

## Interpretative perspectives of thermal phenomena and the role of RTL exploration in 16 year old students

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**Summary.** — In this paper we present a study aimed at identifying the interpretative perspectives and possible elements for the conceptual change in the interpretation of thermal phenomena of 16 year old students. There is an extensive research literature in physics education, highlighting persistent inconsistencies in interpretive ideas about thermal phenomena at all age levels. Common sense ideas, calorimetric interpretations are intertwined with the thermodynamic view based on states and processes. This seems mainly due to the fact that in school curricula, the concepts of thermal equilibrium, temperature, internal energy and thermal properties of materials are often addressed with a thermostatic and calorimetric approach poorly connected to the thermodynamic view of phenomena. With sensors in RTL mode that highlight thermal states and processes, we proposed the experimental exploration of some thermal phenomena to 64 students from 3 upper secondary school classes who had studied thermal phenomena with a calorimetric approach in order to understand the ways in which the desired conceptual change towards a thermodynamic reading could be promoted. The results of a qualitative analysis of the interpretations show us that an RTL approach is suitable for constructing the concept of temperature as a state property, an interpretative pivot of thermal interaction phenomena. Even in thermometric conduction processes this is an important basis, although a more in-depth interpretation in terms of energy seems to be necessary.

### 1. – Introduction

A wide literature in Physics Education Research has shown that many learning problems stem from unclear ideas and non-epistemic ontologies of temperature, heat, and the first law of thermodynamics. In particular, the interpretation of thermal phenomena represents an obstacle at all ages and becomes an even greater problem at university level for the study of thermodynamics.

Meltzer [1] compiled a bibliography of more than 200 research papers on learning thermal concepts (heat, heat conduction, temperature, thermal equilibrium, etc.) among pre-college students dating back to at least the late 1970s. Kesidou *et al.* [2] provided a summary of the work on heat and temperature up to 1995. Erickson [3-5] reported that the conceptions of heat of Canadian children (age  $\sim 12$ ) were material in nature, as if it were a fluid that can accumulate and flow. Temperature has been described as a measure of the amount of heat. Cold was considered a material substance, separate from heat,

and, for example, children described larger ice cubes as colder. Tiberghien [6] reported similar conceptions among French children of the same age. Engel Clough and Driver [7] reported that misconceptions about thermal conduction by very young children were still prevalent among secondary school students in the UK (up to the age of 16), including beliefs that heat and cold are different substances and that metals attract cold. Linn and Songer [8] and Lewis and Linn [9] described the intuitive conceptions of U.S. middle school students, reporting that only 3% of students met a strong criterion for distinguishing heat and temperature before education, and 14% explicitly described them as a single concept. Jasien and Oberem [10] conducted a quantitative study on students' understanding of the concepts of heat and temperature using a written survey with specific questions and concluded that their results suggested substantial student confusion about the concepts of thermal equilibrium, the physical basis of thermal conduction, temperature change, and the relationship between heat transfer and specific heat.

Christensen *et al.* [11] studied students' understanding of heat, temperature, and specific heat capacity at a large public university in the United States. From the research, the authors highlight two results. First, a small but significant number of students responded that heat transfers were not the same in the context of calorimetry. Second, a large number of students seemed to reverse the correct reasoning, concluding that the object with higher specific heat would also have a greater temperature change. Loverude *et al.* [12] reported their study on students' understanding of the first law of thermodynamics; this is a work closely related to that of Kautz *et al.* [13] described above, with authors and datasets overlapping. The study revealed a widespread confusion between heat, temperature, and internal energy, reflecting similar results to previous work, for example, a student who could not figure out whether the "heat in the system" was internal energy, temperature, or was related to heat. The students suggested that the insulation prevented temperature change rather than heat exchange. Other students were unable to recognize heat and work as independent means of internal energy change. This seemed to reflect the confusion between state variables such as internal energy and process-dependent quantities such as heat or work. Meltzer [14] published a widely cited report on students' understanding of the first law of thermodynamics. The written questions were about two processes on a PV diagram, with the same start and end states but different paths. The results of the paper corroborated previous findings and provided additional insight into the students' reasoning, framing the students' difficulties more explicitly in terms of understanding state functions.

