Heat and constitutive relations in adiabatic and isothermal compression of air: An investigation of student reasoning

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ABSTRACT: This paper reports on an investigation of student understanding of adiabatic and isothermal compression of air. At the time of the study, the students were studying thermal physics as part of introductory physics. The theory of the dynamics of heat discussed in the course uses entropy and temperature as primitive concepts from the start. The first part covered before the study was performed dealt with dynamical models of heating and cooling at constant volume. Adiabatic compression was demonstrated and discussed very briefly. The investigation of understanding of adiabatic compression shows that students treat the temperature rise as a constitutive problem involving heat rather than as a general one involving work and the first law. Either heat is generated by friction to account for the temperature rise, or the heat of the air is compressed into a smaller space. The latter view was common knowledge in the first half of the 19th century and was used formally as the constitutive theory of latent and specific heats—describing the response of gases to heat or heating—in research up to and including Clausius' and Kelvin's work. It has recently been used as the basis of the constitutive theory of ideal fluids in the dynamical theory of heat. As to the second phenomenon, students successfully explain, and construct the *T*-*s* diagram of, isothermal compression of air without ever having dealt with this example in class or in homework. The view of student understanding of thermodynamics emerging here contrasts sharply with that of a recent investigation dealing with adiabatic compression published in AJP **70**,137-148,2002.

One of the principal objects of practical research … is to find the point of view from which the subject appears in its greatest simplicity. J.W. Gibbs.[1]

If, then, it is more important for purposes of instruction and the like to familiarize the learner with the second law, than to defer its statement as long as possible, the use of the entropy-temperature diagram may serve a useful purpose in the popularizing of this science. J.W. Gibbs.[2]

I Introduction

It has been known for a good number of years that non-scientists' (and in some cases also scientists') preconceptions about heat and thermal phenomena are at odds with the classical presentation of the subject in physics.[3] Depending on the age and sophistication of learners, heat and temperature are mixed up. Most importantly, however, notions of heat as a kind of "invisible substance" are widespread and resistant to formal education.[4]

Most investigations so far have dealt with heat and heat transfer in the case of bodies undergoing processes at constant volume. A recent study of student reasoning extends our knowledge into the area of adiabatic compression of gases.[5] It demonstrates a low level of student understanding.[6] The authors show that students fail to consider the work done; use incorrect microscopic reasoning; show confusion among heat, work, temperature, and internal energy. Students also show difficulties with the concept of work in mechanics.

The failure to consider the work done in adiabatic compression is pronounced.[7] The authors of the study[5] suggest "that we should ensure that students can apply the concept of work in simple mechanical contexts before introducing the complexities of thermal physics."[8]

If so few students "spontaneously invoked the concept of work,"[9] what are their spontaneous concepts? My memory of informal discussions in class and elsewhere indicated that non-scientists have a strong intuitive feeling about the reasons for the behavior of air in adiabatic compression. Here is an example of a typical conversation between a physicist (P) and a non-scientist (N) concerning the rapid compression of air.[10]

P: If you compress air quickly what happens to its temperature?

N: It gets hotter.

P: Yes, its temperature rises very much. Why is this?

N: During compression, the molecules of the air rub against each other, causing heat.

P: This does indeed happen, but air is not very viscous. Therefore, it is highly unlikely, that such a strong increase of temperature would happen.

N: In that case it must be that the heat of the air is compressed into a smaller space.

It appears to be a matter of intuition and everyday experience that the temperature rise in adiabatic compression of air must have something to do with heat, and with how air responds to heat. We either need more heat to make the air warmer—and we know that we can get heat from rubbing—or the heat of the air is found in a smaller space after compression, again making the air hotter. What struck me about the second notion is that it is a special case of the following concept described lucidly 175 years ago by J.Ivory:[11]

> The absolute heat which causes a given rise of temperature, or a given dilatation, is resolvable into two distinct parts; of which one is capable of producing the given rise of temperature, when the volume of the air remains constant; and the other enters into the air, and somehow unites with it while it is expanding … . The first may be called the heat of temperature; and the second might very properly be named the heat of expansion; but I shall use the well known term, latent heat, understanding by it the heat that accumulates in a mass of air when the volume increases, and is again extricated from it when the volume decreases.

The idea expressed here combines the concept of a heat function—which all early thermodynamicists accepted—with the constitutive law of latent and specific heats which formed the basis of thermodynamics up to and including the work of Clausius and Kelvin.[12] The latter assumption explains adiabatic processes.[13] It has recently been used as the basis of the constitutive theory of ideal fluids within the dynamical theory of heat.[14] In its simplest form, the dynamics of heat is a uniform systems version of continuum physics.[15] Examining heat in this way makes it clear that the entropy is the fundamental property that is transported in thermal processes, and that the temperature is the corresponding potential.[16] The resulting theory of the creation, flow, and balance of entropy provides the foundation of a truly dynamical theory of heat that unites thermodynamics and heat transfer into a single subject.

