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Thermodynamics, not just thermal physics

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ABSTRACT. This paper presents a proposal for the teaching of Thermodynamics which takes as a starting point the intuitive ideas of students. The presentation of the results of inquiries about the understanding and misunderstandings of students leads us to the suggestion that the features of process and time are important components to intuitive schemes, of course, without any formalization. Then it is assumed that the final state of knowledge could consist of the understanding of the thermodynamics process according to the development of the subject in this century. A scheme of a didactical path is illustrated. A list of possible issues for discussion concludes this paper.

Key words: thermodynamics, intuitive schemes, physics teaching.

RESUMO. Termodinâmica, e não somente física térmica. O presente artigo apresenta uma proposta para o ensino de Termodinâmica que tem como ponto de partida as idéias intuitivas dos estudantes. A apresentação dos resultados de investigações sobre a compreensão e "enganos" dos estudantes nos leva a sugerir que características de processo e tempo são componentes importantes para os esquemas intuitivos, claro que sem qualquer formalização. Assume-se, então, que o estado final de conhecimento poderia consistir na compreensão da Termodinâmica de processo de acordo com o desenvolvimento desse tema neste século. Um esquema de itinerário didático é apresentado. Uma lista de possíveis assuntos para discussão conclui o artigo.

Palavras-chave: termodinâmica, esquemas intuitivos, ensino de física.

"The theory of heat as a form of energy is called Thermodynamics. In the same way the theory of the equilibrium of heat could be called thermostatics and that of the motion of heat thermokinematics" (Maxwell, 1904).

Maxwell's words are a good starting point for a reflection on the teaching of thermodynamics as they focus on an ambiguity in the language which, while clear for Maxwell, has been forgotten in the following years up to our times. It is true that, while he entitled his book "The theory of heat", now the word "heat" seems to have disappeared from the titles which correctly explicit in "thermal physics" the central role of temperature in the description and explanation of the processes which lead to equilibrium.

Equilibrium then statics: thermostatics is not a common word for what we teach (under different titles) mainly concerned with the equilibrium properties of macroscopic systems and only indirectly related to the true dynamics toward equilibrium which involves temperature changes due not only to the transfer of heat. The statistical approach, already presented by Maxwell with great care in defining the epistemological meaning of the kinetic theory of gases, seems to have gained a specific didactical validity while the phenomenology of processes, which remains restricted to heat transfers, seems to have lost the didactical importance it had for Maxwell.

Yet, students have problems in understanding the generality of thermodynamics concerning more the application to any macroscopic system approaching equilibrium and statistical ideas, than clarifying the issue, which seem to bring more confusion.

In the section entitled *"Schemes of understanding of students and teachers"* (section 2) I will report on the problems of Italian students and teachers. I will show, through a comparison among children at the ages of 11-13 years old, that some of these problems are not due to naive schemes of understanding (Sciarretta *et al*, 1990), but are induced by the traditional teaching. An analysis of textbooks in other languages (de Heer, 1986; Faye, 1981; Young, 1992) shows a similarity of approach in other countries and suggests that it is not only the Italian students who have problems.

In the section entitled *"An approach to the teaching of Thermodynamics"* (section 3) I will present an outline of a didactical approach to thermodynamics (in the following TD) which, starting from students naive ideas, takes into account since from the beginning the developments of TD in this century.

Examples of experimental activities (*"Examples of experimental activities"* - section 4) and of issues for discussion (*"Issues for discussion"* - section 5) will conclude this paper. I hope to raise comments and criticisms in order to improve the effort of communicating thermodynamics ideas to students.

Schemes of understanding of students and teachers

For many years in examination sessions, I collected qualitative information on the understanding and misunderstandings of students about the thermodynamics they were supposed to have learned in a general physics course. Then I decided to document the information by a quantitative inquiry with a paper and pencil test (Vicentini Missoni, 1985). Some of the questions of the text are given in Figure 1. The answer to the first question requires to choose the TD systems among the objects on the list by expliciting a definition.