This picture, which does not seem to have changed, requires a study of how to produce the conceptual change from common sense to the thermodynamic interpretation of thermal phenomena or even the double conceptual change from common sense to calorimetric interpretation and from this to thermodynamics.

Previous studies carried out by us on the implementation of sensor-based proposals in Real Time Lab (RTL) mode [15] have allowed us to make the hypothesis that experimental exploration in this mode can favor thermodynamic interpretation. In this paper we report on this study.

## 2. – Research framework

The main aspects that emerge from the literature seem to be the following:

- the traditional calorimetric interpretive approach negatively influences the way states and processes are interpreted in thermodynamics, *i.e.*, students who have

approached problems from a calorimetric perspective have been accustomed to thinking in terms of equilibria and heat as entities and not in terms of processes;

- the separation between calorimetry and thermodynamics negatively affects the understanding of the concept of energy, which is not recognized as a state property that is conserved and transformed;
- thermal equilibrium is not seen in dynamic terms as the result of a process of temperature variation and the very concept of temperature measurement is not associated with a state of a system;
- the concept of internal energy is not clear, nor is it the result of processes that modify it: it is necessary to give meaning to the first law of thermodynamics.

The main lines of research that intertwine in this study are disciplinary conceptual analysis, the study of learning processes and conceptual change, the use of RTL devices for experimental activity. The theoretical framework of reference is that of entangled research methods in the identification of educational proposals, with analysis of learning processes with qualitative methods integrated in an active mode of experimentation, supported by tutorials [16]. This research looks at the interpretations of thermal phenomena in a vertical perspective [16-18], with an approach aimed at conceptual change and overcoming interpretative knots [19-24], *i.e.*, those common-sense ideas of phenomena that contrast with the scientific vision. Data collection is through tutorials, which are analyzed in terms of conceptual classes to find how an IBL approach based on RTL devices can contribute to conceptual change.

### 3. – Research methods and questions

The RTL approach chosen allows students to look at the phenomenon by means of time evolution of the temperature plotted in real time with the process explored. The tutorials that ask at the same time questions stimulus prediction, reading the phenomenon and its interpretation, impose a reflection on how temperature, *i.e.*, the descriptive quantity of the process, changes over time, and how this is posed in terms consistent with interpretation and previous knowledge. We chose students from three third classes of a scientific high school, who treated the study of thermal phenomena with a calorimetric method to focus on conceptual change.

Research questions are the following:

- 1) How the traditional calorimetric approach influences the interpretative reasoning on simple phenomena on thermal interaction among systems.
- 2) How an RTL analysis of thermal phenomena can help in the conceptual change from a calorimetric to a thermodynamic way of thinking.
- 3) How an RTL-based analysis of thermal phenomena helps students to distinguish between dynamic processes and equilibrium states.

### 4. – Sample and research

Three third classes of the scientific high school were involved, for a total of 66 16 year old students (22 respectively from classes A, D and L) in a series of three experimental

workshops of 5 hours each. The workshops were held in the physics laboratory of the University of Udine (Italy) in the period March–April 2024.

The equipment used consists of common materials, a self-built insulated bar and a data acquisition system with the computer, which reads the temperature of 4 sensors in 4 minutes and shows the time evolution on the screen [25]. The tutorials used in the activity were constructed as stimulus cards, which, in accordance with our research mode [15], asked for prediction, reflection on the experiment, comparison of results with prediction and interpretation.

The rationale of the activities carried out for the research are presented in table I.

For each workshop we asked the students to make a prediction, to be able to analyze the conceptual perspectives in each prediction, we asked to conduct the experiment and to compare the results with the prediction. Table II shows the stimulus questions asked for this purpose.

The phenomenon of heating ratio or thermometric conduction in a wall was proposed by applying the Fourier equation, and students are asked to highlight the same and different aspects with respect to their prediction.

