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COMPREHENSION OF TEMPERATURE WHEN SOLVING A THERMODYNAMIC TASK

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Abstract. *The present study focus the presence and role of deep qualitative conceptual knowledge of temperature among a group of ten individuals (n=10), academic well-educated and experienced in science, when solving a task about changes in temperature of a given thermodynamic system. The aim is to find out the variation of comprehension of temperature in the task solving process.*
Data is ga*thered by interviews based on the thinking aloud method. The interviews were video-recorded and verbatim transcribed. Transcriptions were analysed by using a two dimensional semiotic/ semantic analysing schema (acronym 2-D SAS). The results revealed a broad variation in the comprehension of the term temperature in the given context. The three informants who produced correct answers structured the task by identifying the scientifically appropriate referent and sense of the term temperature according to the given context.*
Key words: *semantics, comprehension, temperature, referent, qualitative analysis.*

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Introduction

There is an extensive amount of studies about students and teachers' conceptions of the physical concept temperature and where the focus should be when it comes to teach and learn this concept (cf. Duit, 2010)[1]. de Berg (2008) has summarized studies on students' conceptions of heat and temperature during some twenty years, indicating that student's conceptions of these concepts are often at variance with the qualitative scientific meanings. Galili and Lehavi (2006) have shown that also science teachers have trouble defining concepts within the thermodynamic domain. However, most of the studies about the comprehension of heat and temperature are conducted with students at the primary and secondary levels. To elucidate the qualitative comprehension of the scientific concept of temperature we turned to well-educated individuals. Hence, in the present study we investigate if and how individuals, who have studied on the tertiary level, qualitatively reason about temperature when it is embedded in a thermodynamic task. The task is constructed in such a way that it enables a rich qualitative discussion, not primarily inviting to algorithmic/ algebraic approaches and solutions. Our focus is on how the informants are comprehending temperature from a semantic point of view. Already in the late thirties Weinberg (1939) stressed the importance of paying attention to semantics in physics education with special focus on the correlation between symbols and referents. He claims that:

1 Science education research has revealed a lot of ethnographic information on how the words heat and temperature are used among learners (e.g. Carlton, 2000; Erickson & Tiberghien, 1985; Goedhart & Kaper, 2002; S Kesidou & Duit, 1993; S. Kesidou, Duit, & Glynn, 1995; Roller, 1950; Shayer & Wylam, 1981; Stavy & Berkovitz, 1980; Taber, 2000; A. Tiberghien, 1983; A Tiberghien, 1985; Tisza, 1966; Wiser, 1987).

> A person has good physical intuition if he can choose from the flock of physics symbols which he commands those symbols whose structure is most like the structure in the physical reality, and if he can recognize structure in the physical reality to which he can correspond known symbols of similar structure (Weinberg, 1939, p. 107).

The actual meaning of different words/symbols was also stressed in the1960's by Feynman, Leighton & Sands (1989). Williams (1999) addressed attention to word-meaning in physics education by pointing to the fact that one and the same word can have different meanings in different contexts. Wiser & Amin (2001), in their study of heat, looked at language integration between what is usually referred to as every day language and the scientific language to gain a higher level of understanding. They stress the fact that a word like heat appearing in both languages brings up the need for ontological awareness and changes. Ontology deals with questions concerning the existence of entities, viz. the referents of concepts. The issue of ontology in concept teaching and learning is also a main focus in Chi and Slotta (1993) and Reiner, Slotta, Chi and Resnick (2000). Their position is that concepts like heat and temperature are often interpreted by novices in science as matter based, when from a scientific point of view they are emergent phenomena. Their suggestion to remediation of students' every-day conceptions is to make them aware of the correct ontology. A recent study in that vein is Haglund, Jeppsson and Strömdahl (2010) who investigated the multiple senses and referents of entropy. This multiplicity seems to constitute one of the challenges in teaching and learning the scientific meaning of entropy.