The correct answer (all objects may be considered TD systems as a TD system is any object in which the internal properties may change by effect of external actions) does not seem to be shared by university students and secondary school teachers (who, in Italy, have followed a four-year university course in physics) as shown in table 1.

The definition of TD system is given by the majority either by referring to the variables PVT (pressure, volume, temperature) or to the exchange of heat and work. This shows that the treatment of a gas, without care in explaining that this is the best emblematic system for introducing the state variables, induces a restriction on the application of TD ideas. The objects excluded from the definition are, in first instance, the magnet, the spring and the moon, followed by the electrical and the biological ones. It thus seems that students acquire, from a general physics course, of knowledge separating compartments: the mechanical one in which one can find the moon and springs, the electromagnetic one with batteries, magnets and bulbs, and the thermal one with fluids, ice in dewar vessels and thermal engines including refrigerators.

The question about the melting of ice cubes has also been used in more recent inquiries on the initial knowledge of beginning university students and in an inquiry with middle school students and teachers. All the answers are shown in table 2. The improvement in the correct answers from middle school students to university beginners and to 3rd year university students and teachers is an indication of a positive effect of school communication. In all cases, however, the time difference (which is in the order of 1-2 hours) is generally underestimated (5 minutes, less than 1/2 hour). Of course, "time" does not belong to the list of thermodynamic variables! (as Truesdell (Truesdell, 1980) says, time was so excluded from the consideration that the symbol "t" was free to be used for temperature).

The questions about the sensations of touching a wooden or metallic object (correctly explained by the different rate of exchange of heat from the human body - a heat source at constant temperature) is surprising for the low number of correct answers with correct explanations (~10% for middle school students to ~ 30% for university students and ~ 50% for secondary school teachers).

A correct answer with an incorrect explanation (at the order of 50% for all samples) may be caused by everyday life experience and thus may indicate lack of correspondence of the physics learned in school with common experience.

The question about the bottle has a very low (2-3%) number of correct answers (the decrease of the boiling temperature with decreasing pressure leading to the triple point).

It thus seems that the general aspects of phase transitions lack in the teaching (which focuses on the constancy of temperature in the change of state) or are not at all understood.

Finally, the request for a synthetic definition of some thermodynamic "words" seemed to appear generally difficult and many students simply did not answer it.

From the answers, I obtained the information:

a) heat is a "form of energy" or a property of objects, and the operational definition $Q = mc_s \Delta T$ is seldom given;
b) temperature is "the measure of heat" or related to the kinetic energy of molecules;
c) pressure is the ratio force/surface with no consideration of the vectorial character of force and pressure;
d) entropy and enthalpy find formal definition while internal energy does not;
e) for specific heat a large number of correct calorimetric definitions are given but little connection with either internal energy or entropy.

In order to distinguish between problems related to naive physics schemes and misunderstandings of the science taught in school a second inquiry was made some years later again, by means of a paper and pencil test, on a sample of middle school children (11-13 years old) and secondary school teachers. Some of the questions asked are shown in Figure 2.

Concerning the temperature of material objects (question 1) the zero law of thermodynamics, while known by the majority of teachers (but not all!) is unknown by the majority of students. This fact suggests that students make reference to the real life phenomenology where the law is seldom applied. Objects are, largely, subdivided into “cold” and “neutral” as they are felt when touched. Sensory experience is also invoked for the answers to questions 2 and 3 (that I already discussed in the comparison with university students) but the importance of the constant temperature of the human body is not mentioned in the students explanations.

In the answers to questions 4 and 5 students and teachers practically all predicted an increase in temperature. Friction, heat, work and molecules were mentioned as reasons for the increase. In many cases, the logic of the explanation involved the sequence: work produces heat which leads to the temperature increase. A further analysis was then made of the five questions (all connected to a scientific framework with the knowledge of the thermal properties of materials and with thermal effects) by comparing the answers of each interviewed with the conceptual map (Novak, 1984) of the questions (details are given in Sciarreta *et al*, 1990).