TABLE I. – *Description of the activities proposed in the three workshops.*

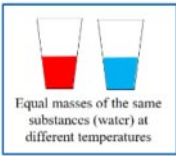
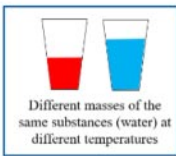
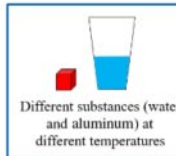
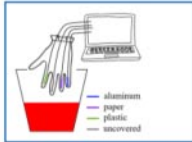
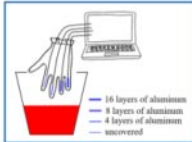
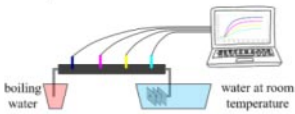
<b>1st workshop.</b> The role of temperature, mass and substance in reaching thermal equilibrium in interactions	<b>1st activity</b> Thermal interaction between equal masses of water at different temperature.   Equal masses of the same substances (water) at different temperatures	<b>2nd activity</b> Thermal interaction between different masses of water at different temperature.   Different masses of the same substances (water) at different temperatures	<b>3rd activity</b> Thermal interaction between different masses of different substances (water and a cube of aluminum) at different temperature.   Different substances (water and aluminum) at different temperatures
	<b>1st activity</b> Time evolution of the temperature of 4 sensors wrapped with different materials when moved from room temperature context to an environment at different temperatures.   — aluminum — paper — plastic — uncovered	<b>2nd activity</b> Time evolution of the temperature of 4 sensors wrapped with different masses of the same material when moved from a room temperature context to an environment at different temperatures.   — 16 layers of aluminum — 8 layers of aluminum — 4 layers of aluminum — uncovered	
	<b>1st activity</b> Time evolution of the temperature in 4 points of an aluminum bar when one end is subjected to a thermal step, while the other is kept at room temperature.   boiling water      water at room temperature	<b>2nd activity</b> Analysis of the conduction process explored in the busbar for a wall of a building: some cases of multi-layer of different material of a wall with initial and terminal walls at a fixed temperature are analyzed.	

TABLE II. – Questions posed to students for each proposed workshop.

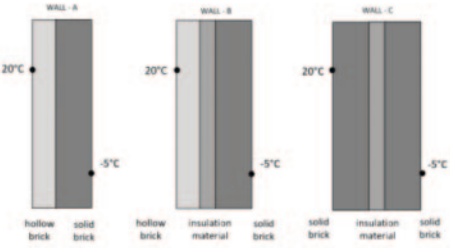
<p><b>1st workshop.</b> For the three experiences the students answered the following questions:</p>	
<p>Q1: Describe your prediction regarding the interaction of the two considered systems.                  Q2: Sketch the time evolution of temperature.                  Q3: Try writing a law that describes the phenomenon.</p>	<p>Q1: What kind of confirmations and differences emerge from the experiment compared to the predictions?                  Q2: Represent the temporal evolution of the temperature and describe confirmations and differences that emerge from the experiment compared to the predictions.                  Q3: Write a law that describes the phenomenon.</p>
<p><b>2nd workshop.</b> For the two experiences the students answered the following questions:</p>	
<p>Q1: Describe your expectations about the interaction between the four sensors and water at a higher temperature.                  Q2: Sketch the time evolution of temperature for the four sensors.</p>	<p>Q1: What kind of confirmations and differences emerge from the experiment compared to the predictions?                  Q2: Represent the temporal evolution of the temperature and describe confirmations and differences that emerge from the experiment compared to the predictions.</p>
<p><b>3rd workshop.</b> For the first experiences the students answered the following questions:</p>	
<p>Q1: Are you expecting that the temporal evolution of the temperature over time will be the same for the 4 sensors placed at different points of the barrier? (Explain.)                  Q2: Sketch the temperature change over time for the four sensors.                  Q3: Choose the graph that represents the temperature of the 4 sensors a few seconds after starting the experiment.</p>	
	<p>A: sensor on the bar closest to the boiling water                  D: sensor on the bar closest to the room temperature water</p>
<p>Q4: Choose the graph that represents the temperature of the 4 sensors after 20 minutes from the start of the experiment.</p>	
	<p>A: sensor on the bar closest to the boiling water                  D: sensor on the bar closest to the room temperature water</p>

