Finding the optimum level of simplification: the case of teaching about heat and temperature

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Physics presents many conceptual difficulties for learners, and the teacher has to balance the desire to teach good science with the need to pitch material at a level such that pupils can cope. There will always be a compromise between the depth and range of material we would wish to cover, and what pupils are likely to be able to successfully understand in the time available. Part of a teacher's job, therefore, is to re-interpret curriculum content for pupils. Decisions have to be made about the level of detail and complication that is appropriate to be true to both the subject and the learners. It is argued here that, whilst simplification is necessary, a point will be reached where the logical structure of the subject is compromised. It is suggested that recent recommendations in *Physics Education* about teaching heat and temperature may have reached such a point.

One aspect of teaching any topic, especially at an introductory level, is finding the most appropriate level of simplification of the subject matter. *Physics Education* has recently published Kevin Carlton's discussion of how to teach introductory thermal physics (Carlton 2000). Carlton recognizes the conceptual difficulties faced by many pupils when they are introduced to ideas about 'heat' in physics, and he provides an analysis of which ideas are essential and should be taught at this level—and of which aspects provide too much complication and should be deferred until later, rather than risk confusing pupils. I believe that Carlton's standpoint is valid, and that his general approach is sound. However, I also believe that Carlton's recommendations have a major fault, and that following his approach may confuse pupils.

It is suggested in this paper that the balance between providing an account of the physics that is simple enough to be understood by pupils, and yet 'near enough' to be a good first approximation, is not met in Carlton's paper. In particular his approach is not logically consistent. As there is so much of value in Carlton's discussion and, since judging just where to pitch class presentations is a key issue (and is always going to be open to debate), a consideration of his recommendations provides a useful case study in finding the appropriate level of simplification.

Children's science, curriculum science, teacher's science. . .

It is now well accepted that children bring to lessons a wide range of alternative ideas about

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scientific topics which are at odds with the accepted scientific view (Driver and Erickson 1983, Gilbert and Watts 1983). Indeed, such alternative conceptions have been identified across the entire science curriculum (Driver *et al* 1994). One important aspect of the teacher's craft is to elicit such ideas from pupils, and to use a knowledge of such ideas to inform teaching. The teacher has the task of persuading pupils why the scientific viewpoint is more fruitful than their alternative conceptions. This, however, is a simplistic description of what is a very complex process.

Before the research into the 'preconceptions' and 'intuitive ideas' that pupils bring to class was widely disseminated, it was found that many teachers operated with a crude model of teaching as *transferring knowledge into the empty vessels of pupils' minds* (Fox 1983). There is a danger of substituting this clearly inadequate image with another: i.e. that the teacher's role is to *replace pupils' naive ideas with a correct scientific understanding*. In practice 'correct science' is that fluid body of knowledge represented by the currently accepted scientific literature, and no school pupil is expected to attain this level of understanding. Indeed, few physicists will understand their subject at this level (except perhaps in a very narrow field where they are part of the group that defines what is 'currently accepted'). Certainly the knowledge of the school teacher will not match this frontier level of knowledge and understanding, and the school curriculum will present a further simplification of the science as the version to which pupils should work.

Gilbert and co-workers (1982) pointed out that the teacher's attempts to interpret curriculum science (through the lens of her own 'teacher's science') to pupils already holding a range of children's science was likely to result in a variety of outcomes, ranging from no change in the pupils' original ideas, to completely operating with the new ideas, but with most pupils undergoing some intermediate level of change by developing hybrid concepts or operating with a mixture of new and established thinking.

From this perspective, part of the skill of the science teacher is to judge the appropriate *level of simplification*, the *order* in which to present ideas, and the *pace* at which to deliver the 'chunks' of science in order to help pupils construct as scientifically valid a model of a topic as possible. Clearly this is a highly complicated task, which will only be effectively undertaken if the teacher herself can integrate three different types of knowledge: (*a*) of the science content of the curriculum, (*b*) of how pupils learn and (*c*) of the children's science currently in place. The last will clearly be different for each class.

What leads us to change our minds?

Driver (1983) long ago pointed out that as pupils interpret experiments from the perspective of their present understanding, our classroom practicals are often ineffective at demonstrating the principles they are meant to exemplify. In this, pupils reflect practising scientists (Collins and Pinch 1993), who are able to construe most results as either supporting their position or being based on flawed procedure! Much has been written about why pupils tend to hold on to (or, at least, later return to) their alternative thinking despite the efforts of teachers. Although it is recognized that accepting a new way of thinking is a complex (and slow) process, it is thought that this may be largely understood in logical terms: when the pupil finds that the new ideas 'make more sense' than the alternative ones, she is likely to increasingly use the new ideas (Taber 2000b).