The analysis led to the classification in the four categories below:

a) Answers in which reference is made to three thermal properties (heat conductivity, heat, temperature): 22% of students and 48% of teachers;
b) Answers in which reference is made to temperature and a process like property: 21% of students, 22% teachers;
c) Answers in which reference is made to temperature and a state like property: 29% students, 12% teachers, and
d) Answers in which only temperature is taken into account: 28% students, 18% teachers.

The distribution of students and teachers is surprising on one side for the relatively high percentange of students in the categories which consider process-like properties (~ 50%) and on the other side for the non-negligible amount of teachers in the forth category (the farthest from the scientific framework).

We are, thus led to conclude that the process features have a strong influence on intuitive schemes of thermal effects while the focus on the statics aspects in the teaching practice produces undesirable cancellation of the naive intuition.

The intuitive schemes then, seem to be a reasonable starting point for understanding the thermodynamics process once it may act as cognitive obstacles for accepting a thermostatic framework.

In the following years I was able to systematically confirm the results shown above in my teaching activity (a course on thermodynamics for four-year university physics students, inservice courses for teachers). I have often used at the beginning of the didactical activities, the building of conceptual maps as a diagnostic test.

The results practically obtained in all maps were:

a) Thermodynamics was restricted to systems described by the variables P, V, T;
b) The phenomenology of processes, besides heat transfer, was ignored;
c) The concept of “equilibrium” was missing;
d) Entropy was related to an undefined “disorder”.

Moreover in discussions, with both students and teachers, it was clear that a cognitive obstacle to the understanding of the concept of entropy, its usefullness and plausibility for explaining equilibrium, was related to the inequality sign in the relation of entropy to heat. The obstacle could be overcome by explaining the distinction between entropy flux and entropy production, and by distinguishing quasi-static processes and real irreversible processes.

1 - Which objects, on the following list may be called “Thermodynamic Systems”? Why? Battery, Magnet, Yogurth, Piece of wax, Cat, Spring, Tree, Resistor, Freezer, Ice cube, Helium balloon, Kettle with boiling water, Gasoline tank, Thermos with warm milk, The moon.

2 - You have two small tables (25 cm x 15 cm x 2 mm) one made of wood and one made of metal. You place, at the same moment an ice cube taken from the freezer in the centre of each of them. Which ice cube will melt first? Give, if it is the case, an estimate of the difference in the time involved.

3 - In Rome a metal object feels cooler to the touch than a wooden object. Will it be the same in an African town where the temperature is 43°C in the shade?

4 - Describe what will happen in a glass bottle containing water at room temperature when it is connected to a vacuum pump and the pressure diminishes.

5 - Define, synthetically, the meaning of the following words: Heat, Latent heat, Specific heat, Temperature, Pressure, Entropy, Internal Energy, Enthalpy, Thermal energy, Thermal equilibrium.

Figure 1. Questions used in the first inquiry

1 - In a room, where temperature is 20°C, there are, with you, a cat, a bowl of water with several fishes, a marble table, a wool cushion, a wood hanger and a metal cutter. Can you say if their temperature is less, more or the same as the room temperature? If the room temperature increases (diminishes) 10°C, what happens to the temperature of the objects and animals?

2 - Same as the question 2 of Figure 1.

3 - Same as the question 3 of Figure 1.

4 - A glass of milk is kept in motion in a kitchen mixer for some time. Will its temperature remain constant, increase or decrease?

5 - After working on a wall with a drill, do you think that the temperature of the drill will remain constant, increase, decrease?