## 5. – Results

In the first Workshop all the students predicted that a final equilibrium temperature is the outcome of the thermal interaction between the two systems of equal mass of

TABLE II. – *Continued.*

<p>Q5: The temperature measured by each sensor at different points along the bar:</p> <ul style="list-style-type: none"> <li>- will it continue to increase because it is heated continuously?</li> <li>- will it continue to increase because it is thermally insulated?</li> <li>- will it increase for a certain interval of time and then all the sensors will reach the same constant temperature value?</li> <li>- will it increase for a certain interval of time and then each sensor will reach a different but constant temperature?</li> </ul> <p>Q6: Sketch the time evolution of temperature for the four sensors; describe the representation and explain your prediction.</p> <p>After the experiment</p> <p>Q1: Describe the obtained graph highlighting what the similarities and differences are compared to your predictions.</p> <p>Q2: With reference to forecast questions Q3 and Q4, what can you say about the answers you gave previously?</p> <p>Q3: What did you learn from this experience that you did not know.</p>
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<p><b>3rd workshop.</b> For the second experiences the students answered the following questions:</p> <p>Q1: Sketch the temperature change in each layer of building material (solid brick, hollow brick, insulation material).</p>  <p>Q2: Sketch the temperature change in each layer of building material when the order of the layer materials is changed.</p> <p>Q3: Consider 3 walls composed of a homogeneous material of different thicknesses <math>s_1 &lt; s_2 &lt; s_3</math> and make considerations about the heating ratio (thermal flux) through the three layers F, G, H in 1 second.</p> <table border="1" data-bbox="308 1207 511 1276"> <tr> <td><input type="checkbox"/></td> <td><math>Q_F &gt; Q_G &gt; Q_H</math></td> </tr> <tr> <td><input type="checkbox"/></td> <td><math>Q_F = Q_G = Q_H</math></td> </tr> <tr> <td><input type="checkbox"/></td> <td><math>Q_F &lt; Q_G &lt; Q_H</math></td> </tr> </table> <p>Q4: Consider a wall composed of 3 different materials (a: solid brick; b: hollow brick, c: insulation material) and make considerations about the heating ration through the 3 layers of material in 1 second.</p>	<input type="checkbox"/>	$Q_F > Q_G > Q_H$	<input type="checkbox"/>	$Q_F = Q_G = Q_H$	<input type="checkbox"/>	$Q_F < Q_G < Q_H$
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water at different temperatures, but two main perspectives emerge to explain equilibrium temperature:

- one predicted it by simple or weighted average, having as a conceptual referent the time evolution of temperature (dark blue columns in fig. 1),
- the other took the heat exchanged as a conceptual reference (light blue in fig. 1).

When other variables (mass or substance) in addition to temperature are involved in a thermal interaction process, students no longer look for prediction at the evolution of temperature, which is the descriptive quantity of the process, and look at an entity (heat) whose balance needs to be taken, so the calorimetric view prevails over the thermodynamic one (fig. 1).

Answers after the experiments (fig. 2), show that students change the explanatory perspective and move from an interpretation related to the balance between heat possessed and heat given up toward a law describing the change in temperature.

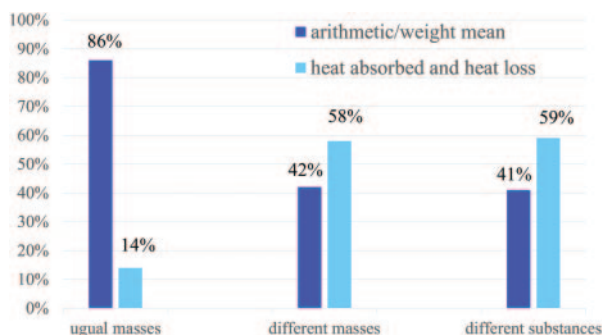


Fig. 1. – Conceptual referents for predictions in the three activities of the first workshop.

