of state and state function are fundamental to thermal physics and provide a starting point for the analysis of all thermodynamic phenomena and processes. Question#3 on the written quiz probes understanding of these con- cepts. (This question was not administered in 1999 and 2000.) In the 2001 sample, 73% responded correctly to this question, saying that the total energy change in the two pro- cesses would be the same. In the interview sample, 88% provided this correct response. Of the students in the latter sample, 78% provided an acceptable explanation of their an- swer, that is, they either associated the energy change of the atoms with the temperature change and noted that these changes would be equal for the two processes, or they ex- plicitly stated that the energy (or internal energy) was a state function and depended only on initial and final states, was independent of path, etc. A similar problem dealing with this issue is Interview Question #7. As shown in Table III, 90%of students in the interview sample gave a correct answer to this question with an acceptable explanation.

In 1999, instead of Question #3 as shown in Fig. 2, the following question was presented: ''Consider a system that begins in State A, undergoes Process #1 to arrive at State B, and then undergoes the *reverse* of Process #2, thereby arriv- ing once again at State A. During this entire back-and-forth process (A B A), does the internal energy of the system (E_{int}) undergo a *net increase*, a *net decrease*, or *no net change*? Explain your answer.''

Of the 186 students in the 1999 sample, 85% correctly answered that the internal energy of the system would un- dergo no net change in the cyclic process described; 70% gave an acceptable explanation for their answer. These re- sults along with those from 2001 suggest that students be-
come comfortable with the idea that a thermodynamic sys- tem might be in one or another state, where a

state is characterized by a certain value for the total energy con- tained within the system. They seem to realize that in making a transition from one state to another, the particular process involved in the transition does not affect the net energy change, and that the net change is determined only by the initial and final states. When the system follows a route that brings it back to that initial state, they are able to see that the total energy also must return to its initial value.

During the course of the interviews, it was evident that students associated not only a specific energy value with a given thermodynamic state, but realized that each state was characterized by well-defined values for the pressure, vol- ume, and temperature as well. Although very few students spontaneously articulated a precise definition of ‘‘state,’’ state function, or internal energy, they solved problems and provided explanations in a manner that was consistent withat least a rudimentary understanding of those concepts. (This conclusion is in marked contrast to the conclusions of Kaper and Goedhart in relation to Dutch chemistry students in a thermodynamics course.[11])

Many of the conceptual difficulties encountered by stu- dents in the context of thermal physics seemed to stem from an overgeneralization of the concept of state function. In thermal physics, quantities (such as heat transfer and work) which are *not* state functions, but instead characterize spe- cific thermodynamic processes, are equally as important as state functions to understanding and applying thermody- namic principles. Most of our remaining discussion will be devoted to analyzing students' reasoning regarding these process-dependent quantities, as well as the first law of ther- modynamics which relates these quantities to the internalenergy.

C. Work as a mechanism of energy transfer

An elementary notion in thermal physics is that if a system characterized by a well-defined pressure undergoes a quasi- static process in which a boundary is displaced, energy is transferred between the system and the surrounding environ- ment in the form of work. If the volume of the system in- creases, internal energy of the system is transferred to the environment and we say that work is done *by* the system; conversely, if the volume decreases, work is done *on* the system and energy is transferred *to* it. The critical distinction

Table III. Responses to Interview Questions (N=32).

Question	Response	Proportion giving response
#1		
	Work is done *on* the gas	31%
	Work is done *by* the gas (*correct*)	69%
#2		
	Increases by x Joules	47%
	Increases by less than x Joules	41%
	with correct explanation	*28%*
	with incorrect explanation	*13%*
	Remains unchanged	9%
	Uncertain	3%
#3		
	Increase	31%
	Decrease	13%
	Remain unchanged (*correct*)	56%
#4		
	No	59%
	Yes, from water to gas	3%
	Yes, from gas to water	38%
	with correct explanation	*31%*
	with incorrect explanation	*6%*
#5		
	Decreases by less than y Joules	16%
	Decreases by y Joules	84%

	(*correct*)	
#6, i		
	Greater than zero	16%
	Equal to zero	63%
	Less than zero (*correct*)	19%
	No response	3%
#6, ii		
	Greater than zero	9%
	Equal to zero	69%
	Less than zero	16%
	with correct explanation	*13%*
	with incorrect explanation	*3%*
	Uncertain	6%
#7[a]		
	All equal (*correct*)	90%
	Other response, or none	10%
#8[b]		
	$\|W_1\|=\|Q_1\|=0$	50%
	$\|W_1\|=\|Q_1\|$G0 (*correct*)	16%
	Uncertain	6%
	Other response	28%

[a]N=30.
[b]Responses regarding Process #1 only.

is not so much in recognizing whether the words ‘‘by’’ or ‘‘on’’ should be used in a particular instance; rather, it is essential to recognize whether energy is transferred *into* or *out of* a system as a result of the process.

