Teaching about heat and temperature

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Students encountering thermal physics at introductory level often have difficulty distinguishing between heat and temperature. It has been found with teacher education students at Canterbury Christ Church University College that challenging misconceptions by experiment and through discussion can quickly enable them to acquire the necessary concepts to equip them to develop their understanding of thermal physics. The key concepts are those of thermal equilibrium, the notion of flow of heat energy and the ability to differentiate between heat and temperature. This paper outlines a possible combination of activities to illustrate how this may be accomplished.

Thermal physics is a branch of physics that most people will recognize. For many, it is one with which they are familiar in the sense that they have experience of the subject gained from an early age. This experience will perhaps begin when a newborn infant feels the cold of the outside world in comparison to the warmth of the uterus. The same familiarity is not true for all branches of physics, even though they affect our daily lives in a fundamental way.

This familiarity with thermal physics is at the same time an advantage and a disadvantage to the physics educator. The constructivist perspective on education [1] explains how it is necessary to reflect upon the knowledge that the students have on arrival at the class and to build upon this to develop a scientific understanding of the concept. In the case of thermal physics there is a lot of past experience upon which to build. The difficulty, however, is that along with useful experiential knowledge the students also bring along with them a great deal of misconception which must be addressed.

Studies with very young children who have received no formal teaching about thermal physics show that they have learned, by experience, that certain things feel warm to the touch and others feel cold. Albert [2] found that for four and five year-olds the notion of heat as a substance that could be found in objects was prevalent. Thus the link is made between heat and the material from which an object is made. Later at age eight it was found that the notion of heat as something more dynamic that flows becomes popular. At a later stage of development the prevailing idea is one in which heat is treated as though it were a fluid that flows between bodies [3, 4]. This idea is consistent with the old Caloric theory of heat which pre-dated Rumford's work. Despite the fact that these studies dealt with younger children, Clough and Driver [5] found that such concepts are held by children at least up to age 16. It would appear that ideas about thermal physics are built up by experience through childhood and remain until challenged by situations that they fail to explain. It is the role of the teacher to discover the ideas held by the students and to present them with concrete examples that bring about this restructuring of the world view on the concepts of thermal physics. Clough and Driver [5, p 182] point out that this should be done by giving the students the 'opportunities to explore ideas in a non-threatening atmosphere'. They also warn of the danger of misinterpreting the ability of students to respond to questions about thermal physics by repeating formal definitions or patterns

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of speech. This behaviour does not necessarily mean that they have achieved a full grasp of the difficult underlying concepts.

Thomaz *et al* [6] suggest that there are five common misconceptions held about heat. These are that heat is a kind of substance, the inability to differentiate between heat and temperature, a confusion between temperature and the 'feel' of an object, that the application of heat to a body always results in a rise in temperature and a misunderstanding of the temperature of a phase transition. The last two of these misconceptions are supported by the findings of Nachimias *et al* [7], who found that 80% of the students in their study were unaware of the fact that the temperature of water remains constant whilst it is being boiled.

One of the major difficulties with temperature is that it cannot be measured directly. As McIldowie [8] explains, students have little trouble understanding how to measure length because the process is a simple one. An object that has graduations on it is compared directly with the length to be measured. Even measuring time is similar in this respect in that a direct comparison is made between the time taken for the hand of a stopwatch to rotate through a certain angle and the time between two events. Temperature is different. A thermometer relies on the variation of a thermometric property. It is this variation that is monitored and not the temperature directly. Temperature is therefore perceived as something internal.

As far as 'heat' is concerned, there is even some difference of opinion about the meaning of the term amongst some science teachers. Mak and Young [9, p 466] discuss the idea and define heat as 'the macroscopic energy transfer by nonmechanical and nonelectrical means and [it] is equal to the difference between the internal energy and the work done.' Referring to the equation of the first law of thermodynamics, the energy transfer described as heat supplied, ΔQ, is defined as

$$\Delta Q = \Delta U - \Delta W$$

where ΔU is the change in internal energy and ΔW is the work done on the working system. The heat should be distinguished from the change in internal energy ΔU. Many students are unaware of the difference, particularly in the early stages of their study of thermal physics because, to simplify matters, it is often the case that the work done on the system, ΔW, is considered to be zero. However, with regard to students at an introductory level definitions such as this are too advanced. Therefore, in agreement with Mak and Young [9, p 468], in this paper the term 'heat flow' will be taken to mean 'the process by which energy transfers occur as a result of a temperature difference' and heat means 'the energy transferred in the process'.

In order to enable the students to progress in studies of thermal physics it is considered essential that they have mastered two fundamental concepts. They must have a concept of thermal equilibrium and they must have a concept of the difference between heat and temperature [10].