This highlights that experimental activity can play an important role in conceptual change when it concerns the interpretive and process aspects of a phenomenon. Temperature assumes a role of state property in interpretative terms: the ground is prepared for an interpretation in terms of the internal energy of the system. However, the presence of multiple variables influences the change of perspective in the interpretation of the phenomenon. In particular, the percentage of students who change their perspective by assigning temperature a key role in interpreting the phenomenon rises from 86% to 100% for the equal masses experiment (first two columns in fig. 2), rises from 42% to 81% for the different masses experiment (second two columns in fig. 2) and rises from 41% to 81% for the different substances experiment (third two columns in fig. 2).

The second set of experimental activities concerns the time evolution of each sensor which from room temperature is placed in a container at 40° C (of great mass, therefore almost a thermostat) when:

- each of the 4 sensors is wrapped in films of the same mass of different substances (aluminum, paper, plastic and an uncovered sensor);
- each of the 4 sensors is wrapped in multiple layers of aluminum foil.

Students predict that sensors wrapped with different materials heat up differently (fig. 3): only 1/3 of the students recognize that they reach a common equilibrium temperature (Group A), 21% imagine that the sensors reach different equilibrium temperatures (Group B), 20% do not recognize that an equilibrium temperature is reached (Group C),

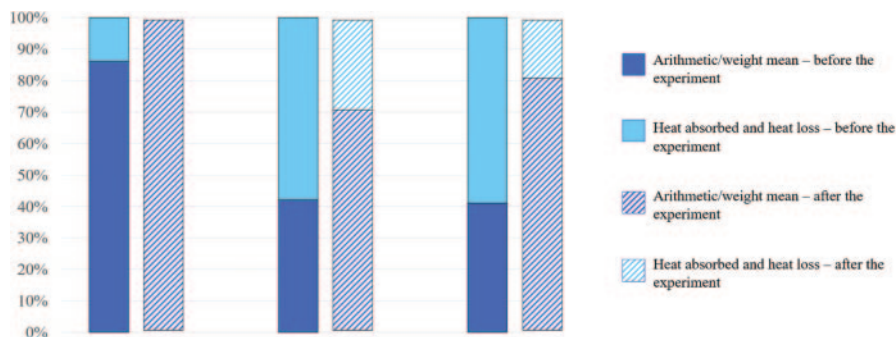


Fig. 2. – Answers in percentages to the 3 activities of the first workshop after the activities.

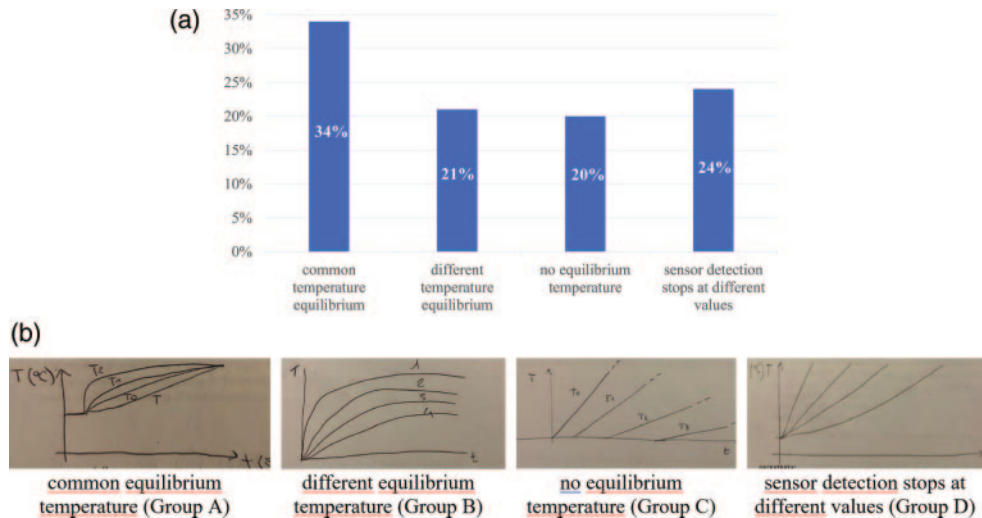


Fig. 3. – (a) Predictions (percentages) of temperature evolution for the activities of the second workshop. (b) Predictions of temperature evolution (drawing of students) for the activities of the second workshop.

and finally, 24% say that the different heating of each sensor seems to occur up to the same temperature without reaching a common equilibrium temperature (Group D).