I have been teaching an evolving version of this theory as a part of my course on introductory physics for engineering students for some years. I wanted to know how my students would react to a discussion of the phenomenon of adiabatic compression, and how their (intuitive) views could be related to the models constructed in the course. In short, they mostly react like the non-scientist in the exchange reported above. Moreover, they successfully use the balance of entropy and intuitive knowledge of the response of gases to heat and heating to predict the form of the *T-s* diagram of isothermal compression.

In the following pages, the introductory physics course and its part on thermal physics are described (Section II). The constitutive theory of the ideal gas based on the concepts of latent and specific heats is detailed in Section III. Section IV describes the study of student understanding, and gives results and interpretations.

II Thermodynamics in the introductory physics course

The introductory physics course for engineering students, including the part on thermodynamics, will be described briefly to give the reader the necessary background to put into perspective the investigation of student understanding reported below in Section IV.

A. Physics of dynamical systems (PDS)

Students in mechanical engineering or in data analysis and process design take introductory physics for engineers during their first year.[17,18] They have three periods of 90 minutes each of physics for the 34 weeks of the first two semesters. Two of the periods are in the class room in groups of about 20 students, one is held in a studio in groups of 10 (I only have a tiny studio room, so a class of 20 has to be divided into two groups). Since the students' course load is heavy (some 16 to 17 90-minute periods per week) they have little time to spend on studying and homework. According to their own accounting, they spend an additional 2.5 to 3 hours per week on physics.

I have divided the course into three parts (Table 1). During the first 10 weeks, all three periods—classroom and studio—are devoted to the introductory subjects of hydraulics and electricity. Students study dynamical processes and learn to create system dynamics models. A presentation of a summary of theoretical concepts usually follows the practical work. The concepts learned are centered around principles of accounting and the study of some useful constitutive laws. If physics is structured according to modern continuum physics, analogies between different fields can be made use of. I put great emphasis on the development of modeling methodologies, both on paper and at the computer.

After hydraulics and electricity have been covered sufficiently, they are revisited and the concept of energy is introduced. I use a description of the concept which relies heavily on the idea of energy carriers[19] and energy released or bound in processes.[20]

After the introductory subjects, the course is divided into two parts. The time in the class room (2 periods per week) is reserved for mechanics (see Table 1), whereas thermodynamics is treated in the studio for one period per week.[21] In the studio, active student work accounts for about 75 percent of the time, whereas in the classroom it may be as little as 30 to 40%. Thermodynamics and mechanics are treated according to the foundations laid in the introduction. Students learn about the laws of balance of entropy, momentum, and angular momentum, and they are confronted with important cases of constitutive laws. The energy concept takes the same form as in hydraulics or electricity. Modeling follows the study of practical situations and includes *RC*, *RL*, and *RCL* systems.

Table 1: Overview of the parts of the PDS course

Part	**Class periods**[a]
Storage and flow of fluids and electricity Inductive behavior in fluids and electricity Energy in physical processes (Transport and change of substances)[b]	30[c]
The dynamics of heat (DoH) Thermodynamics: Gases and radiation Chemical processes and heat Heat Transfer: Entropy Transport Mechanisms	24[d]
Rotational Systems Balance and Transport of Momentum Motion in 2D and 3D Combined Rotation and Translation	48[e]

a. One period lasts for 90 minutes.

b. This subject is commonly left out for lack of time.

c. Lectures, recitation, and studio.

d. Studio. DoH takes 10 of the 24 studio periods.

e. Lectures and recitation.

B. A dynamical theory of heat

The part of thermodynamics relevant for our study of student understanding is the chapter on the dynamics of heat (DoH in Table 1). Essentially, DoH uses the theory of the dynamics of heat which makes use of the entropy balance and constitutive laws for dynamical processes right from the start. As with hydraulics, electricity, and motion, the goal is to learn to create dynamical models that explain processes found in the lab or in real life. It uses the ideas created in the introductory chapters on the flow of fluids and electricity, and on the energy principle.

Here I will describe what happened during the first studio period only, since the subject of adiabatic compression was briefly demonstrated and discussed there. At the time of the study, the students had not worked on gases any further.