Figure 2. Questions used in the second inquiry

Table 1. Answers to the questions about thermodynamic systems (in percentage)

	Correct answer	Wrong answer	No answer
Teachers	0	100	0
2nd y students 1982	18	79	3
3rd y students 1982	6	86	8
3rd y students 1985	37	63	0

Table 2. Answers about ice cubes (in percentage)

	First on metal	First on wood	At the same time
3rd y Univ. students 1985	70	12	10
Univ. beginners 1995	54	20	24
Univ. begginers 1996	51	20	28
Univ. beginners 1997	54	21	18
Univ. beginners 1998	52	27	18
Middle School Students 1989	15	73	10
Second School Teachers 1989	82	2	12

An approach to the teaching of thermodynamics

A choice of learning outcomes. The goal of a course in TD may be stated, in TD terminology, as stimulating a learning process that brings the students from an initial state of knowledge to a final one. As indications of the initial state of knowledge we may assume (from the inquiries shown in section 2) that students, before or independently of the school communication, have acquired from everyday experiences a frame in which some characteristics of the processes involving temperature changes are reasonably (with respect to the scientific frame) taken into account. In this frame "time" is an important variable, changes in temperature may be caused by the transfer of heat or work, equilibrium is in no need of explanation.

As for the definition of the final state of knowledge (which, of course, is a choice of the teacher) we must look at the actual state of the scientific knowledge in order to decide which elements of it should become part of the culture of a physics student or teacher, or of any ordinary citizen.

The conceptual framework of thermodynamics has, in fact, changed since the beginning of the century (Tarsitani, 1996) with the logical definition of the thermostatic aspects (Tisza, 1966; Callen, 1960), the general formal treatment of near equilibrium processes (De groot, 1951; Dembigh, 1950)) and the more recent development of rational and extended thermodynamics (Jou, 1988).

Moreover, the century has seen advances in the understanding of phase transitions and the development of low temperature physics including superfluidity and superconductivity.

From the mathematical point of view the algorithm of the response (or memory) function (Pippard, 1985) has shown its validity in the treatment of the properties of material systems.

All these developments have taken place quite independent of the statistical mechanical approach, with occasional overlap, such as in the general treatment of fluctuations around equilibrium states (in particular the fluctuation/dissipation theorem).

We may summarize the advances in thermodynamic knowledge in two main features: the coming together of different sectors of physics under the same overarching framework of equilibrium and dissipation and the reestablishment of a strong connection between the dynamic of processes and the statics of equilibrium (time is definitely a thermodynamic variable!).

It thus seems that the intuitive roots of students' understanding are closer to contemporary knowledge than to the static frame of the birth of thermodynamic.

Thus I suggest that the teaching start from an accurate description and discussion of the phenomenology of processes considering as minimum requirements for learning:

a) The understanding that the central problem of thermodynamics is the explanation of equilibrium and of the processes leading to it (Callen, 1960; Tisza, 1966);
b) The understanding that thermodynamics is a "game" between energy and entropy, the variables that are assumed to take care of the conservative (energy) and dissipative (entropy) aspects of any process (Wanderlingh, 1995;
c) The appreciation of the generality of the thermodynamic scheme in physics (Hollinger, 1985; Falk, 1968).

An experimental course. The main features of the course I have been experimenting (Vicentini Missoni, 1992) may be summarized in:

a) an initial focus on the phenomenology of processes tending towards equilibrium in different sectors (motion, thermal and electrical processes);
b) the focus on "equilibrium" as the fundamental problem of thermodynamics;
c) the use of "energy" as a primitive concept and a through discussion of "conservation/ dissipation".
d) Entropy production as the key feature of irreversibility.

For each of the four points I will give, below some indications of the didactical approach, which may be used with students who already have some knowledge of mechanics and electromagnetism.

Introduction of various phenomena in which a system is brought from one constrained equilibrium situation to another by the elimination of a constraint thus, initiating the process.

- Flow of a liquid in two connected vessels,
- Movement of a container (more or less filled) along a semicircular guide (see section 4);
- Approach to thermal equilibrium;
- Discharge of a condenser in an R, L circuit;
- Diffusion;
- Eventually clock reactions.

The qualitative analysis of these phenomena leads naturally to the introduction of "intensive" and "extensive" variables. The intensive variables characterize the interaction of the system under consideration with the external environment while the extensive ones characterize the internal properties of the system.