Problem solving in physics has been studied from a spectrum of perspectives. Specifically, Larkin, McDermott, Simon, & Simon (1980) have concluded that there is a distinct difference between a knowledge development model, also known as forward approach (Chi, 2006a) working with the given information in the task to the goal, characteristic for an expert and a mean-ends model, also known as backward approach, characteristic for a novice, focusing on known formulas where the desirable quantity is included. Larkin et al. (1980), Chi (2006a, 2006b) and Chi, Feltovich, & Glaser (1981) have drawn attention to qualitative analysis and cognitive effort in the task solving process as two important criteria in which experts excel. Qualitative analysis is tied to the time spent of analysing and developing an appropriate representation of the task. Cognitive effort can generally be described as the load to retrieve relevant domain knowledge. Typically, experts exhibit high qualitative analysis and low cognitive effort since they have good relevant domain knowledge.

Even if there is an extensive research literature on students' conceptions of temperature, there is a need for more fine grained studies with particular focus on the comprehension of the term from a polysemous (meaning variation) perspective. Experienced individuals at the tertiary level are used as informants in that endeavor. Our hypothesis is that they can generate rich data. The aim of the present study is to carry through a qualitative exploratory investigation to find out the variation of the comprehension of temperature when solving a task in thermodynamics and what comprehension is required to make a correct solution of the task.

The fine-grained analysis of the comprehension of temperature is done by using a two dimensional semantic semiotic analysing schema, acronym 2-D SAS (Strömdahl, 2009, under revision). The task-solving model of Larkin et al (1980) is applied to describe the informants encounter and processing of the task..

Methodology of Research

Sample

The informants comprise ten (n=10) well-educated and experienced individuals in natural sciences in Sweden: two science teachers (T1 and T2), one in mathematics and physics one in chemistry and science, four science teacher students (TS1…TS4), three physics students and one chemistry student following a teacher training program for Swedish upper secondary school and four PhD-students (DS1... DS4), active within the research areas of physics (2), chemistry (1) and biology (1). The science teacher

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students had studied for at least three years and the PhD-students have about two to three years research studies. The science teachers had more than 20 years of teaching experience at the upper secondary level each. All informants are acquainted with thermodynamics on a more or less advanced level and they all participated voluntarily. No evaluation or assessment is made between neither the individuals or within the group of informants. They make up a heterogeneous sample (cf. Robson, 2002) of well-educated and experienced individuals in natural sciences to obtain qualitative variation in the approaches to the task given. In the excerpts from the interviews in the analysis and result sections the two interviewers (the authors) are denoted I1 and I2.

Research Design

The thinking aloud method (cf. Pressley & Afflerbach's, 1995; Someren, Barnard, & Sandberg, 1994) within interview settings was used to collect data to capture the informants' detailed articulation of the task and its solution in individual video recorded sessions. The formulation of the task is of such a character that it is not possible to come up with a productive and successful solution if qualitative knowledge about the concept temperature and its referent within the kinetic gas theory is not known (for detailed information about kinetic gas theory see standard literature in physics). Neither is it possible to come up with a successful solution only by using formulae learnt by heart. The task was distributed to the informants as a written text:

Two kg of an ideal gas are placed in container A, and another four kg of the same ideal gas are placed in container B. The total kinetic energy of the gas molecules in A (that is, the sum of the energies of the individual molecules) is ***exactly equal*** to the total kinetic energy of the gas molecules in B. The two containers are placed into thermal contact with each other, but insulated from all other objects in the surrounding environment.

When the two containers come into contact with each other:

A. Will the temperature of container A increase, decrease, or remain the same?

B. Will the temperature of container B increase, decrease, or remain the same?

Explain your answers to these questions.

The task is included in a collection of thermodynamic tasks developed and elaborated by David Meltzer[2] used in other contexts and for another purpose.

The interview setting allowed the informants to speak in an open-ended manner about what they were reading from the written text and how they thought about the solution of the task in communication with the interviewers. The interviewers' role was to keep up the informant's explicit oral reasoning on the task-solving process. The recordings were verbatim transcribed.

The task contains a number of essential concepts that have to be discerned and interpreted. There are three definitions of *mass* that circulate; quantity of matter, inertia and the triad of meanings derived from Einstein (Robinsson, 2004). The idea of mass has bewildered many researchers and teachers/pupils e.g. (Barton, 1946; Roch, 2005). In the present task solving context, mass as a quantity of matter grasped as a number of molecules is the most relevant interpretation.

An *isolated system* is a system that is closed from all matter and energy in the surrounding environment.

The sum of the *kinetic energy* and the potential energy of the molecules is a system's *internal energy* (U), when the system is at rest as a whole.