The first studio period started with a 40 minute lecture. I demonstrated several phenomena (heating of water; melting of ice; Peltier element in heat pump mode as a wall between two bodies of water; Stirling engine; compression of air in a cylinder with a piston containing a small piece of German tinder). All phenomena were discussed using the words “heat” and “temperature.” A thought experiment in which a body of water was divided into two parts revealed that heat was divided with the bodies, whereas temperature was not. Heat and temperature were accepted as the extensive and intensive thermal quantities, respectively. As a result, my students and I came up with a description of heat as a quantity that can be stored and can flow. Also, if heat flows from hot to cold, energy is released (Stirling engine), and we need energy to pump heat from cold to hot (Peltier heat pump). At this point I made it clear to them that the quantity we had called “heat” carries the name of entropy in thermodynamics.

Then we briefly discussed what happens in a real electric pump and its reverse, i.e., a turbine with generator. Since heat is produced in both cases (whereas all other processes can be reversed), it is clear that this quantity is not conserved. It is one-sided: it is produced in irreversible processes such as friction, fires, charge flowing through wires, absorption of light, etc. Since heat is entropy, we now know that entropy can be stored, it can flow, and it can be produced.

We finally revisited the adiabatic compression of air and started a discussion of how to explain the observed rise of temperature. My students reacted like the non-scientist in the exchange described in Section I. Their first explanation was that friction between the molecules was to blame: entropy would be produced, leading to the observed increase of temperature. When I pointed out to them that (1) the viscosity of the air was too small for this effect and that (2) the process was almost reversible, the next answer was that the entropy of the air was compressed into a smaller volume. In each of the six studio groups, the same exchange took place, and in each case I stopped the discussion at this point—after a student had offered this reason—saying that we could accept this explanation. It is important to note that isothermal compression or expansion of a gas were never discussed, nor were they subject of assignments or homework.

Finally, I took the opportunity to introduce the temperature entropy diagram, and we sketched the diagram for adiabatic compression. It did not seem to be difficult to see that the process is represented by a vertical line going up.

Energy, energy transfer, and energy balances for gases were not used or discussed during the course leading up to the study.

III The constitutive problem of fluids

Historically, the first detailed treatment of the problem of the thermodynamics of (ideal) fluids was presented by Carnot.[22] Apart from what we call Carnot’s theorem, he relied on the notion of a heat function, and the theory of latent and specific heats. Later, Clausius[23] abandoned the heat function but retained the other elements of the theory. Here I will briefly describe the constitutive theory of the ideal gas that results if we start with the balance of entropy and combine it with the theory of latent and specific heats (latent entropy and entropy capacitance).[24,25,26]

A. The balance of entropy

The law of balance of entropy relates the rate of change of the entropy of a body to the sum of all entropy currents and the rate of production of entropy:

$$\dot{S} = I_{S,net} + \Pi_S \tag{1}$$

If we treat the body of gas we are dealing with as an ideal uniform fluid,[27] there cannot be any entropy production:

$$\dot{S} = I_{S,net} \tag{2}$$

B. Constitutive relations

We need a relation that allows us to relate the pressure of the fluid to its volume and temperature. This is the equation of state. We will only deal with the ideal gas here:

$$PV = nRT \tag{3}$$

Now we formulate the constitutive relation that expresses the response of the fluid to heating I_S (since the fluid is ideal, we can replace the heating by the rate of change of the entropy). As we know from experience, the heating is related to the rates of change of volume and of temperature.[28] Therefore, we can express our assumption as follows:

$$\dot{S} = \Lambda_V \dot{V} + K_V \dot{T} \quad (4)$$

Λ_V is the latent entropy (with respect to volume), and K_V symbolizes the entropy capacitance (at constant volume).

C. Solution of the constitutive problem

The constitutive problem of the ideal gas is to find the latent entropy and the entropy capacitance. If we start with the relation between power, entropy flux, and temperature difference known from the physics of dynamical systems (or, alternatively, if we accept Carnot's axiom) we can determine the latent entropy on the basis of theory:

$$\Lambda_V = \frac{nR}{V} \quad (5)$$

Using the ideal gas law, we can derive the following expression for the entropy capacitance (where γ is the ratio of the entropy capacitances at constant pressure and at constant volume):

$$K_V = \frac{nR}{\gamma - 1}\frac{1}{T} \quad (6)$$

If we measure the ratio of the capacitances (for example, in Rüchardt's experiment[29]), the second constitutive property of the ideal gas is determined.

D. Adiabatic processes of the ideal gas

The well known relations for adiabatic processes of the ideal gas are derived from the foregoing by applying the condition of zero entropy flow (or zero rate of change of entropy):

$$0 = \Lambda_V \dot{V} + K_V \dot{T} \quad (7)$$

This is the formal expression of the intuitive and informal view that in adiabatic compression "the heat of the air has been compressed into a smaller space."