Loverude *et al.* have described and documented many of the difficulties students encounter when studying the concept of work, both in the context of mechanics and in that of thermal physics.[20] They showed that few students were spon- taneously able to invoke the concept of work when discuss- ing the adiabatic compression of an ideal gas. Students were unable to understand that an entity called work could bring about a change in the internal energy of a system. There was a tendency to treat the concept of work as superfluous, as unconnected to temperature changes in gases, or on the other hand, as being essentially synonymous with heat. Many stu- dents were unable to recognize that heat and work are inde- pendent means of energy transfer.

The results of our investigation fully support their conclu- sions and offer additional insight into the nature of student reasoning regarding work in the context of thermodynamics. Responses given during the interviews to Questions #1 and #2 reveal that approximately 1/3 to 1/2 of the students in the interview sample have a substantial confusion regarding this concept.

Interview Question #1 asks students whether positive work is done on or by the gas during the isobaric expansion process from time *A* to time *B*. To answer, a student must recognize that the expansion of a system corresponds to posi- tive work being done by the system on the surrounding en- vironment. However, 31% of the students in the interview sample said that the expansion process described in Question #1 corresponded to positive work being done *on* the gas by the environment. They backed up their answer with explana- tions that made it clear that this error was not merely a se- mantic confusion:

> ‘‘[S31] The gas is expanding and for it to expand, heat or energy or something had to be put into it to get it to expand. And, since the only option of putting stuff into the gas is ‘*a*’ [*positive work done on the gas by the environment*], that’s why I picked ‘*a*.’ ’’
> ‘‘[S20] The environment would be water and stuff ... water would be part of that, and since it moved the piston up ... the environment did work on

> the gas, since it made the gas expand and the piston moved up ... water was heating up, doing work on the gas, making it expand.''

These and similar responses suggest that many students simply do not realize that as the gas expands against its sur- rounding environment, the gas *loses* energy as a result of the work done during the process. They realize that there is en- ergy transfer to the gas in the form of heat, but do not seem to recognize that there is energy transfer away from the gas in the form of work. Instead, as previously pointed out in Ref. 20, students make a fundamental error by identifying ''work'' with energy transfer in the form of heat, and in general they have difficulty distinguishing between the two quantities. In the case of adiabatic compression, students in the Loverude *et al.*[20] study had used ''heat'' when ''work'' would have been appropriate. Analogously, in the case of isobaric expansion, students often use the word ''work'' to refer to a heating process. The belief that positive work is done *on* a system by the environment during an expansion process has not been previously reported.

It is interesting to compare this observation to results of a study by Goldring and Osborne[26] of students taking A-level physics in London secondary schools. (This level is roughly equivalent to introductory college physics in the U.S.) They found that more than half of the students in their study claimed that work is done both when an object is heated and also whenever energy is transferred. Similarly, nearly half said that heat is always created when work is done.

The problem of not recognizing the energy-transfer aspect of macroscopic work plays an even more significant role in students' responses to Interview Question #2, and it is this set of responses that validates the interpretation of students' thinking proposed above in connection with Question #1. Students are told that the gas absorbs *x* Joules of energy from the water during the heating-expansion process, and are asked what will happen to the total kinetic energy of all the gas molecules. The correct answer (''increases, but by less than *x* Joules'') was given by 41% of the students, but only 28% could provide a correct explanation such as this stu- dent's answer:

> ''[S9] Some heat energy that comes in goes to ex- panding, and some goes to increasing the kinetic energy of the gas.''

Almost half of the students (47%) answered that ''the total kinetic energy of all of the gas molecules increases by *x* Joules,'' with explanations such as

> ''[S3] For it to increase by less than *x* Joules that energy would have to go somewhere, so that would say that the potential energy of the gas had increased, and I don't see how that would be hap- pening.''
>
> ''[S4] There would be conservation of energy. If you add that much, it's going to have to increase by that much.''
>
> ''[S5] Kinetic energy is going to increase by *x* Joules because, I assume that there's no work done by expansion, that it doesn't take any kind of en- ergy to expand the cylinder, which means that all of my energy is translated into temperature change.''

This fundamental confusion regarding the energy-transfer role of work is a very serious obstacle to understanding the basic principles of thermal physics, and in particular serves as a nearly insuperable barrier to grasping the meaning of the first law of thermodynamics.