Assessment of starting position

Before any tuition on the subject of thermal physics takes place it is important to establish what the students' past experience and learning has led them to think about the subjects of heat and temperature. In my class this is attempted by dividing the class into groups and then getting each group to negotiate and agree a definition of each of the terms 'Heat' and 'Temperature'. These definitions are then written down, put on display and discussed during a plenary session. At this stage the students are provided with encouragement but no intervention. After a number of definitions have been presented the students are asked to decide if they think heat and temperature are the same thing. When answers to this have been decided upon the students are asked to name the units of measurement for each quantity.

Invariably answers to the first question contain phrases such as 'Heat is the energy of a hot substance' and 'Temperature is a measure of the heat'. Many describe temperature as a measure of how hot or cold something feels. There is a general consensus that the two are not identical. One student expressed the opinion that there would not be two words in use if they meant the same thing. However, the definitions of the two terms do not usually lead to the identification of a clear difference. Most often the word 'energy' is associated with heat and the term 'measure' is associated with temperature. Most students are able to provide the correct units for heat and temperature, and when it is pointed out that these do not agree, they are usually convinced that there must be a difference between heat and temperature.

Development

Most commonly the idea that temperature is a measure of the ‘hotness’ or ‘coldness’ is put forward, and when pressed the students refer to a high temperature object feeling hot and a low temperature one feeling cold. One of my favourite ways of encouraging the students to consider this more carefully is to provide them with three bowls containing water at 0 °C (a mixture of ice and water), 42 °C and 55 °C or as hot as the students can comfortably bear. They are asked to place one hand in each of the extreme temperatures and use words like ‘hot’ and ‘cold’ to describe them. After a minute or so they are asked to place the cold hand in the middle bowl and describe the temperature. This is normally described as being warm. Next the hot hand is placed in the middle bowl and this time the temperature is described as being cool. The conflict convinces the students that ‘feel’ is not a good way of explaining temperature.

The next step is possibly the most difficult one. The students are able to predict that if left in the room for long enough the ice will melt and the water in the cold bowl will warm up. This is everyday experience. Similarly they are able to predict that the water in the hot bowl will cool down. Discussion of what is happening here usually leads to questions such as ‘How does the hot bowl cool down?’ and ‘When does it stop cooling down?’ The answers to these questions lead to the notion that heat energy will travel from a hot body to a cooler body. At this stage use is made of the students’ idea that heat may behave as though it were a fluid and is able to flow from one body to another. (It is useful here to refer to the earlier discussion where heat and energy were tied together.) Also important is the recognition that this will stop when the hot body cools down sufficiently that it is no longer hotter than its surroundings. Buried here, of course, are the zeroth and second laws of thermodynamics. Guided discussion usually leads the students to be able to claim that two bodies are at the same temperature when there is no spontaneous net flow of heat energy between them. They are usually also persuaded that when not in equilibrium the body at the higher temperature will be transferring heat energy to the one at the lower temperature. Thus meaning is supplied to the expression that one body is hotter than another.

Most often students are able to recognize that if two bodies are left in a room at a constant temperature for long enough they will eventually reach the same temperature as each other and the room. To put this to the test the students are asked if a large lump of iron, such as a 1 kg mass, and a block of expanded polystyrene which have been left in the room overnight are at the same temperature. They must agree to this if they have agreed to the statement at the start of this paragraph. However, when they are asked to feel each object they notice that the iron feels cold but that the polystyrene feels warm. To help resolve the conflict between feel and intellectual conviction a discussion about how the two may be reconciled is started. When asked if the hand is at the same temperature as the iron and polystyrene most students are able to realize that it is not and that something feels cold if there is a discernible flow of heat energy from the hand to the body, and that in the case of the iron the outflow of heat energy is noticeably more rapid than when the hand is surrounded by the air of the room and that the polystyrene impedes the flow so that it feels warmer than the room.

So far the students have been asked to recognize that when placed in thermal contact two bodies will eventually reach thermal equilibrium, and that this means that they are at the same temperature. Furthermore they should recognize that body A is defined as being at a higher temperature than body B if there is a spontaneous net flow of heat energy from A to B when they are placed in thermal contact. No mention has been made of thermometers or scales of temperature.

To begin to address the concept of heat the students are asked to consider a thought experiment. They are asked to say whether they think that pouring the contents of a kettle full of boiling water into the sea in winter will raise the temperature to the summer level. Naturally they deny that it will. They are then asked which is at the higher temperature, the kettle of water or the sea in the summer. They should use the heat energy flow criterion above to establish that the kettle is at the higher temperature, although to date no student has argued otherwise. The next question is asked to establish which contains more heat energy, the kettle or the sea during the summer. The fact that the heat energy content of the kettle was unable to raise the sea temperature from its winter level to its summer one shows that there is more heat energy in the sea, and that combining these two answers proves that heat and temperature are not the same thing.