E. Whatever happened to latent heat?

The simple yet powerful constitutive law describing the response of fluids to heat (or heating) is not generally known today. The notion of latent heat of a gas is utterly absent from thermodynamics. So, where did the concept go? Kelvin explained in 1878:[30]

> It has become of late years somewhat the fashion to decry the designation of latent heat, because it had been very often stated in language involving the assumption of the materiality of heat. Now that we know heat to be a mode of motion, and not a material substance, the old "impressive, clear, and wrong" statements regarding latent heat, evolution and absorption of heat by compression, specific heats of bodies and quantities of heat possessed by them, are summarily discarded. But they have not yet been generally enough followed by equally clear and concise statements of what we now know to be the truth.

His words only hint at the loss physics has suffered. With the latent heat went the sense of the importance of constitutive laws for a theory of processes, and with the "quantities of heat possessed by [bodies]"[31] a simple path toward the extensive thermal quantity—what today we call entropy—disappeared.[26] Finally, thermodynamics as a theory of the dynamics of heat, vanished from the scene.

IV The study: Spontaneous reasoning and understanding

The study used a two-part questionnaire presenting problems centered around two phenomena: adiabatic and isothermal compression of air. All parts asked for qualitative answers, or for diagrams. Some directly probed intuitive reasoning. The questionnaire is shown in the Appendix. In the following, the organization and the results of the study are described. Interpretations are offered at the end of this section.

A. The study

The questions can be put into four categories: (1) description and explanation of adiabatic compression; (2) description and explanation of isothermal compression; (3) probing of intuitive notions regarding the cause of the temperature rise in adiabatic compression; and (4) general questions about previous education in thermal physics and time spent on studying adiabatic compression in the studio and in homework.

To understand the relevance (or lack of relevance) of the responses regarding intuitive notions, it has to be mentioned that Questions 6 through 10 were asked one week after the first five. My main source of "uninhibited" expression of intuitive notions comes from the limited discussion in the studio (Section IIB).

The students who participated in this study (N = 52) were in their first year of one of three engineering courses (Mechanical Engineering (N = 18), Computer Science in Mechanical Engineering (N = 14), Data Analysis and Process Design (N = 20)). They took the Physics of Dynamical Systems (PDS) course during the first year.

The study was performed during Weeks 5 and 6 of the thermodynamics studio, i.e., after the first four periods on the dynamics of heat (DoH, see Table 1). At the time, most teams were working on creating *T-s* diagrams of water and of glycol from experimental data. Until then, they had spent some 40 minutes on average working on the example of adiabatic compression of air, including sketching of the appropriate *T-s* diagram, during the first week of the studio and on homework.

B. Results

Results are listed according to the four categories of questions. In general, percentages of students giving certain responses are reported.

Adiabatic compression. Q1. 94% of the answers are correct (86% say, that entropy stays constant; 33% say that entropy is compressed into a smaller space). 63% of the explanations are correct (57% use or mention the balance of entropy).

Q2. 98% of the students say that the temperature must increase. 46% of the students give correct explanations (entropy is squeezed into smaller volume), 8% give no explanation. 13% of the answers refer to the gas law or pressure, 19% to microscopic models (half of them talk about friction between molecules), 6% use explanations based on friction, 6% give other reasons. A single student mentions energy expended in compression.

Q3. 65% of the students correctly state that the energy should go up (only 25% give the correct explanation that energy is added in compression).

Q4. 92% of the *T-s* diagrams of adiabatic compression are drawn correctly.

Isothermal compression. Q5. 92% of the answers are correct, and 83% of the explanations (cooling: 33%, extracting entropy: 46%, alternative: 4%).

Q6. a. It's intuitively clear, but I could not explain why (26%); b. I have already worked with such processes (22%); c. I derived this on the basis of what we have already discussed (54%); d. I have learned this earlier (18%); e. I have heard or read about this (8%). f. other reasons… (0%). If we neglect multiple occurrences, 75% of the students know the answer intuitively or derive it on the basis of what was discussed in the course (adiabatic compression, entropy, and temperature).

The four students who answered Q5 incorrectly, said that they had worked with isothermal processes and/or had learned about them before. They did not claim intuition, nor did they reason about the process.

Q7. 68% of the *T-s* diagrams are correct. A total of 50% of the explanations are correct, and 18% of the students do not give an explanation. There are no incorrect explanations (of the correct diagrams). It is interesting to see that 12 students manage to draw a wrong diagram, even though they stated before in Q5 that either the entropy would decrease or entropy had to be removed.

Q8. 28% of the answers are right, and 6% of the explanations. 72% of the answers are wrong (explanations given: energy decreases because of cooling: 20%; energy increases because of compression: 20%; other: 32%).