D. Belief that work is a state function

P-*V* diagrams permit a simple interpretation of the work done by a system during a process as the area under the curve describing the process. Many elementary problems in- volve calculations of work done during different processes linking common initial and final states, in order to illustrate and emphasize the concept that work is a process-dependent function and not a state function. It is all the more remark- able, then, that the results of our investigation show so clearly that approximately one quarter of all students in our samples are confused about this fundamental concept. This corroborates the findings of Ref. 20, which documented widespread misunderstanding of this concept among both in- troductory and advanced physics students when it was pre- sented in the context of *P*-*V* diagrams.

Table I shows responses to Question #1, comparing the work done by two different processes linking initial state *A* and final state *B*. In this diagram, it is very clear that the area under the curve representing process #1 is greater than the area under the curve representing process #2, and so the work *W* done by the system is greater for process #1. How- ever, 30% of the students who answered the written diagnos-tic in 1999, 2000, and 2001 asserted that the work done during process #1 would be equal to the work done during process #2. Of the students who were asked to provide an explanation, 19% explicitly argued that work was indepen- dent of the path. Similarly, 22% of the interview subjects claimed that $W_1=W_2$, all of whom made an explicit argu- ment asserting that work was independent of process, for example: ''work is a state function,'' ''no matter what route

you take to get to state B from A, it's still the same amount of work,'' ''for work done take state A minus state B; the process to get there doesn't matter.''

It is evident that many students come to very directly as- sociate thermodynamic work with properties (and even spe- cific phrases) discussed by instructors and texts only in con- nection with internal energy and other state functions. This is consistent with the conclusion of Ref. 20 that students fre- quently have difficulty in distinguishing among work, heat, and internal energy, and in particular with their finding that many students explicitly assert the path independence of work. As they point out, it seems that overgeneralization of (poorly understood) experience with conservative forces may contribute to students' confusion about these issues.

E. Belief that heat is a state function

Among the most striking results of our investigation is that a very significant fraction of introductory students in our sample (between one third and one half) developed the idea that heat (or ''heat transfer'') is a state function, independent of process. In view of all textbooks' strenuous and oft- repeated emphasis that heat transfer is a process-dependent quantity and not a state function, this is a remarkable obser- vation. Although several studies have noted a confusion be- tween heat and internal energy, none have explicitly and sys- tematically probed students regarding their understanding of the *path-dependent* property of heat transfer.[27]

Question #2 may be answered by realizing that $\Delta U_1 =\Delta U_2$ and then employing the first law of thermodynamics to obtain $Q_1—W_1=Q_2—W_2$. Because the diagram shows that $W_1>W_2$, we can conclude that $Q_1>Q_2$. However, well over a third (38%) of the 653 students responding to Ques- tion #2, and 47% of the students in the interview sample answering the same question, asserted that the heat absorbed by the system during process #1 would be equal to that ab- sorbed during process #2. Moreover, 21% of the students in the written sample, and 44% of those in the interview sample, offered explicit arguments regarding the path- independence of heat, for example: ''I believe that heat trans- fer is like energy in the fact that it is a state function and doesn't matter the path since they end at the same point''; ''transfer of heat doesn't matter on the path you take''; ''they both end up at the same PV value so ... they both have the same Q or heat transfer.'' About 150 students offered argu- ments similar to these either in their written responses or during the interviews.

Strong support for the idea that heat is process- independent was consistent in all four student samples. The only other explanation (aside from the correct explanation) to gain any significant support on Question #2 was one that ascribed higher *Q* in process #1 simply to ''higher pressure,'' without giving any consideration to the initial and final states of the two processes.

Also remarkable is that the belief in the process indepen- dence of heat was widespread even among students who clearly understood that work is not a state function, as well as among those who mistakenly believed that work also is independent of process. Of the students who incorrectly an- swered that $W_1=W_2$, about half also asserted that $Q_1=Q_2$ (1999: 40%; 2000: 51%; 2001: 53%; interview sample: 43%). However, this mistaken notion regarding heat is nearly as common among the students who realize that work is dependent of process, and who correctly answered that

$W_1>W_2$. Of this group, more than one third also asserted that $Q_1=Q_2$ (1999: 29%; 2000: 41%; 2001: 34%; interview sample: 50%).