The types of criteria which are believed to enter into this process of shifting between using different conceptual frameworks include the range of phenomena (or problems) to which the ideas seem to apply, and how well the ideas fit with other areas of knowledge. As it takes time to explore and appreciate the worth of new ideas, conceptual change is often a slow process. It is also, usually, a largely subconscious process. Ideas are also judged in terms of what we might call the pupils' epistemological commitments. Children, just like scientists, may 'expect' correct theories to have certain characteristics. Again, these expectations may be tacit, so the pupils are not always aware of the criteria they use when judging scientific ideas. One such epistemological commitment is to expect ideas to be logically consistent, and most physicists would probably feel this is one criterion we should encourage our pupils to use.

Carlton's recommendations for teaching introductory thermal physics

Having established some background, I now turn to consider Kevin Carlton's suggestions for how to teach introductory thermal physics. Although I will argue that his specific recommendations are seriously flawed, I believe that Carlton has made a valuable contribution to the debate.

Carlton's paper:

- acknowledges the difficult nature of the concepts involved for most learners;
- points out that pupils are likely to come to lessons with their own alternative ideas in place;
- stresses the importance of making learners' existing ideas explicit, and using them as a starting point for constructing scientific understanding;
- attempts to tease out a level of presentation that is both simple enough for pupils to understand and adopt, and yet is scientifically valid.

Such an approach is needed to help pupils develop their scientific understanding, rather than just learn the subject by rote in a meaningless way.

Carlton has analysed the subject matter of thermal physics and reflected on his experience of (*a*) learners' likely alternative conceptions, and (*b*) how much progress is feasible in an introductory course. He suggests which aspects of the topic should be emphasized, and which aspects are more sensibly deferred. In this way, recommendations are made about the *optimum level of simplification.*

In particular Carlton identifies 'two fundamental concepts', which he seeks to teach through a range of discussion, demonstrations and thought experiments:

> They must have a concept of thermal equilibrium and they must have a concept of the *difference between heat and temperature.*
> (p 102, emphasis added.)

There is little here to disagree with, and indeed the National Curriculum for state schools in England requires that at the lower secondary level, i.e. ages 11–14, 'Pupils should be taught ... the distinction between temperature and heat, and that differences in temperature can lead to transfer of energy' (DfEE/QCA 1999, p 36). As might be expected, it is when Carlton suggests *how* to simplify the physics concerned that his ideas become more contentious. In particular, his choice of definition of heat is problematic:

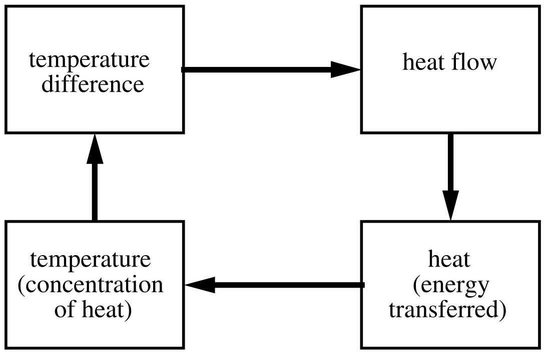

Figure 1. A scheme for heat and temperature, based on Carlton (2000).

> 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'.
> (p 102, emphasis added.)

Using this definition, Carlton leads his students to the idea that 'temperature is a measure of the concentration of heat energy' (p 104). These connotations, in turn, lead to the relationships between concepts shown in the scheme in figure 1.

This scheme suggests that a difference in temperature leads to heat flow, which causes a change in the 'heat' energy in a body, which in turn changes its temperature ('concentration of heat energy'). Carlton accepts that his approach has limitations, but believes these are acceptable:

> 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.
> (p 104, emphasis added)

This scheme does not call upon ideas of internal energy, and does not require the learner to switch between macroscopic phenomena (heat, temperature) and molecular models (kinetic energy of molecules) to explain how heat and temperature are related. This keeps the analysis simple, which is important at an introductory level. But this level of simplification is achieved at the cost of clarity and consistency in the ideas used.

For a body that has been warmed from absolute zero, without changing state, its final temperature might reasonably be said to reflect the concentration of the 'energy transferred' *to it* 'as a result of a temperature difference' (i.e. 'the concentration of heat energy' in Carlton's terms). However, the definition does not apply to any body that does not start at zero Kelvin (which, in practice, means it never applies!)

This, although not desirable, is perhaps allowable, as many of our definitions refer to ideal or theoretical conditions. However, there is a clear inconsistency if a change of state has occurred. If a sample of ice, at absolute zero, is placed in a laboratory at room temperature, the temperature of the ice will increase as heating occurs. At 273 K the ice temperature could be seen to reflect the concentration of energy transferred to it. Yet as it melts (due to the continued heat flow, i.e. 'energy transfer ... as a result of a temperature difference') the concentration of 'the energy transferred in the process' *increases without a change in temperature*. If temperature *was* 'a measure of the concentration of heat energy', then the temperature should increase during melting—but of course this is not what happens. The system of definitions is logically inconsistent, and thus inadequate and potentially confusing. Worse, application of these definitions would reinforce the common alternative conception that temperature always increases when heating takes place (and so, pupils argue, water must always be hotter than ice, and steam must always be hotter than water).