Spontaneous reasoning and intuitive notions. Q9. As with other questions, many students (18%) offer a description in place of an explanation. Where explanations are given, they point to heat as the source of intuitive knowledge. More than half of the students mention heat, and 50% use one of the following explanations: friction between molecules (26%), general friction (12%), heat in smaller volume (12%), heat must somehow have been added (2%). 4% of the answers use the idea that molecules have less space, 16% use pressure, the gas law, and molecules moving faster. Two students mention work and conversion of work into heat. 10% of the students say they cannot remember intuitive notions, 4% offer alternative explanations. (Multiple answers were possible.)

Q10. Since it is difficult to probe spontaneous reasoning, especially after instruction has taken place, I offered my students some "intuitive" answers and asked them which of these, if any, they would prefer. The results are as follows. a. During compression, the molecules of the air rub against each other strongly and produce heat (38%); b. The heat that already resides in the gas is compressed into a smaller space (56%); c. By compressing the air we add heat from outside (0%); d. As a consequence of the work done by the person (4%); e. After the compression, the molecules have less space, and hit the walls more strongly… (22%); f. Other explanations…(2%).

General questions. Q11. 33 of the 50 students reporting had less than 8 hours of thermal physics before taking the present course; 44 had had less than 15 hours in total.

Q12. The average of hours spent on thermal physics of gases before the present course was less than 4.

Q13. Students spent an average of 40 minutes on studying adiabatic compression after the 10 minutes of presentation and discussion in the studio.

C. Conclusions

Students have difficulties recalling intuitive notions, that much is certain from their answers to Question 9. Many, if not most, of the answers show the imprint of schooling.

Moreover, some students (18%) don't seem to know what constitutes an explanation: they give detailed descriptions of what is happening when we use a bicycle pump, but do not answer the question as to why this happens. A student writes: "When I first worked with Diesel engines as a mechanic, I believe the reason given was that the air heats up as a result of compression."

Still, this much is certain: students are seeking heat in what is happening (in adiabatic compression). A relative majority of the students mention friction—mainly of the molecules—and explain that it leads to the production of heat. Moreover, the form of the answers shows that this concept is least influenced by previous schooling: it is the most spontaneous if judged by the absence of jargon.

Even when they do not mention heat directly, and instead use little particles in their reasoning, we can see that it is heat our students are thinking of: heat manifests itself in the motion of the particles, and more heat (higher temperature) requires faster motion, or more or harder collisions. Looked at from this angle, there is hardly an answer that does not involve the notion of heat.

Again, the form of many of the answers to Question 9 demonstrates that the body's response to compression is the result of its response to heat: we need more heat in a body if we want it to be hotter, or the "density of heat" has to be higher. [If the temperature is not allowed to increase, heat must be removed (see Question 5).]

Even though few of the answers offering the idea of "squeezing heat or entropy" into a smaller volume may be really spontaneous, the idea is accepted as intuitive by almost 60% of the students (Question 10), and it is used by most of these as the explanation for the temperature change in adiabatic compression in the earlier part of the study (Question 2). No one expresses the belief that heat is transferred as a consequence of compression. Students do not confuse "heat" and "work" as different ways of transferring energy.

The more formal parts of the questionnaire—those asking for descriptions of what happens in the form of words or *T-s* diagrams—demonstrate that many, if not most, of the students in this study easily accept the notion of entropy and properly use it (Questions 2, 4, 5 and 7). They correctly answer the question as to what happens to the entropy of the air in adiabatic compression (Question 1), but their explanations are not always concise: 25% mention that there is no entropy transfer, 10% say that there is no entropy production, and 22% use the full power of the law of balance and mention both reasons. The form of the explanations and the fact that 27% take the description (entropy is constant and is compressed) as an explanation seems to indicate that the question of the balance of entropy is simply trivial. The constitutive problem appears to be the more important one.

The question of what happens to the temperature of the gas in adiabatic compression (Question 2) is answered correctly by all but one student (who states that the temperature has nothing to do with this process). About half of the explanations are correct (same amount of entropy in smaller space). The incorrect answers make use of the equation of state of the ideal gas, generally refer to the "fact" that higher pressure means higher temperature, or refer to friction (unspecified, or between molecules). A single student explains that energy has been expended in compression.

The notion of entropy content, and heating and cooling as entropy transfer (Question 1), together with the explanation of adiabatic processes (Question 2), allow my students to predict the outcome of a process we never worked on in class (isothermal compression, Question 5) and draw the *T-s* diagram correctly in 67% of all cases (Question 7). When asked why they knew this, they responded that it was either intuitively clear or that they reasoned about it on the basis of the concepts accepted so far in 75% of the cases (Question 6).