This observation of students' belief in a state-function property for heat is consistent with the findings of other re- searchers, although as noted it goes well beyond what has previously been reported. The tendency of students to mis- takenly identify heat with the state function internal energy was noted and

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discussed in Ref. 20 and the same observation was made by Berger and Wiesner in their interviews with advanced-level German university students in the teacher preparation program who had studied thermodynamics.[17] Manthei and Täubert[28] reported similar observations in an analysis of written responses on questions posed to advanced-level German high-school students. They, too, found a tendency to identify heat with internal energy, aswell as a widespread inability to correctly identify heat as a ‘‘process quantity’’ instead of a ‘‘state quantity.’’ Similarly, a great deal of confusion was found regarding the definition of heat among entrants at a British university,[18] and Kaper and Goedhart[11] concluded that Dutch chemistry students often treat heat as a state function.

It appears that the confounding of heat with internal en- ergy, noted in Refs. 20 and 28, extends to an explicit asso- ciation of the state-function property with heat. This confu- sion is quite analogous to the set of mistaken associations developed by many students in connection with work, as described in Sec. V D. We must consider the possibility that students’ familiarity with the equation $Q=mc\ \Delta T$ and its use in elementary calorimetry problems may contribute to their confusion regarding the nature of heat.

F. Belief that net work done and net heat transferred during a cyclic process are zero

The single most prevalent misconception encountered dur- ing our investigation was the strong belief expressed during the interviews that during a cyclic process, the net work done by the system or the net heat transferred to the system must be zero. In Ref. 20 it was noted that many students believe that the net work in a cyclic process must be zero due to the zero net change in volume. This belief often is so tenacious as to override other considerations that would imply nonzero net work.[20] In our investigation, this finding is corroborated and amplified by uncovering a parallel belief in the necessity of zero net heat transfer during a cyclic process. This belief regarding zero net heat transfer has not been documented in the literature.

Interview Question #6 asks students to consider the entire process that had been described, beginning at time *A* and ending at time *D*. They were asked whether the net work done by the gas, and the total heat transferred to the gas, are positive, negative, or zero. (‘‘Total heat transferred’’ matches the terminology of the course textbook.) Only a small minor- ity of students realized that the net work done (35%) or that the total heat transferred (25%) would be nonzero. Less than one fifth of the students could give correct answers with satisfactory explanations to the work question (19%) or the heat question (13%). Only three students in the entire sample (9%) gave fully correct responses to both parts of Question #6, such as this answer:

> ‘‘[S17] The total work was less than zero. I drew a diagram, pressure versus volume, and the path thatI scratched out here is counterclockwise, which
>
> suggests negative work ... [The total heat transfer] is less than zero ... in order to have negative work done it needs to have less than zero heat trans- ferred to it if it’s to maintain its same initial state
> ... Negative work done by the gas, so if it absorbs heat here, its output is going to have to be work plus heat. So, the total heat transfer is negative because this heat coming out of the gas is greater than the heat going into it, because it includes the energy from the work and the heat going into it.’’

Of the students in the interview sample, 75% either be- lieved that the net work done by the gas, or the total heat transferred to the gas, or both, would be zero for the entire process. More than half (56%) said that both the net work done and the total heat transferred throughout the entire pro- cess would be zero. In almost every case, the reasoning was the same: Because the final position of the piston was the same as its initial position, the negative work would cancel the positive work; because the final temperature was the same as the initial temperature, the heat transferred into the system would be balanced by the heat transferred out of the system:

> ‘‘[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.’’
> ‘‘[S27] The work done by the gas on the environ- ment is positive in the first steps where the

piston goes up, but then when it goes back down it's negative. And so, since it ends up in the sameplace, the net work is zero.''

''[S21] The heat transferred to the gas ... is equal to zero ... The gas was heated up, but it still re- turned to its equilibrium temperature. So whateverenergy was added to it was distributed back to the room.''

Students were asked to explain how they could be surethat the magnitude of the positive work (or heat) would ex- actly equal the magnitude of the negative work (or heat). In nearly every case, the students again referred to the equality of the final and initial values of the volume and temperature. Some students argued (as also was reported in Ref. 20) that because $W=\int P\,dV$ and $\Delta V=0$, ''work equals zero.''

Interview Question #8 was another opportunity to probe students' thinking on this matter. Here students were asked to rank the absolute values of the net work done by the gas and total heat transferred to the gas, both for the process that takes place between times A and D (symbolized by $|W_1|$ and $|Q_1|$, respectively), and for a similar process with initial and final states the same as before, but characterized by higher intermediate values of the pressure and temperature. When- ever there appeared to be a discrepancy in the students' an- swers for Questions #6 and #8, they were asked to comment or resolve the discrepancy. (The tables reflect students' final decisions in all cases.) Table III shows the students' re- sponses to Question #8 regarding process #1 (time A to time D) only. Exactly half answered that $|W_1|=|Q_1|=0$, while only 16% stated correctly that $|W_1|=|Q_1|$G0. Overall, 66% claimed either that $|W_1|=0$, or that $|Q_1|=0$, or that both equal zero. The responses to Question #8 thus confirm the results from Question #6.