At the same time one obtains the definition of the zeroth law for all equilibrium situations (constancy of the related intensive variables) and a first formulation of the 2nd law in the form of "all processes end in an equilibrium state".

The following problems remain to be solved:
i - what characterizes the object of study of the systems?
ii - how can we describe quantitatively the phenomenology process?
iii - what are the equilibrium properties of different systems?

i - The characterization of the systems is recognized in the fact that in all cases the system has an interior which may change due to the effect of external actions. Mass and volume are two obvious variables for describing the interior. Now that the atomic model is a well-accepted scientific model, it is also easy to suggest that any simple system will be also characterized by an internal energy and that another variable (which we may already call entropy) will be needed to give account of interation among the components. The problem is then shifted to the establishment of the relation of the internal properties with the external actions.

ii - The processes are caused by the difference in a variable *I* which tends to cancel away, by the transfer of another variable *X* from one part of the system to another $\Delta I \rightarrow 0$.

We one may take the functional dependence $\Delta I = \Delta I(t)$ as a description of the process. In all the phenomena considered the experimental behaviour is that of decaying oscillations with two limiting cases: a) perfect oscillatory behaviour (no equilibrium); b) decay without oscillation leading to equilibrium.

Analyzing each case in detail, we may introduce the extensive variables *X* conjugate to the intensive *I* leading the process (mass for the movement, heat for the thermal case, electric charge for the condenser).

A formal description for all processes is then proposed by the relation (Vicentini, 1992, 1997)

$$\Delta I = a\Phi + b(d\Phi / dt)$$

where,

$$\Phi = (dX / dt)$$

where the first term characterizes the decay toward equilibrium (with a relaxation time τ related to the parameter a) that one may call the "dissipative part of the process" and the 2nd term characterizes the oscillations around the equilibrium situation (with a period T related to b) that one may call the "conservative part of the process".

Another formal description of the processes is available in the memory function algorithm which relates the "effect" Φ to the "cause" ΔI by the relation

$$\Phi = \int_{-\infty}^{t} R(t - t')\Delta I(t')dt'$$

An exponentially decaying memory function $R = R_0 e^{-dt}$, in fact, leads to the relation, between ΔI and Φ as written above.

The equilibrium properties. Starting from the definition of "equilibrium state" as the state in which the variables do not change in time, one analyzes the phenomenological relations among the variables for:

- gases - perfect and V. der Waals (with a possible exercise of data analysis on CO_2

isotherms) which leads to the introduction of the Kelvin temperature, the phase diagrams pV and pT, the phase transitions including the critical and triple point.

- Liquids - the thermal expansion law of thermology.
- Solids - thermal expansion and stress/strain relations, in particular Hooke's law. Question: does a spring change its temperature when strected or compressed?
- $P = \chi_c E$ for dielectric materials, $E = 0$ for conducting materials.
- $M = \chi_m H$ para-dia-ferromagnetic behaviour, Langevin Weiss equation - Curie point.
- Photon gas.

Toward an explanation. An explanation of the phenomena may be searched for by introducing a new variable. We will introduce the variable *Energy* by assuming that in the initial constrained equilibrium situation the system is characterized by a “Potential Energy” (where “potential” means that it may drive some action).

This potential energy will be a function of the extensive variables of the system U = U(X). The analysis of the ideal case of oscillatory behaviour in which the system periodically leads to the introduction of a “kinetic energy” T which is a function of the generalized velocity.

For this case the conservation law (U + T = constant) applies.

For the decaying oscillatory behaviour the conservation of energy will require the introduction of an internal energy U_i such that

$$U_i + U + T = \text{const}$$

Then, the change in internal energy ΔU_i from an equilibrium state A to another equilibrium state B will be expressed by

$$\Delta U_i = \Delta U$$

Joule experients may now be used to relate ΔU_i to the external actions Q (contact with a system at different temperature $Q = mc_s \Delta T$) and L (transfer of energy by work-mechanical, electrical, ... dL = IdX (pdV, PdE, MdH) corresponding to the loss of potential energy of the external source by the transfer inside the system).

$$\Delta U_i = Q - L$$

However one aspect of Joule experients is left with no answer (why does the work action always produce an increase of temperature? The true aspect of irreversibility (Dodé, 1965)).