An *ideal gas* is a gas in which the individual finite size of molecules and the forces between them can be neglected. An ideal gas is one that fulfils the ideal gas equation $pV = nRT$, where p = pressure, V = volume, n = amount of substance (chemical amount), R = molar gas constant and T = temperature.[3]

Thermal contact is a situation where it is possible for energy to exchange between two interacting systems. Thermal contact intends contingency for exchange of *heat* (q), which is all form of energy transport that is not work (w). The sum of work and heat are therefore equal to the total change of

2 Personal communication with Professor David Meltzer via e-mail.

3 In the paper all physical quantities and units are supposed to be in accordance with The International System of Units (SI).

energy, which makes up the first law of thermodynamics $\Delta U = q + w$.

A possible start to solve the task is to simultaneously discern key concepts and make a sketch of the task situation.

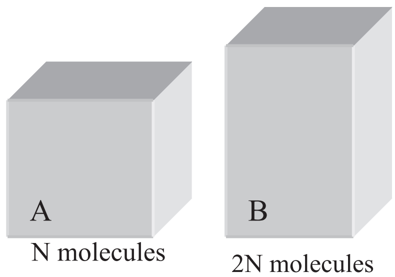

Figure 1: A sketch of the task situation.

As noticed above in the specific task context, mass is to be interpreted as a certain number of molecules. Hence, the container with four kg of ideal gas contains twice the number of molecules as the container with two kg of the same ideal gas (Figure 1). As stated in the scientific clarification below (kinetic gas theory), temperature in the bulk gas is proportional to the average translational kinetic energy of the gas molecules. Thus, even though the two gases in A and B individually have the same total ("exactly equal") kinetic energy, the gas in container *A* has twice the average kinetic energy *per molecule* compared to the molecules in container *B*. In other words, since container A contains N molecules and B contains 2N molecules the energy per molecule is container A, $E_k^A = \frac{E^{tot}{}_k}{N}$ and in container B $E_k^B = \frac{E^{tot}{}_k}{2N}$. Since there is more energy in average per molecule in A, consequently the temperature is higher in A than in B ($T_A > T_B$). When the containers are put in thermal contact there is a temperature gradient between the containers meaning a spontaneous energy exchange between the two containers (Figure 2). According to the zeroth law of thermodynamics, heat (q) flows spontaneously from the body with higher temperature (T_A) to the body with lower temperature (T_B).Thermal equilibrium is reached, which is observed when the temperature is the same of the two containers.

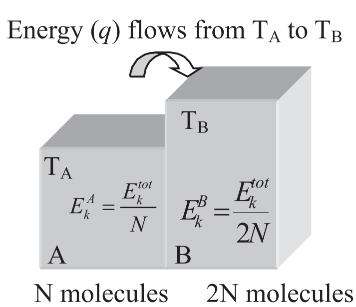

Figure 2: Thermal contact between two systems A and B.

Therefore the temperature of the gas in container *A* will decrease and the temperature of the gas in container *B* will increase. This is a solution to the task.

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Data Analysis

The data were analysed qualitatively. The task solving process was captured by the categories forward and backward approaches (cf. Chi, 2006a; Chi, 2006b; Chi, et al., 1981; Larkin, et al., 1980). The fine grained qualitative analysis was done by applying a two dimensional semiotic/semantic analysing schema (acronym 2-D SAS). This schema is elaborated with the purpose to analyze scientific terms, especially physical quantities, for educational purposes Strömdahl (2009, under revision). The 2-D SAS approach has been used in a previous study to discuss the educational implications when introducing the concept of entropy (Haglund, et al., 2010). The structure of the schema is that, a word is analyzed in two dimensions (Figure 3). The vertical axis refers to various meanings (polysemy) of a word and the horizontal axis refers to the discernment of the semiotic elements word, concept and referent. The referents are the typically non-linguistic entities' that language describes, e.g. objects and phenomena or aspects of object and phenomena. Concepts are the mental or cognitive representations and words are phonological and/or graphic symbols. Following the reasoning of Andersen (2001), referents are identified in the phenomenal world-as-perceived. Particularly, the referent of a formal scientific concept is regarded as an aspect of an idealised and prototypical model. A more thorough discussion of the concept of reference is presented in a conference report (Strömdahl, Haglund, & Jeppsson, 2010) and in an extended version of the report (Strömdahl, Haglund & Jeppsson, in preparation).