As will be discussed, only a minority of the students re- ferred to a P-V diagram when answering Interview Ques- tions #1– 8. However, at the end of the interview, all students were asked to carefully draw a P-V diagram representing processes #1 and #2. More than 90% of them ultimately drew a diagram of a cyclic process. It is noteworthy that only four students realized that their diagrams implied an error in their initial response that $|W_1|=0$ or $|Q_1|=0$. (These stu- dents' final answers are reflected in the tabulated data.) Sev- eral other students expressed misgivings regarding the pos- sible inconsistencies of their answers, but were unable to arrive at a correct resolution.

In the study of Ref. 20, students in an algebra-based course were presented with a P-V diagram that correspondedto the process described here. Although one might expect thepresence of the diagram to have made the problem easier, about half of the students in that study asserted that the net work done by the gas during the process was zero, typically mentioning that there was no net change in volume. It seems clear that the ''no net change in volume'' theme plays a dominant role in student reasoning. The results of our inves- tigation further suggest that the same could be said about the ''no net change in temperature'' theme.

G. Confusion regarding isothermal processes and thethermal reservoir

Students' responses to Interview Question #4 revealed ad- ditional aspects of their difficulties in applying the work con- cept, and also manifest a deep misunderstanding of the con- cept of thermal reservoir. This question refers to the isothermal compression that occurs between time B and time C; the question asks whether there is any net energy flow between the gas and the water reservoir during this process. Only 31% of the students answered correctly with an accept- able explanation, with acceptable being loosely defined to include explanations such as:

''[S6] There'd be a flow of energy from the gas tothe water. Because, when you compress a gas, nor- mally it would heat things up. And so, if every- thing is remaining at somewhat of an equilibrium, I'm just going to assume, because it's in such a large environment, that that kind of heat would kind of dissipate into the environment.''

Only a small minority of these acceptable explanations made an explicit reference to the unchanging internal energy of the gas or to the first law of thermodynamics. In contrast, 59% of the students said that there would be no net energy flow between gas and water. Invariably, they mentioned that the gas and water temperatures were equal and unchanging:

''[S2] I would think if there was energy flow be- tween the gas and the water, the temperature of thewater would heat up.''

''[S10] There is no energy flow between the gas and the water; it all stayed in the system. Since thetemperature stayed the same, there is no heat flow.''

Most of the students who said that there would be no net energy transfer between the gas and the water reservoir were

asked to comment explicitly on whether there could be any energy transfer to or from a gas undergoing an isothermal process. Most agreed that it would be possible, citing situa- tions such as having ''light or energy coming out,'' having heat energy ''converted into potential energy or kinetic en- ergy,'' ''if heat in equals heat out,'' or if there is ''expansion or contraction.'' However, none of these students believed that the process described in Question #4 fit any of their proposed circumstances.

Isothermal processes are ubiquitous in the introductory thermal physics curriculum, and invariably reference is made to a constant-temperature reservoir with which the system is in contact. The details of how the isothermal process actually takes place are very rarely discussed, with a notable excep- tion in Chabay and Sherwood's text *Matter & Interactions*:[29] ''*As we compress the gas, the temperature in the gas starts to increase. However, this will lead to energy flowing out of the gas into the water, because whenever temperatures differ in two objects that are in thermal contact with each other, there is a transfer of energy from the hotter object to the colder object ... Energy transfer out of the gas will lower the tem- perature of the gas ... Quickly the temperature of the gas will fall back to the temperature of the water. The temperature of the big tub of water on the other hand will hardly change ... Therefore the entire quasistatic compression takes place es- sentially at the temperature of the water, and the final tem- perature of the gas is the same as the initial temperature of the gas.*''

It is clear that most of the students in the interview sample had never understood the details of an isothermal process as described above. They were unable to apply the first law of thermodynamics to a situation in which the isothermal com- pression of an ideal gas immediately implies the existence of a nonzero heat transfer out of the system.

A similar difficulty in understanding the role of a reservoir was noted by van Roon *et al.*[12] in their investigation of col- lege chemistry students in Holland. Moreover, in a study of advanced undergraduate college science students enrolled in physical chemistry courses (at the junior–senior level), Tho- mas and Schwenz[14] reported that 60% of their interview sample believed that ''no heat occurs under isothermal con- ditions.'' Students' tendency to hold that belief also was noted in Refs. 20 and 21. However, our work is the first unambiguous finding, based on a significant sample size, of students' confusion regarding energy transfer during an iso- thermal process.