Another variable, the entropy S, is then required. A variable which is not conserved but created in any real process.

The discussion of thermal engines with quasi-static processes is then used to relate the changes in the new variables to the external actions

$$\Delta S = \int \frac{dQ}{T} \rightarrow \frac{dS}{dt} = \frac{1}{T}\frac{dQ}{dt}$$

It is important to underline that quasi-static processes have a negligible entropy production and therefore the change in entropy is only due to the heat flux. In a real, non-quasi-static process, the entropy production may not be neglected and the entropy change is due to the sum of the entropy flux and the entropy production ΔS_p

$$\Delta S = \int \frac{dQ}{T} + \Delta S_p \rightarrow \frac{dS}{dt} = \frac{1}{T}\frac{dQ}{dt} + \frac{dS_p}{dt}$$

However, since S is a state function, the total change in entropy may be evaluated without considering the details of the real process by imagining an ideal path-quasi-static isotherms and adiabats-leading to the same final state mainly through entropy exchanges

$$\int \frac{dQ}{T}$$

The relation among the internal variables of the system is expressed by the Gibbs relation

$$dU = TdS + \Sigma I_i dX$$

Now the road is ready for introducing the thermostatic formalism with the fundamental relation $U=U(T,S,X_i)$, the derived relations among the intensive variables and the equivalent languages of Helmoltz and Gibbs free energies and enthalpy.

Entropy production in real processes. Starting from the distinction between processes in which the main entropy change is due to an entropy flux (heat conduction processes) and those in which the total entropy change is due to the entropy production (work driven processes) the Joule experiments may be reconsidered in the unexplained irreversible part (the entropy production leads always to a temperature increase, the diminishing of temperature can be obtained only by subtracting heat from the system through conduction).

The phenomenology of processes may then be enlarged to include the crossed stationary processes (Thompson and Peltier effects), the Onsager phenomenological relations and the formal calculation of the entropy production in real processes

$$P_s = \Sigma\Phi_i A_i \qquad A_i = I_i - I_{eq}$$

Joule heat is a very simple example [$A_i=\Delta V$, $\Phi_i=i$, $P_s=i\Delta V$] .

The hypothesis on which recent developments are based may then be introduced (Jou, 1988).

Examples of experimental activities

With interactive experimental activities I intend the use of experimental demonstrations acted in a way that stimulates prediction, observation and explanation of the phenomena by the students themselves. I propose here two examples: the ice cube experiment and the movement of containers more or less filled.

Melting ice cubes. The demonstration starts with the question 2 of Figure 1. In a first discussion students are stimulated to give the reasons. After the discussion they generally agree that the ice cube on the metal table will melt faster.

The prediction of the time difference is then asked. The general answer is from some minutes to half an hour. The correct answer will then be found by showing the phenomena. The ice cubes are put on the tables (chosen of reasonable dimensions to increase the heat transfer from the metal to air). The ice cube on the metal table tends to shift around it where as the ice cube on the wooden table does not move. While the processes take place there is always a vivid discussion about thermodynamic variables (heat, temperature, specific heat, thermal conductivity) but also on epistemological aspects and, why not, on atoms and molecules. After having reached a reasonable description of the processes that takes place in the phenomena the question on “how to reduce the rate of melting on the metal” may lead to further discussion about convection, conduction and radiation processes.

The ice cube on wood is a good “time keeper” for a two-hour didactical activity.

The containers. Three identical cylindrical cans (one empty, one half full, one completely filled with a powdery material like ground coffee) are released from some height on a semicircular guide (Albanese and Scocco, 1996).