Despite all of this, little particles often make their way back into explanations that—predictably—turn out to be wrong. This is particularly clear in the explanations of the temperature rise in adiabatic compression (Question 2). Uneasy about the concepts offered in instruction, or simply left to their own devices, students turn to molecules, motion, friction, pressure, and the ideal gas, as explanations for the true "cause of heat" and the response to heat.

It should not come as a surprise that questions about the energy of the gas in adiabatic compression (Question 3) and in isothermal compression (Question 8) were much harder to answer for my students. Energy of gases was not a part of the course on thermodynamics before the study. There is a sense among students that the energy of the gas increases in adiabatic compression (65%), but only 25% of the students use the balance of energy (energy is added as a result of compression) as an explanation.

Only 14 students (28%) say that the energy of the gas stays constant in isothermal compression, and only 6% give a correct explanation (energy added in compression is extracted in cooling). It is interesting to note that no one thinks that the act of compression leads to a decrease of the energy; for all who mention it, it is clear that compression alone adds energy to the gas.

Are intuitions about heat and the behavior of simple gases strong enough to base the theory of latent and specific heats (Equation 4) upon? After a short qualitative discussion of adiabatic compression, students demonstrate considerable qualitative understanding of thermal phenomena involving air. Therefore, the results of this study leave me optimistic that an appreciation of this constitutive law is not very difficult. I have taught versions of a dynamical theory of the ideal gas for three or four years now, but I have not formally investigated the outcome yet (apart from using standard exams). This remains to be done.

V Summary and outlook

Students are seeking heat in their explanations of adiabatic processes.[32] They clearly treat the behavior of gases as a constitutive problem involving heat.[33] We have seen that this view is expressed concisely by the constitutive theory of latent and specific heats. In this setting, adiabatic compression is what we intuitively know it must be: a special case of the response of bodies to heat in the absence of heating.

What should we expect of a theory of thermodynamics that can do justice to our students' intuitive notions? Our response takes two steps. First, we can adopt the theory of latent and specific heats and combine it with the proper laws of balance to form a theory of thermal processes. This is possible both in the energy and the entropy representations.

Second, we may accept that our students' firm belief in "quantities of heat possessed by bodies" (Kelvin[30]) deserves a constructive response. As demonstrated before, we can make use of this notion and turn it into the formalized concept of entropy.[14,16] While not necessary on purely logical grounds, this step is important if we want to avoid the counter-intuitive and purely formal developments based on heat as a quantity of energy.[26] Again, the phenomenon of adiabatic compression offers a good reason to allow for an equivalent of "the heat of a body": in the absence of heating, it is not easy to see for a student how heat interacts with the material to raise its temperature. The entropy of a body, and the idea of "squeezing" the entropy into a smaller space, offer simple explanations.

When we probe our student's intuitive reasoning and understanding, it is important to know where they stand before we attempt to steer them into a particular direction. It also pays off to know what directions are available to us in teaching. At a time when attempts are made to create base-line tests for thermal physics,[34] it is important to be mindful of this.

Appendix

Questionnaire on student understanding of adiabatic and isothermal compression of air. The questionnaire starts with a photograph of the cylinder and piston used to demonstrate adiabatic compression in the studio.

Category 1: *Adiabatic compression*

Q1. What happens to the entropy of air during rapid compression? Explain your answer.

Q2. What happens to the temperature of the air? Explain your answer.

Q3. What happens to the energy of the air? Explain your answer.

Q4. What does the temperature-entropy diagram of the process look like?

Category 2: *Isothermal compression*

Q5. Air is compressed, but we do not want the temperature to rise. How could we achieve this?

Q6. How do you know what you said in Q5? (a. It's intuitively clear, but I could not explain why; b. I have already worked with such processes; c. I derived this on the basis of what we have already discussed; d. I have learned this earlier; e. I have heard or read about this. f. other reasons…).

Q7. What does the temperature-entropy diagram of the process look like? Give the direction of the processes in the diagram. Explain your answer.

Q8. What will happen with the energy of the gas during compression at constant temperature? Will it remain constant, or will it increase or decrease? Explain your answer.

Category 3: *Spontaneous reasoning and intuitive notions*

Q9. If air is compressed in a cylinder without cooling, the temperature rises sharply. Can you remember your own first intuitive explanation for the phenomenon? What is it?

Q10. If air is compressed in a cylinder without cooling, the temperature rises sharply. Which of the following explanations appears to be the most intuitive one for you today? (a. During compression, the molecules of the air rub against each other strongly and produce heat; b. The heat that already resides in the gas is compressed into a smaller space; c. By compressing the air we add heat from outside; d. As a consequence of the work done by the person; e. After the compression, the molecules have less space, and hit the walls more strongly…; f. Other explanations…)

Category 4: *General questions*

Q11. How much thermodynamics have you had before? Where?