The interaction between the two interacting systems, sensors at different positions along the bar and hot water, is focused on the expected plot of temperature over time. Group A has as its conceptual reference the equilibrium temperatures of the initial and final states, identifying the different substances or masses as responsible for the rate of temperature increase. This view has temperature as the reference quantity for the process. Group B believes that the equilibrium temperature is reached, but determined by the material (or mass) as if what characterizes each process is a different amount of heat absorbed by each system. Group C describes only a different rate of temperature rise in a fixed time, as if it considered only a first part of the process described by Group A. Group D predicts the different rate of temperature rise in reaching the same temperature, which is not recognized as a final state of equilibrium. Answers after experiments show (fig. 4) that Group A increases from 34% to 85% for the case of sensors coated with different material and the same 85% responds to the answers in the case of sensors coated with different thicknesses of the same material. A percentage of 54% of the students did not predict a common equilibrium temperature in the previous activity and have now changed their prediction.

The third workshop concerns thermometric conduction in an aluminum bar insulated laterally and subjected to a thermal step: the bar, initially at room temperature, is

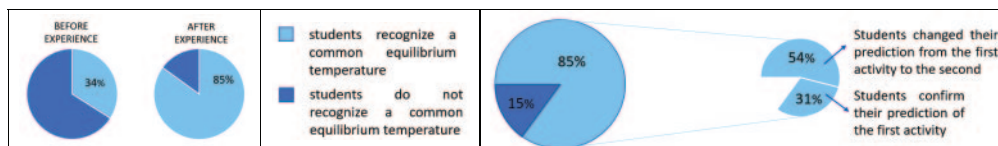


Fig. 4. – Answers in percentages to the 2 activities of the second workshop.

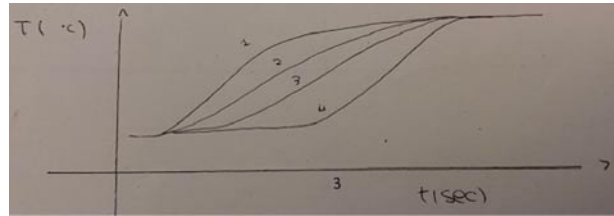


Fig. 5. – Temperature change over time drawn by a student.

placed with one end at boiling water temperature, while the other is kept at room temperature. The process is very different from the previous ones because it is a heating flow involving different spatial regions in which equilibrium is reached due to the spatial position considered.

More than 59% of the students imagine that the 4 sensors reach a common equilibrium temperature (fig. 5) as in the previous case of Group A: they show a difficulty in the distinction between a process that brings the whole system to the same state of thermal equilibrium and a dynamic equilibrium process of heating flux in which the position is decisive for the equilibrium temperature reached.

These results are partly contradictory to the answers to the following question: when students were asked to make a prediction about the temperature of the 4 sensors along the bar, 63% of students chose the two graphs in fig. 6.

The first of these highlights the awareness of a temperature gradient in the busbar, which is considered to evolve towards a constant temperature instead of a linear gradient.

The underlying interpretative difficulty that translates into not associating the temporal evolution of temperature with the spatial one in a process of continuous heating at one extreme with respect to the other has emerged even more evidently in the case of the wall of a building.

The fact that in a dynamic process the sensors do not exhibit a linear gradient is again confirmed by a significant percentage of students (55%). An example can be seen in fig. 7.

More than half of the students (64%) imagine a constant temperature trend within the insulating material layer, thinking that the insulating material is different from other materials because it does not change its temperature when involved in a dynamic process of heat exchange. It can be seen an example in fig. 8.