Two of the containers oscillate a number of times around the equilibrium position. The third one stops immediately. Students are then asked to give reasons for the observed behaviours. In general, students or teachers, tend to correlate the weight of the container with the decay in the oscillations.

The discussion, of course, involves the dissipation of energy and the reasons for it. Friction is claimed for, but the external identity of the containers will not explain the difference. It is then agreed that “energy goes inside”.

It is a good experiment to introduce internal energy and internal degrees of freedom. It is also a good experiment to bring up the conservation/dissipation aspects of phenomena.

Issues for discussion

1. Language. In TD, probably for historical reasons, a number of ambiguities is still present and confusing in the language. Also for the relation with the meanings in everyday language. Examples are “reversible-irreversible-quasistatic” where the use of reversible as a synonim for quasistatic confuses two different criteria of classification (Callen, 1960).

A discussion aimed at a negotiation of meanings may lead to a clarification of the effects of heat and work exchanges, and of the positive aspect of irreversibility - the possibility of equilibrium - contrasted with the negative aspect - the efficiency of engines.

A second example is related to the processes toward thermal equilibrium - usually called “heat exchange processes: conduction-convection-radiation” with no consideration of the true characteristics of the processes of convection (mass transfer) and radiation (which does not involve entropy fluxes).

2. Heat. Usually students and teachers tend to use the word in an everyday meaning and take it as the direct cause of a temperature increase. The use of the expression “work is transformed into heat” strengthens the point. It is then worthwhile discussing the importance of an operational definition of "heat" ($Q = mc_s\Delta T$) which enables the measuring.

"Heat is a form of energy" contrasted with "heat is entropy" is another issue for discussion which points to the different roles of heat (related to the energy flux by the first principle and to the entropy flux by the second) and work (related to energy flux by the first principle and to entropy production by the second). Heat, specific heat, latent heat: how can it be that a name relates a quantity to a process feature while the same name preceded by an adjective indicates a state property?

3. Flux and production of entropy. The treatment of entropy in a process dimension enables a thorough discussion of the contrast between reversible and irreversible changes in temperature: a gas system displaced from the equilibrium situation by a piston may oscillate (in pressure and temperature) indefinitely, a spring compressed and released may oscillate in length and temperature. Second sound in solids or liquid helium is a good example of reversibility (Jou, 1988).

4. Superfluid helium (London, 1954; Atkins, 1959) is a fascinating subject to be included in a TD course for the extraordinary flow and heat conduction properties and as the counter example of the perfect spatial order expected to be reached at $T=0$.

5. Epistemological aspects related to the development of the theoretical framework in relation to technology and phenomenology. Aspects related to the use of an atomic model may find their place here.

6. Phase transitions in an integrated framework. Starting from a comparison of the Van der Waals is equation of state with experimental data the problems of the critical point may be focused, on up to the more recent developments of the scaling laws showing the similarity with the para-ferromagnetic transition (Domb, 1996).

7. Historical aspects: why does the 2^{nd} principle in the formulation of Kelvin seem to suggest that the flow of heat driven by a temperature difference is different from the flow of mass driven by a pressure difference and the flow of electric charge driven by a protential difference? In all cases a difference is needed.

8. Thermodynamics in a gravitational field and in weightlessness (Sychev, 1981).

Again, it's a good theme to establish a connection between "mechanics" and "thermal physics". Also, a good argument for the application to metereological issues.

Some final remarks

In a conference about the teaching of Thermodynamics (Vicentini, 1992) I proposed five questions to the participants (researchers in thermodynamics and researchers in physics education).

The questions were:

1) Should we start teaching from processes or states?
2) What should people, who are not going to become physicists or chemists, know about thermodynamics as some basic cultural knowledge?
3) What is the epistemological importance of thermodynamics?
4) Is thermodynamics useful, necessary, for understanding complexity?
5) Micro-macro-meso: what to do in education?

The conference did not produce a final answer to the questions.

In this article I have tried to show my personal answers, but I do think that the questions are still open and should be addressed by other educators.

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