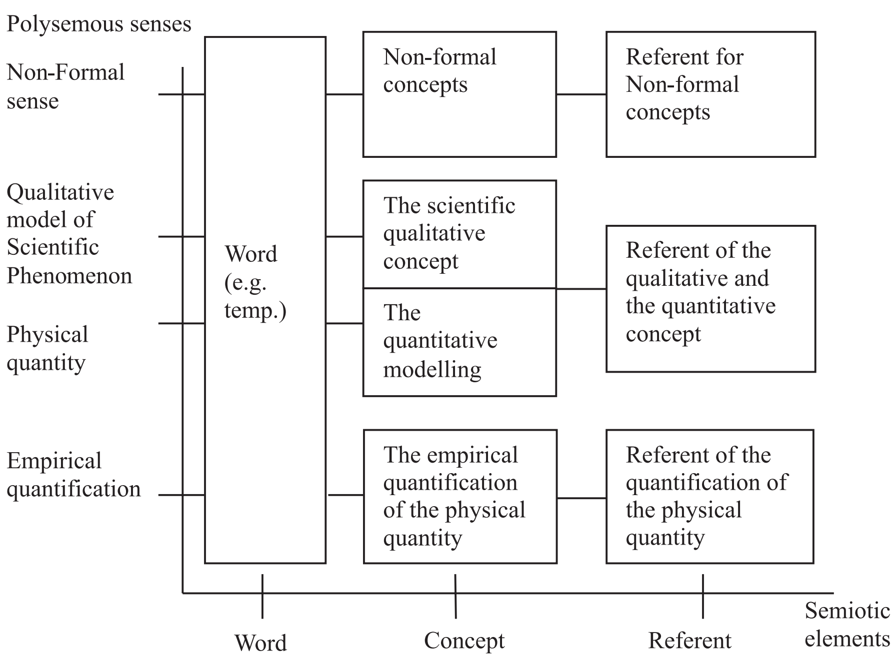

Figure 3: The basic idea of 2-D SAS. Four meaning entrances are discerned, non-formal meanings, the qualitative meaning of a scientific model of a phenomenon or object, a physical quantity and an empirical quantification (a measurement).

Below the 2-D SAS is applied to the word temperature, where non formal and scientific formal concepts and referents can be discerned (Figure 4). The relationships between the referents and concepts in the schema are marked with lines. These relationships are not in focus in this particular study

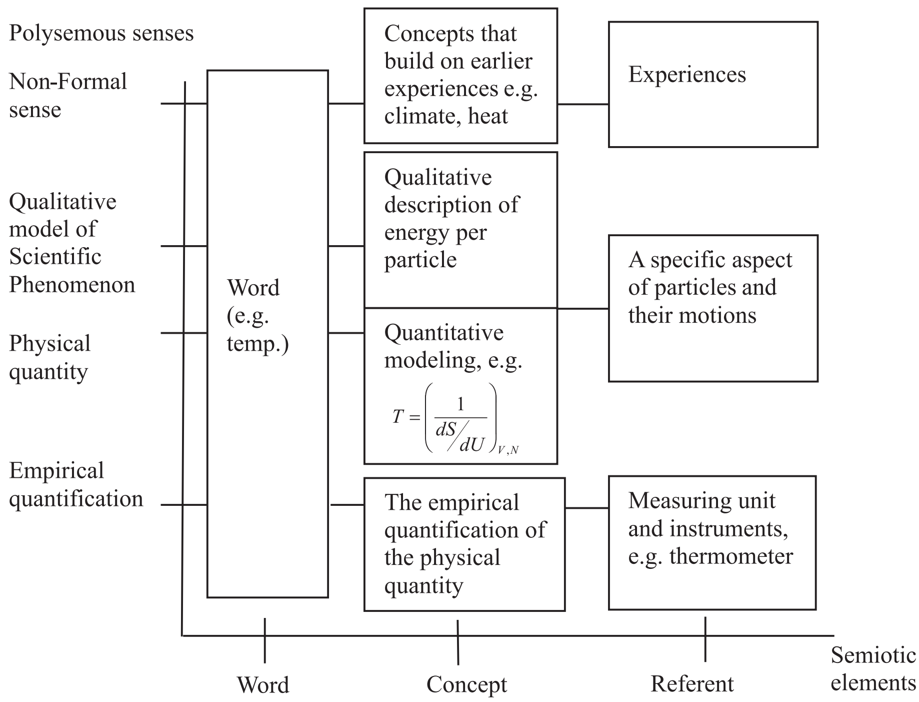

Figure 4: 2-D SAS interpretation of the word temperature, non formally and for an ideal gas.