H. Inability to apply the first law of thermodynamics

In the investigation of Ref. 20, the majority of students examined were unable to employ the first law of thermody- namics to solve problems related to adiabatic compression. Similar difficulties in other contexts were displayed by stu- dents in the present study.

First let us consider students' responses to Question #2: ''Is Q for process #1 greater than, less than, or equal to that for process #2? Please explain your answer.'' (The fact that all relevant values of ΔU, Q and W are positive here mini- mizes the potential confusion regarding signs.) An example of an acceptable student explanation is the following:

''ΔU=Q—W. For the same ΔU, the system with more work done must have more Q input so pro- cess #1 is greater.''

Students' responses to this question are shown in Table II. The percentage of students answering the written diagnostic who gave the response $Q_1>Q_2$ to Question #2—ignoring the explanations offered—ranged from 40% to 56%, and 34% of the interview subjects gave this response as well. However, if we examine the explanations provided by the students, a rather different picture emerges. Of the students answering the written diagnostic, only 11% gave an accept- able explanation based on the first law of thermodynamics. For this analysis, explanations such as the following were considered to be acceptable:

''Q is greater for process 1 since Q=U+W and

W is greater for process 1.''

''*Q* is greater for process one because it does more work, the energy to do this work comes from the Q_{in} .''

Among the students in the interview sample, 19% gave a correct answer with an acceptable explanation. If we add in students who answered that $Q_1<Q_2$ but made only a simple sign error, the proportion with acceptable explanations rises to 15% of the 1999–2001 samples, and to 22% of the inter- view sample.

Application of the first law of thermodynamics is needed to answer Interview Question #6ii; 13% of the interviewed students were able to answer this question correctly with a correct explanation. Although the first law also is required to give a fully correct explanation for Interview Question #4, students were not pressed to provide such an explanation during the interviews. The 31% success rate observed in an- swers for that question might be interpreted as an extreme upper limit on the proportion of students in our samples who were able to make any practical use of the first law of ther- modynamics. Otherwise, our data consistently show that no more than about one in five students in our samples emerged from the introductory physics course with an adequate grasp of the first law of thermodynamics. This conclusion is con- sistent with the findings reported in Ref. 20.

I. Difficulties regarding *P-V* diagrams

It is striking that only 38% of the students in the interview sample spontaneously attempted to use a *P-V* diagram to aid in responding to the questions. In particular for Interview Questions #6 and #8, one might expect that sketching a simple *P-V* diagram would be the quickest and easiest way to find a solution. Indeed, as we noted, several students rec- ognized that they had initially made errors on these questions when prompted by the interviewer to draw a *P-V* diagram. However, it is clear that most of the students were not in the habit of employing *P-V* diagrams when considering thermo- dynamics problems that did not initially provide or refer to such a diagram.

A hint of the difficulties encountered by students in em- ploying *P-V* diagrams is found in the results discussed in Sec. V D. Between a third to a half of all students were unable to give a correct answer with an acceptable explana- tion to Question #1, a problem in which the geometrical interpretation of work might be expected to yield a relatively straightforward answer.

In discussions regarding cyclic processes, heat engines, the second law of thermodynamics, etc., the association of the area contained within the closed curve representing that process with the net work done by the system often plays a central role. However, even after successfully drawing a *P-V* diagram representing a cyclic process (albeit one that often had numerous errors), nearly two thirds of the students in the interview sample remained convinced that the net work done in the process they had represented was zero.

Of the students who were interviewed, 22% were success- ful in drawing a correct *P-V* diagram for process #1. An additional 28% of the students drew a closed-curve diagram that represented the isothermal segment with a straight line (or, in one instance, with a line of incorrect curvature). Nearly all of the remainder—all but two students—drew a closed-curve path, but made one or more of a large assort- ment of errors (for example, curved or sloping lines repre- senting isobaric or isochoric processes, missing processes, direction errors).

The overall impression gathered from observing students draw and interpret their *P-V* diagrams was that these dia- grams represented a resource that was severely underutilized in their problem-solving arsenal. In noting the insights achieved by several of the students when drawing their dia- grams, and the near-misses by some others who failed to carry the reasoning process through to conclusion, it seemed that many students might benefit from additional practice and experience with *P-V* diagrams. The potential instruc- tional benefits of *P-V* diagrams will be discussed further in Sec. VIII.