This discussion leads the students to the idea that temperature is a measure of the concentration of heat energy. Indeed calorimetry experiments using only the specific heat equation

$$\Delta Q = ms\Delta T$$

where ΔQ is the heat energy supplied, m is the mass of the object, s is its specific heat capacity and ΔT is the change in temperature neatly encapsulate the idea of the concentration of heat energy, taking into account the nature of the material under investigation. The proportionality between the quantity of heat energy supplied and the change in temperature reassures the students and explains why there was initial difficulty in separating the meanings of the two.

Before they become too comfortable the students are asked whether it is true that, in the absence of a working device such as a refrigerator, in all cases if a body at a higher temperature is placed in thermal contact with one at a lower temperature there will be a net flow of heat energy from higher to lower. To progress further they must be convinced that this is always true.

They are then presented with a beaker of ice and water mixture. This is placed in the room, which may be at 21 °C or so. They are asked if the ice is taking in heat energy from the room. If they agreed to the statement in the previous paragraph then they must agree that this is so. They are then asked to record the temperature of the ice mixture over time. The temperature, of course, remains at 0 °C until the ice has all melted and only then does it creep up towards room temperature.

Many students are unwilling, at first, to accept that solid ice and melting ice and liquid water can all exist at the same temperature. They instinctively feel that the ice must be colder than the water. They find it difficult to agree that the temperature at which water freezes and the temperature at which ice melts are the same. This is because the direction of flow of heat energy in each case is different. To extract heat energy from the water there must be a lower temperature reservoir to which the heat energy can flow. Similarly to provide heat energy to melt the ice there must be a higher temperature heat reservoir from which heat energy can be extracted. The point they need to appreciate is that it is possible to have a mixture of water and ice where the water is not freezing and the ice is not melting because there is no heat energy flow into or out of the system and the two are in thermal equilibrium, which means that they are at the same temperature. Nevertheless some students remain unconvinced until they have dealt with the idea of latent heat discussed next.

The conclusion to be drawn from this experiment is that supplying heat energy to a body may have the effect of raising its temperature but not necessarily. It may, as in this case, bring about a change in phase without a change in temperature. In order to explain this phenomenon it is necessary to discuss what is happening on a microscopic scale. Here the students are introduced to the idea of internal energy of the system and to the fact that this may take the form of changes to the potential as well as kinetic energy of the molecules. From this discussion the students are led to the idea that only the kinetic energy of the molecules is associated with temperature. Combining this notion with energy density leads to the definition of temperature as a measure of the average kinetic energy of the molecules of a system.

Heat then is the total energy supplied to the system and temperature is identified with the average kinetic energy of the molecules. The potential energy supplied is not manifested as a change in temperature and is therefore termed ‘latent heat’.

At this stage it is not thought prudent to introduce the students to work done on the system but to stick with sorting out the problems associated with heat and temperature. This can leave the students with the idea that internal energy and heat are the same but it is felt that this problem can be dealt with later.

Conclusion

It has been found that following this experience the majority of students are able scientifically to discuss the meaning of thermal equilibrium, heat and temperature. It is dangerous to assume that, because a student is able to recite textbook definitions, they have come to terms with the fundamental underlying principles behind thermal physics. Only by responding to challenging questions and interpreting experimental evidence correctly can this be achieved. In this way the students' pre-course experience can be built upon to enable them to deal with heat and temperature in a way acceptable in a scientific context.

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References

[1] Driver R 1981 Alternative frameworks in science *Eur. J. Sci. Educ.* **3** 93–101
[2] Albert E 1978 Development of the concept of heat in children *Sci. Educ.* **62** 389–99
[3] Erickson G L 1979 Children's conceptions of heat and temperature *Sci. Educ.* **63** 221–30
[4] Tiberghien A 1980 Modes and conditions of learning. An example: the learning of some aspects of the concept of heat *Cognitive Development Research in Science and Mathematics* ed W F Archenhold *et al* (University of Leeds) pp 288–309
[5] Clough E E and Driver R 1985 Secondary students' conceptions of the conduction of heat: bringing together scientific and personal views *Phys. Educ.* **20** 175–82
[6] Thomaz M F, Malaquias I M, Valente M C and Antunes M J 1995 An attempt to overcome alternative conceptions related to heat and temperature *Phys. Educ.* **30** 19–26
[7] Nachimias R, Stavy R and Avrams R 1990 A microcomputer-based diagnostic system for identifying students' conceptions of heat and temperature *Int. J. Sci. Educ.* **12** 123–32
[8] McIldowie E 1998 Introducing temperature scales *Phys. Educ.* **33** 368–72
[9] Mak S and Young K 1987 Misconceptions in the teaching of heat *Sch. Sci. Rev.* **68** (244) 464–70
[10] Wiser M 1988 The differentiation of heat and temperature: An evaluation of the effect of microcomputer teaching on students' misconceptions *Technical Report ED291596* Educational Technology Center, Cambridge, MA