Q12. How much of that was thermodynamics of gases?

Q13. How much time did you spend studying the example of rapid compression of air after it was demonstrated and discussed in the studio?

Notes: Students did not see Question 10 until they had answered Question 9. In Questions 6 and 8, more than one answer could be given.

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[5] M.E. Loverude, C.H. Kautz and P.R.L. Heron, "Student understanding of the first law of thermodynamics: Relating work to the adiabatic compression of an ideal gas," Am.J.Phys. **70**,137-148 (2002).

[6] Reference 5: 10% and 3% of students in an algebra based and a calculus based physics course, respectively, give correct explanations of the phenomenon of adiabatic compression.

[7] Reference 5, p.146: "Even references to the concept of work […] did not seem to trigger application of the first law. […] the importance of this general principle is lost on many students."

[8] Reference 5, p.146.

[9] Reference 5, p.139.

[10] This exchange took place between my wife and myself some time ago. My wife, who is a model of life-long resistance to formal schooling in the sciences, cannot be accused of harboring anything but intuitive ideas about thermal processes. In the study reported here, one of my students responded to the question about his intuitive explanation of the rise of temperature as follows: "Heat is generated by friction. I used to explain the phenomenon like this because I knew that heat is produced in friction."

[11] J. Ivory, "Investigation of the heat extricated from air when it undergoes a given condensation," *Phil. Mag.* (n.s.) **1**, 89–94, 1827.

[12] The theory of latent and specific heats was used by Laplace, Carnot, Clapeyron, Clausius, and Thomson (Lord Kelvin), to name the most prominent researchers. The earlier writers, and Thomson in 1849, used the notion of a heat function in conjunction with the theory of latent and specific heats. Clausius, and later Thomson, departed from this assumption. For details on the historical development, see C.A. Truesdell, *The Tragicomical History of Thermodynamics*, Springer-Verlag, New York, 1980. A modern version of the theory is used by C.A. Truesdell and S. Bharatha, *The Concepts and Logic of Classical Thermodynamics as a Theory of Heat Engines*, Springer-Verlag, New York, 1977. As shown by Truesdell and Bharatha, it is not necessary for the usefulness of the theory of latent and specific heats to assume the existence of a heat function. If we do (as in the text in Reference 14), we arrive at the concept of entropy as a formal expression of the intuitive notion of "heat"; if we don't, we can construct Clausius' thermodynamics. Fundamentally, Truesdell's results show that we do not have to decide what heat "really is" to explain adiabatic processes. In other words, we do not need a complete theory of thermodynamics to solve the example of adiabatic change.

[13] In the absence of heating, the temperature rises if the volume decreases. This assumes that the latent heat is positive, as it commonly is for gases; water in the range of 0°C to 4°C behaves differently (see Truesdell and Bharatha in Reference 12). This, more than anything else, demonstrates that the response of a material to adiabatic compression is a constitutive property.

[14] H.U. Fuchs, *The Dynamics of Heat* (Springer-Verlag, New York, 1996).

[15] C.A. Truesdell and R.A. Toupin, "The Classical Field Theories," in *Encyclopedia of Physics*, v. III/1, S.Flügge ed. (Springer-Verlag, Berlin, 1960). C.A. Truesdell and W. Noll, "The Non-Linear Field Theories of Mechanics," in *Encyclopedia of Physics*, v. III/3, S.Flügge ed. (Springer-Verlag, Berlin, 1965). L.E. Malvern, *Introduction to the Mechanics of a Continuous Medium* (Prentice-Hall, Englewood Cliffs, NJ, 1969). A.C. Eringen, *Continuum Physics*, Vol.I–IV (Academic Press, New York, 1971-1976). I. Müller, *Thermodynamics* (Pitman, Boston, 1985). D. Jou, J. Casas-Vazquez, G. Lebon, *Extended Irreversible Thermodynamics* (Springer-Verlag, Berlin, 1996), 2nd ed. C.A. Truesdell, *Rational Thermodynamics* (Springer-Verlag, New York, 1984), 2nd ed.

[16] H.U. Fuchs, "Entropy in the teaching of introductory thermodynamics," Am. J. Phys. **55**,215-219 (1987).

[17] The background of the course is described in three reports. H.U. Fuchs: "The Continuum Physics Paradigm in Physics Instruction. I. Images and models of change." H.U. Fuchs: "The Continuum Physics Paradigm in Physics Instruction. II. System dynamics modeling of physical processes." H.U. Fuchs: "The Continuum Physics Paradigm in Physics Instruction. III. Using the Second Law." Department of Physics and Mathematics, Zurich University of Applied Sciences at Winterthur, 8401 Winterthur, Switzerland. 1997-1998.