**6. – Concluding remarks**

The interpretation of thermal phenomena requires a clear awareness of state quantities and their role in process description. The concept of thermal equilibrium and the

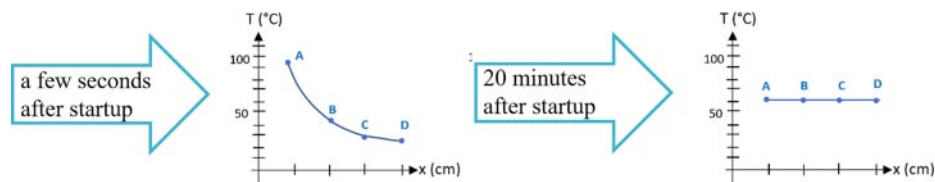


Fig. 6. – Prediction about the temperature of the four sensors along the bar.

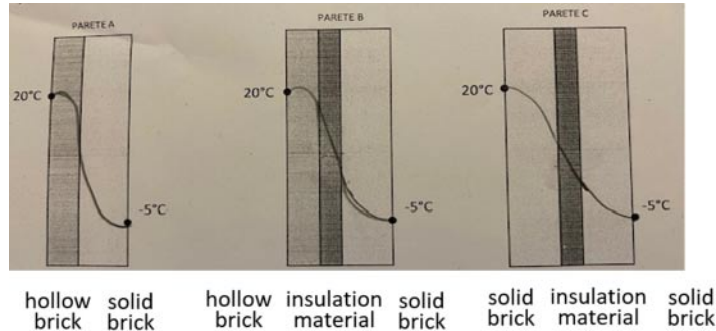


Fig. 7. – Temperature change over position inside a wall drawn by a student.

evolution of interacting systems towards a common state of equilibrium is compromised by an interpretation based on heat as an entity exchanged (and perhaps also thought of as possessed) according to a calorimetric approach.

The analysis of the time evolution of temperature by measuring it during the process with RTL systems results in overcoming this conceptual knot in the assumption of temperature as a state property throughout the process. This seems to help about a third of students (34%) predict the different rate of temperature increase towards equilibrium when other variables such as mass and type of substance are involved. The focus on the temporal evolution of temperature in the examination of the process seems to distract 40% of students from the interpretative task. It seems that in this case a more incisive interpretative request could be enough. However, the calorimetric interpretation seems to continue to influence the predictions of 20% of students for thermal equilibrium even when they are based on the plot of the temporal evolution of temperature in these phenomena. This implies an even more binding attention to temperature as a state property.

Even more important seems to be this interpretative role of temperature as a state quantity in thermometric conduction processes, as in the case of the bar subjected to a thermal step or a multilayer wall. The recognition of a state of local thermal equilibrium and therefore of a final spatial gradient of temperature and its transient seem to be a prerequisite for the interpretation of the process. The latter, often analyzed in terms of heat flux, implies assumptions about the constancy of the flow in each spatial stretch of the system and leaves the idea of heat as an entity that exists and flows, rather than as a process of change of the internal energy of a system and has a correct thermodynamic

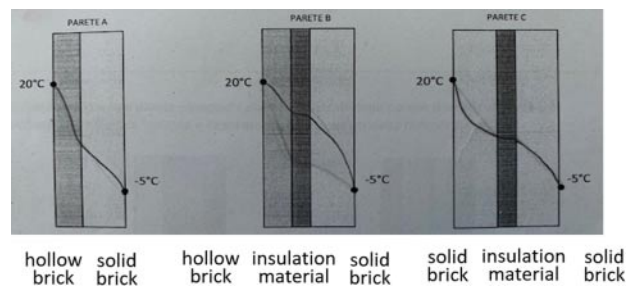


Fig. 8. – Temperature change over position inside a wall drawn by a student.

interpretation in terms of internal energy exchanged between first neighbors. The results of this work not only confirmed the important role of acquiring awareness of temperature as a state property and its interpretative contribution in the processes of thermal interaction that evolve towards equilibrium but they have also given us evidence of the problems that a calorimetric approach creates. They pointed out to us the important conceptual work to be done for the interpretation of thermometric conduction processes. This will in fact be the goal of a future study.

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