In everyday language and contexts, the non formal meaning of temperature is often related to different types of perceptions. Temperature in the kinetic gas theory is proportional to the average kinetic energy of gas molecules where the potential energy of intermolecular interactions can be neglected. This can on one hand qualitatively be modelled as a scientific qualitative concept where temperature is related to energy per particle within the kinetic gas theory. On the other hand temperature, within the theory of statistical mechanics, may be defined as the partial derivative of the entropy *S* with respect to the internal energy *U*, with fixed volume *V* and number of particles *N*: $T = \left(\frac{1}{dS/dU} \right)_{V,N}$. Both these aspects refer to the same referent, namely a certain aspect of particles and their motion. Finally, the empirical quantification of temperature requires the definition of a unit (1K, 1°C, etc.) and suitable measurement equipment, a thermometer.

The interview protocols were analyzed by using the 2-D SAS interpretation of temperature (Figure 4).

Result of Research

The task is an assignment to indentify the referential and conceptual basis of the scientific concept of temperature, not just applying "appropriate equations". A key issue is to find out the connection between temperature and the average translational energy of gas molecules and how the scientific referent and concept of temperature is connected to the data and conditions of the given task.

Three of the informants discerned and interpreted correctly the essential concepts and their related referents in order to solve the task. They typically approached the task by working from the given state to the goal, the *forward approach*. In this case the qualitative senses of quantities are in focus which is confirmed by DS1 and DS3:

> **I2:** What do you think is the problem … or what is the difficulty for this task?
> **DS1:** to translate … you get information about one concept then you shall translate … and

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express to another concept. One has information about kinetic energy and should express the answer in terms of temperature […] …ehh it says that the total kinetic energy of the gas molecules in A. is exactly equal to the total kinetic energy of the gas molecules in B .. ehh… but there is twice as much gas in B and therefore there must be twice as much molecules so therefore it must …

TS4, DS1 and DS3 all started reading the question carefully, took their time and made a first sketch, modelling the specific system specified by the task, and took their starting point in the referent of aspects of moving particles. From there on they discerned what was necessary to solve the task. How these informants approached the task is illustrated by excerpts from the interview with TS4. TS4 made a sketch:

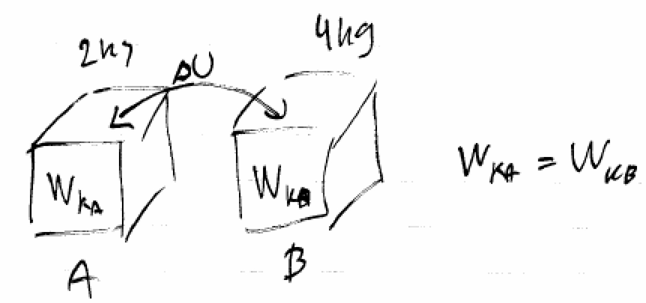

Figure 5: TS4's sketch.

The meaning of thermal contact according to TS4 is the double cusped arrow denoted by ΔU, which is indicating an exchange of energy. W_{KA} and W_{KB} denote the kinetic energy of the ideal gases in the containers A and B.

TS4…when these two [the systems A and B] are in thermal contact… if it reduces in one it must increases in the other one. Or if it is equal, there is no process going on. One could call them a communicated system. […]
So if one gets the answer to A the answer to B is obvious, since we don't have any external influence on the system. Ehh … so the thing one should have is how much … [TS4 is silent for a moment] … it is … the first one think of is… ahh… it is equal amount of energy really … so the first thought is that nothing can move at any direction. But that is not what actually decides

The underlined quotation is an essential statement and a turning-point in TS4's reasoning, who quickly moved on by declaring,

TS4: One could say something about that the energy in B is divided on twice as much material as A and then one could say... for that reason will the average velocity at a particle in A be greater than the average velocity in B because there is half amount of particles in 2kg that fly's around and they get double portion of energy in average per particle that result in that they fly much faster. Actually we have double temperature in A as B ….. should it be… when one put them in thermal contact will the temperature in A decrease and in B increase.