VI. COMMENT REGARDING RELIABILITY OF THE DATA

There is evidence that our data might actually somewhat overstate the average level of knowledge in the full class population. The discussion regarding the characterization of the interview sample makes it

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Vol-10 Issue-1 January 2020

clear that the performance of that group is likely to be higher than the class average. More-over, all of the written diagnostic instruments were adminis- tered either to students who were attending (optional) recita- tion sections, or who were present in class on the last day of the semester. In previous investigations at ISU, we have found that the average exam scores of students attending recitation sections are somewhat higher than the scores of the full class population. For the present investigation, this factor was examined by administering a question on the final exam during the Spring 2001 semester.

The final exam question (see Fig. 4) involved two different processes connecting common initial and final states (similar to the questions on the written diagnostic). As can be seen from the breakdown of student responses (N=407), only 33% gave the correct answer (C) that both the work done and the heat absorbed could be different in the two processes. 37% of the students believed that the work done must be the same, while 51% thought that the heat absorbed must be the same. On the written diagnostic questions in that same class (N=279), 41% of the responses represented views consis- tent with the correct answer on the final exam question, that is, that $W_1 G W_2$ and that $Q_1 G Q_2$. This performance is sig- nificantly better (p=0.03) than the proportion of correct re- sponses on the final exam. Moreover, only 41% of the re- sponses on the written diagnostic claimed that the heat absorbed had to be the same for the two processes, compared to 51% on the final exam. (Performance on the work ques- tion was similar.) The performance of the full class on the

A system consisting of a quantity of ideal gas is in equilibrium state "A." It is slowly heated and as it expands, its pressure varies. It ends up in equilibrium state "B." Now suppose that the same quantity of ideal gas again starts in state "A," but undergoes a **different** thermodynamic process (i.e., follows a different path on a P-V diagram), only to end up again in the same state "B" as before. Consider the net work done by the system and the net heat absorbed by the system during these two different processes. Which of these statements is true?

A. The work done may be different in the two processes, but the heat absorbed must be the same.

B. The work done must be the same in the two processes, but the heat absorbed may be different.

C. The work done may be different in the two processes, and the heat absorbed may be different in the two processes.

D. Both the work done and the heat absorbed must be the same in the two processes, but are not equal to zero.

E. Both the work done and the heat absorbed by the system must be equal to zero in both processes.

***Responses* (N = 407):**

(A) 28% (B) 14% (C) 33%

(D) 20% (E) 3% No response: 2%

Fig. 4. Question used on final exam of Spring 2001 course, with a break-down of students' responses.

final exam was somewhat inferior to that shown by the popu-lation that responded to the written diagnostic.

VII. DISCUSSION

Decades of research have documented substantial learning difficulties among pre-university students with regard to heat, temperature and related concepts, but the possible im- plications of these findings for university students have been uncertain. The work of Loverude *et al.*[20] and of the present investigation, along with work in several different countries, all suggest that a large proportion of students in introductory university physics courses emerge with an insufficient func- tional understanding of the fundamental principles of ther- modynamics to allow problem solving in unfamiliar con-texts.

It is clear that a fundamental conceptual difficulty stems from the fact that heat transfer, work and internal energy are diverse forms of the same fundamental quantity, that is, ''en- ergy,'' and are all expressed in the same units. Many students simply do not understand why a distinction must be made among the three quantities, or indeed that such a distinction has any fundamental significance; one of the students in the

Berger and Wiesner study called this distinction ''hairsplit- ting'' [*Haarspalterei*].[17] One of the subjects in our interview sample, when invited to explain what he found particularly confusing about the heat–work–energy relationship, offered this comment: ''How is it acceptable for something called 'work' to have the same units as something called 'heat' and something called 'energy'?'' Another student, when pressed to explain the distinction, said: ''Maybe work and heat are kind of the same thing, just a transfer of energy in both cases.''

Part of this confusion stems from the ubiquitous and well- documented difficulty of learning to make a clear conceptual distinction between a quantity and the *change* or *rate of change* in that same quantity, for example: velocity and acceleration,[30] magnetic flux and the *change* in magnetic flux,[31] potential and field.[32] Many students do not learn that heat transfer and work both represent changes in a system's internal energy, and that they therefore are not properties associated with a given state of a system, but rather with the transition between two such states. This problem is exacer- bated by two other distinct difficulties, both well docu- mented: (1) the use in colloquial speech of the word ''heat'' or ''heat energy'' [18,33] (and equivalents in other languages, for example *chaleur* [French][34] or *Wärme* [German][17]) to correspond to a concept that is actually closer to what physi- cists would call ''internal energy;'' and (2) the major concep- tual difficulties faced by introductory students in mastering the work concept itself in a mechanics context, let alone within the less familiar context of thermodynamics.[20] Thus, introductory students are faced with the task of learning two distinct and somewhat subtle concepts—heat and work— when their everyday familiarity with those terms tends to lead them in precisely the wrong conceptual direction.