[18] Part of the course content is contained in the text book by T. Borer, P. Frommenwiler, H.U. Fuchs, et al., "Physik, ein systemdynamischer Zugang", Sauerlaender, Aarau (Switzerland) 2000.

[19] G.B. Schmid, "Energy and its carriers," Phys.Educ. **17**, 212-218 (1982). G. Falk, F. Herrmann, and G.B. Schmid, "Energy forms or energy carriers?" Am.J.Phys. **51**(12),

1074-1077 (1983). F. Herrmann and G.B. Schmid, “The Poynting vector field and the energy flow within a transformer,” Am.J. Phys. **54**(6),528-531 (1986).

[20] Reference 14, p.28-34.

[21] The studio is the setting of an Integrated System-dynamics Learning Environment (ISLE). The thermodynamics part of the ISLE was developed by H.U. Fuchs, G. Ecoffey, and E. Schuetz, “Integrated System-dynamics Learning Environment (ISLE): Project Report,” Zurich University of Applied Sciences at Winterthur, July 2001.

[22] S. Carnot, *Reflections on the Motive Power of Fire* (1824). Translated by R.H. Thurston, Dover Publications, New York 1960.

[23] R. Clausius, “Über die bewegende Kraft der Wärme und die Gesetze, welche sich daraus für die Wärmelehre selbst ableiten lassen,” Annalen der Physik und Chemie **155**, 368-397 (1850).

[24] Reference 14, p.170-189, and p.244-289.

[25] It has been mentioned before in Reference 12, that the constitutive theory of latent and specific heats was used by *all* thermodynamicists from about 1800 to 1860, irrespective of whether or not they maintained the notion of a heat function. (Depending upon what we take for granted, the constitutive quantities in the law are quantities referring to energy or to entropy, respectively.) In the dynamics of heat I use the assumption of a heat function and quickly turn it into a generalized version of the concept of entropy as it is used in continuum thermodynamics today (p.51-66 of Reference 14, and Reference 16).

[26] H.U. Fuchs, “A surrealistic tale of electricity,” Am. J. Phys. **54**,907-909 (1986), demonstrated by example that the form of the theory obtained on the basis of energy quantities and the First Law is unacceptable in any other field of physics. It is as if I were to create a “mechanical theory of water” to replace the “fluid theory of water.” In the “mechanical” theory, I would identify “water” with “energy transferred in hydraulic processes” (in “filling and discharging”). As a crowning achievement, I could derive the existence of “reduced water” (water divided by gravitational potential), give the new quantity an artificial name (how about “hydropy”?), and never realize that I have “rediscovered” water as a fluid.

[27] Reference 14, p.153-157.

[28] If we want a general theory of ideal fluids that includes water having a temperature around 4°C, the theory must use temperature and volume (not temperature and pressure, for example) as independent variables. See the book by Truesdell and Bharatha mentioned in 12. This demonstrates the importance of the latent heat (or latent entropy) for a general understanding of thermodynamics.

[29] G. Torzo et al., “A new microcomputer-based laboratory version of the Rüchardt experiment for measuring the ratio $\gamma = C_P / C_V$ in air,” Am. J. Phys. **69**,1205-1211 (2001).

[30] W. Thomson: “Heat,” Encyclopedia Brittanica, 9th ed., 1878.

[31] To paraphrase Kelvin (Reference 30), it has become of late years somewhat the fashion to decry the designation of heat as a noun (R.H. Romer, “Heat is not a noun,” Editorial, Am. J. Phys. **69**,107-109,2001). But the concept has not yet been generally enough followed by equally clear and concise statements of what we now know to be important for understanding.

[32] This appears to be true as well for the study referred to in Reference 5. Since the change of temperature in adiabatic compression *must* have something to do with heat, students relate compression to “heat caused by pressing the piston inward” (p.142), interpret ΔU as heat, or use models involving little particles whose motion represents heat.

[33] Students sometimes refer to laws of balance in passing (except, naturally, in Questions 1, 3, and 8), but only in conjunction with constitutive arguments, and only in the case of heat (entropy has to be removed in isothermal compression, otherwise the air will get hotter; Question 5). They do not relate energy and the balance of energy to the constitutive problem. In the case of reasoning involving little particles, laws of balance are completely absent.

[34] S. Yeo and M. Zadnik, “Introductory Thermal Concept Evaluation,” The Physics Teacher **39**,496-504 (2001). In particular, see Question 22 in their Thermal Concept Evaluation.