This approach is similar to what DS1 and DS3 report when they are speaking about thermal contact. There is one more common denominator that brings TS4, DS1 and DS3 together. They all express how they try to find out more than one explanation to physical concepts when they act as teachers and laboratory assistants. Evidently a multidimensional understanding of physical concepts and referents makes it possible for them to correctly apply them in different contexts and eventually come up with successful solutions, like they did about the current task.

Figure 6 depicts the task solving trajectory, for DS1, DS3 and STS4, identifying temperature as related to the referent of molecules and their motion.

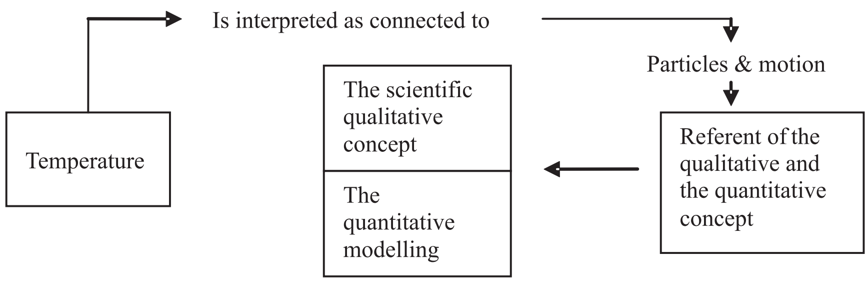

Figure 6: DS1, DS3 and TS4 did all start in the referent of the scientific phenomena temperature by talking about particles and motion.

Seven of the informants are using the backward approach to find a solution to the task They start to describe temperature on the basis of their everyday knowledge or of different concepts and formulas that they connect to temperature, for example the ideal gas law. An obvious pattern among the seven informants is a faith in formulae.

T1 is pondering about all formulas that comes to mind and seems to have difficulty to sort out what is important or not.

> **T1:** well it is nothing that one has put a lot of time in … well the physics B [a physics course in upper secondary school in Sweden] in upper secondary school involves so many concepts … somebody has estimated how many formulas there are in physics B and it should be about …. […] there are an endless number of formulas … that one should teach … it is difficult to know what formulas one could skip and which formulas one wishes to stress for the students […] although I feel more that if all particles in A are the sum of the kinetic energy in A are equal to the sum of the kinetic energy in B …This could mean that this container is bigger. […] therefore the density of energy must be equal in some way … and then it doesn't matter if one put them together … but on he other hand there are no such thing as mass in something like this (T1 writes down PV=nRT)

Even if you know that the concept kinetic energy is related to temperature it is necessary to know exactly what the relation means. T1 made a sketch of the system (Figure 7), but where the referent of temperature is indistinct, by not specifying the essential discernment of the average motion (translational energy) per molecule Therefore, it is not possible for T1 to come up with a correct solution.

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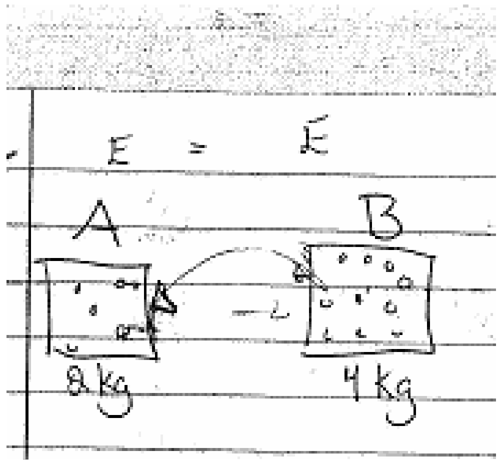

Figure 7: T1 interpret the situation with two different amounts of ideal gases.

With essentially the same reasoning concerning the meaning of temperature for an ideal gas TS1 performed a similar solution.