It is ironic that the students' apparent ability to compre- hend the concepts of state and state function actually may contribute to their confusion regarding process-dependent quantities such as heat and work. Students learn to become well aware that there exist quantities that are independent of process, and that energy of a state is one of these quantities. Perhaps due to their already weak grasp of the concepts of heat and work, many students improperly transfer, in their own minds, various properties of state functions either to heat, or work or both.[35] Certainly, the fact that mechanics courses frequently highlight the path-independent work done by conservative forces may contribute to this confusion, as may extensive use of the equation $Q=mc\ \Delta T$ in calorimetry problems.

Heat engines, refrigerators and an analysis based on the second law of thermodynamics crucially depend on the non- zero net heat transfer to, and the net work done by, a ther- modynamic system during a cyclic process. This concept was among the most poorly understood among the students in our interview sample, and the difficulty regarding cyclic processes was directly traceable to the confusion regarding the fundamental properties of heat and work.

Another area of confusion might be traced to the limiting approximations frequently—and often tacitly—invoked in making physical arguments regarding idealized processes. Experienced physicists automatically, even unconsciously, ''fill in the dots'' in their own minds when describing, for instance, an isothermal process and the meaning of a thermal reservoir. They have in mind the model involving very small (and therefore negligible) temperature excursions described by Chabay and Sherwood.[29] The overwhelming majority of textbook discussions treat this and similar idealized pro- cesses only very cursorily; our data suggest that for most students, such treatments are inadequate.

VIII. MPLICATIONS FOR INSTRUCTIONAL STRATEGIES

Loverude *et al.* have pointed out that a crucial first step to improving student learning of thermodynamics concepts lies in solidifying the student's understanding of the concept of work in the more familiar context of mechanics, with par- ticular attention to the distinction between positive and nega- tive work.[20] Beyond that first step, it seems clear that little progress can be made without first guiding the student to a clear understanding that work in the thermodynamic sense can alter the internal energy of a system, and that heat or heat transfer in the context of thermodynamics refers to a *change* in some system's internal energy, or equivalently that it rep- resents a quantity of energy that is being transferred fromone system to another.

As discussed in Sec. V B, most students seem comfortable with the notion of internal energy as a quantity that is char- acteristic of the state of the system. One might try to take advantage of this understanding by eliciting from studentsthe distinction between the amount of energy in a system at agiven moment, and a change in that quantity brought about by various distinct methods, for example, through macro- scopic forces leading to changes in a system's volume, and through alterations that occur due to temperature differences without changes in the system's volume.

The instructional utility of employing multiple representa- tions of physics concepts has been demonstrated in numer- ous research investigations in physics education.[36] The re- sults of our investigation suggest that significant learning dividends might result from additional instructional focus on the creation, interpretation, and manipulation of *P*-*V* dia- grams representing various thermodynamic processes. In particular, students might benefit from practice in converting between a diagrammatic representation and a physical de- scription of a given process, especially in the context of cy- clic processes.

Our results demonstrate that certain fundamental concepts and idealizations often taken for granted by instructors are very troublesome for many students (for example, the rela- tion between temperature and kinetic energy of an ideal gas, or the meaning of thermal reservoir). The recalcitrance of these difficulties suggests that it might be particularly useful to guide students to articulate these principles themselves, and to provide their own justifications for commonly used idealizations.

Loverude[21] has described the development and testing of curricular materials based on the research reported in Ref. 20.[37] Students' learning difficulties showed a strong tendency to persist even after research-based instruction, although sig- nificant improvements were demonstrated. His report of the initial testing of their curricular materials makes it clear that the task of improving student learning in thermodynamics is challenging indeed.

IX. CONCLUSION

This investigation examined student learning of thermody- namics concepts in four separate offerings of the introduc- tory calculus-based general physics course at a large public university over a period of three academic years. Several different course instructors, recitation instructors and text- books were represented in these offerings. Results from the different population samples consistently showed that large proportions of the students in the courses emerged with a number of fundamental conceptual difficulties regarding the first law of thermodynamics, the definition and meaning of thermodynamic work, and the process-dependent nature of heat, including a belief that net heat absorbed and net work done by a system undergoing a cyclic process must be zero. Results of this investigation are in excellent agreement with those published in a recent study carried out at several other comparable institutions,[20] and are consistent with reports from several different European countries.[16–18,26,28,34] We conclude that substantial changes in instruction will be re- quired if the level of students' mastery of thermodynamics concepts is to be significantly improved in introductory courses.

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