> **TS1**: The two containers are placed in thermal contact … ok (TS1 draws a sketch) […] but are isolated from all other objects in the surroundings
> **I1**: Yes!
> **TS1**: When the two containers *come into contact with each other* in a, will the temperature decrease, increase or remain the same? […] remain the same! (T1 writes down the answer) […] since the kinetic energy in each particle are the same, isn't it. (a rhetorical question posed by TS1)

Apart from temperature the task contained other essential concepts that have to be discerned and interpreted if a successful elaboration of the task should be possible. For instance T2 struggles with the concept of thermal contact:

> **T2**: The total kinetic energy of the gas molecules in A… is exactly the amount of energy (adding things in the figure) is equal to the amount there […] the two containers are placed in thermal contact, but isolated from other … has that something to do with heat? … Thermal contact, that is a new expression for me, I have never heard that before […] But why does is says thermal contact? Has that anything to do with temperature?
> **I1**: Well
> **T2**: Then it says that the two containers come in contact with each other […] will the temperature increase or decrease … does this mean that the gases can move freely?

Thermal contact is an essential concept in the task, making it possible for energy to exchange between two interacting system A and B. If it is indistinct what happens with the energy, it is not possible to solve the task. For some of the informants terms like temperature are only words/symbols fitting in to different formulae like the ideal gas law (PV = nRT).

> **DS2**: I am trying to remember the ideal gas law, ehh, well, let me see? (the informant thinks for a while) well, how was it? I have some numbers popping up in my head, but is like …

Formulae manipulation is a shared common denominator for the seven interviewers applying the backward approach to the task solving process.

The outcome of the analysis of the empirical data is summarized in Table 1 and Figure 8. In Table 1 all informants are classified according to their strategic approach to the task solving process. Notice that the index for backward approaches (backward 1 - 4) is a way of separating different trajectories in the task solving process connected the interpretation of temperature in the 2 D SAS analysis as depicted in Figure 8.

Table 1. The distribution of the different strategic approaches among the informants.

	Forward	Backward 1	Backward 2	Backward 3	Backward 4
DS1	X				
DS2			X		
DS3	X				
DS4				X	
TS1		X			X
TS2				X	
TS3				X	
TS4	X				
T1		X			
T2				X	

In Figure 8 the vertical column denotes the strategic approaches. The horizontal row denotes the comprehension of temperature according to the 2-D SAS terminology. The curved line visualizes how the informants interpret and works with the term temperature and the arrows show the temporal development. Figure 8 should be interpreted in connection to the section below.

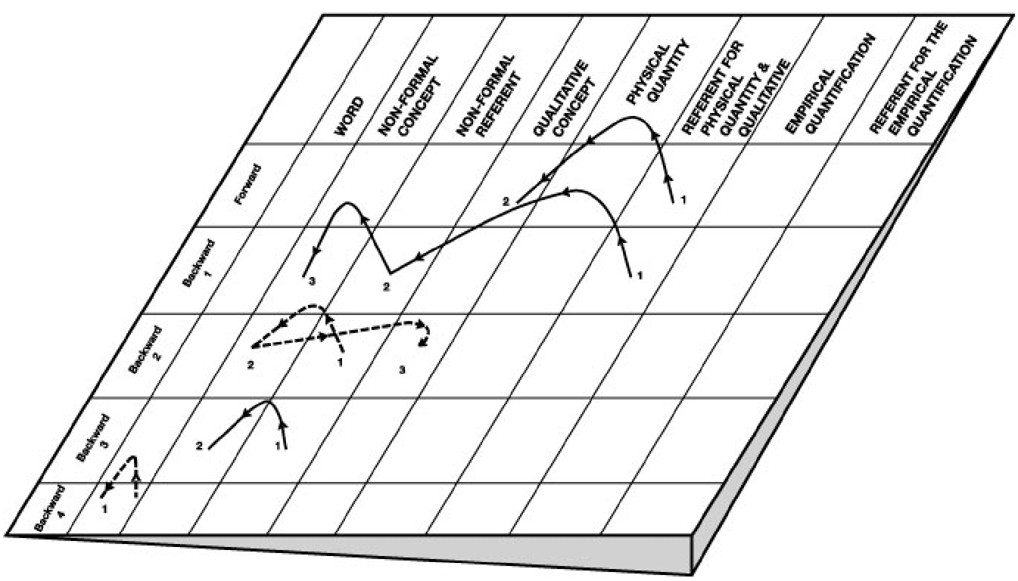

Figure 8: Outline of the solving trajectories among the informants according to the task solving processes where the numbers in the boxes correspond to the explanatory text below.

The three informants' strategic approach classified as "the forward group" interpret the word temperature rooted in the correct aspect of the referent (1) by talking about particles and their motion and eventually end up in the concept of the scientific phenomenon (2) which makes it possible to solve the task together with the other information given in the task.

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T1, categorised as processing the task "backward 1" started similar to "the forward group" in the referent of the scientific phenomena (1) by talking about particles and motion. However this thread is not fulfilled by identifying the correct scientific concept. Instead, the non-formal concept of temperature (3) via the non-formal referent (2) is decisive for the incorrect solution of the task.

DS2, categorised as processing the task "backward 2"starts unlike the forward and the backward-group 1 by talking about Non-Formal referents (1) for temperature, nevertheless, within a scientific context (2) and end up in a region near the qualitative concept of temperature (3),. DS2 actually ends up somewhere in middle of non-formal concepts/conceptions and the qualitative concept of temperature. The dashed line in figure 8 indicates that DS2 moves back and forth between a non-formal referent and a scientific concept of temperature.

T2, TS2, TS3 and DS4, categorized as processing the task "backward 3" did not express a clear connection between word, referent and concept. They typically talked irregularly about different non- formal referents (1) and non-formal concepts (2) related to thermodynamics.

TS1, categorised as processing the task "backward 4"used words without a specific meaning (1), even though the words are related to the thermal domain. The words where not put in any particular context or in any scientific situation, it was just "talk".

The results show that the comprehension of temperature is varying among the informants when confronted with one and the same thermodynamic task. Deep qualitative knowledge of the scientific referent and sense of temperature is decisive for the solution of the task. Only the three informants who produce that kind of knowledge in the given context were able to achieve a correct solution.

Discussion

In this study, we have used a two dimensional semantic/semiotic analyzing schema, acronym 2-D SAS, to analyze how ten academically well-educated experienced individuals comprehend temperature, when solving a thermodynamic task. Three of the informants show a conscious strategy to conceptually explicate the term temperature in relation to the other information given in the task. They identify temperature as referring to the motion of the molecules, namely temperature as proportional to the average motion (kinetic translational energy) of the molecules. This explicit identification of the scientific meaning of temperature makes up a base for the combination of other information in the task to end up in a correct solution. On the other hand, the other seven informants did not comprehend temperature in a successful way according to the task context, but relied on their knowledge of temperature (T) as primarily an entity appearing in formulas like the ideal gas law, $pV = RT$. However, without the qualitative knowledge of the referent and sense of temperature there is no possibility to solve the task. The present results points to the importance of explicitly communicating the significance of the referent and sense of temperature to students in educational settings, viz. the results confirms that more effort should be spent on what words actually means (cf. Feynman, et al., 1989; Haglund, et al., 2010; Weinberg, 1939; Williams, 1999). Our results also confirms that science teachers have trouble defining certain concepts within the thermodynamic domain as noticed by Galili & Lehavi (2006). As an alternative to the common idea in science education research that addressing learners' everyday knowledge about a concept in the initial stage of learning is the most fruitful way to introduce a scientific concept (cf., e.g. Wiser & Amin, 2001) we suggest that pointing out the correct referent (ontology) of a scientific concept seems to be a necessary prerequisite for a successful acquisition of the concept (Chi & Slotta, 1993; Reiner, et al., 2000; Weinberg, 1939). However, our results show that it is not enough to know the correct ontology on a general level, e.g. just discerning materialistic or emergent aspects. The specific referent, e.g. the correct aspect of the molecular motion must be discerned, like in the case of temperature.

Chi (2006a) has drawn attention to qualitative analyses and cognitive effort as two important criteria in which experts excel. This was confirmed in this study where high qualitative analysis and low cognitive effort where characteristic for the three informants who managed to come up with an explanation of the concept of temperature for a productive elaboration of the task. The seven informants who failed to solve the task are less concerned with qualitative analyses and the representation of the task. High cognitive effort was shown among them searching for relevant knowledge, however failing, by more or less focussing on algorithmic knowledge which was a blind alley in the task solving process.

The 2-D SAS approach makes it possible to do a fine-grained analysis of word-meaning and has shown a potential to make conceptual difficulties of physical quantities explicit, in this case temperature, with the possibility to inform remediation efforts in teaching and learning. However, further empirical research is needed to prove its usefulness.

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