An analysis of the relationship between heat and temperature

An analysis of the basic ideas involved in explaining the relationship between heat and temperature is represented in the alternative scheme shown as figure 2, which is taken from teaching materials used at Homerton College (Taber 1999). This figure is based upon a definition that heat is energy in the process of being transferred due to a difference of temperature (Pitt 1977, Slesser 1988). Like Carlton's analysis, this ignores the complications due to considering work done as volume changes.

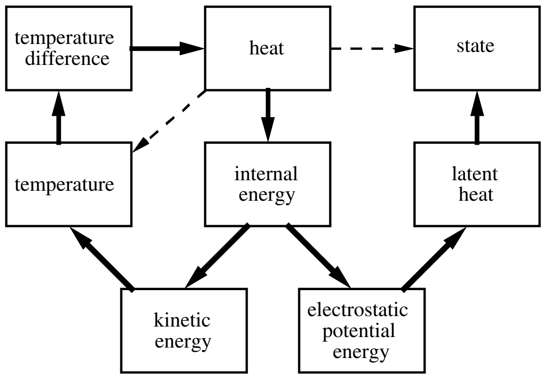

Figure 2. The scheme used to relate heat and temperature at Homerton.

Heat flows due to a temperature difference, and this can lead to a change in temperature (i.e. negative feedback), or a change in state. This is explained in terms of a molecular model, where the heat flow increases the internal energy of the particles. This internal energy can be kinetic and potential, and temperature is a measure of the average *kinetic* energy of the particles. I would suggest that this is a consistent, albeit incomplete, scheme.

This is the level of analysis used in initial teacher training with postgraduate students at Homerton College. The scheme may be considered as a concept map, with each arrow representing a relationship between the concepts in the boxes it connects (Taber 1994). Trainee teachers should be able to explain each of these relationships. Carlton makes much the same analysis in his paper, but then uses definitions that are not consistent with this scheme.

Discussion: what degree of simplification is useful?

The issue at stake here is not whether it is acceptable, or appropriate, to simplify physics content when planning teaching. This is an essential part of the teacher's craft. However, just as there are levels of physics presentation that pupils will not understand, *there are episodes of understandable teaching that are no longer physics*. The educational psychologist Jerome Bruner is supposed to have claimed that it was possible to make any topic sensible to any child in an intellectually valid way. It is tempting to see the challenge as finding an approach simple enough to be understood—but this is only half the task.

This is important because I would argue that it is often better not to teach a topic at all, than to teach in a way that will have to be 'untaught' later. Research evidence shows that while the learning of scientific ideas is a slow process, the 'unlearning' of invalid ideas can be even more drawn out. Indeed such ideas may fall into disuse, but the memory trace probably never completely fades (Taber 1995a, 2000a). It is usually assumed that the prior conceptions pupils bring to science classes derive from their early experiences of their physical environment. Yet evidence from chemistry education suggests that significant alternative conceptions can also derive from earlier teaching—where ideas presented are imprecise or logically incomplete (Taber 1998).

From this perspective a key distinction the teacher has to make is between those simplifications that ignore complications whilst conveying the essence of the physics, and those that distort the true nature of the ideas to be learnt. With Carlton, I would agree that it is sensible to teach about heat and temperature without introducing the *complication* of work done by changes in volume. This can be learnt about later as an additional factor that does not *fundamentally* change the concepts of heat and temperature. However, I do *not* accept Carlton's approach to defining heat as the energy that has been transferred, and temperature as a measure of the concentration of heat energy. Although this leads to a simpler scheme, it also leads to logical inconsistency, and the potential for much confusion later.

It is well known that children tend to have their own alternative frameworks for understanding aspects of energy (Watts 1983, Brook 1986), and this is not helped by the unfortunate way that teachers and textbooks use a wide range of different terms for the forms that energy takes (Taber 1989). Although defining heat as *energy in the process of being transferred due to a difference in temperature* is rather wordy, the teacher does not have to teach the definition by rote (Taber 1995b) as long as she is consistent in using 'heat' for this, and only this, concept. Other concepts that are distinct from this must be given different labels so that pupils have a chance to appreciate and learn these distinctions. This means either using terms such as internal energy and enthalpy, or not undertaking any teaching that needs such concepts.

Similarly, temperature should either be seen in qualitative, subjective, terms as a measure of how hot something is, or it should be linked to the average kinetic energy of the molecules present (as in the Homerton scheme in figure 2). Although it may be tempting to keep things simple by relating temperature to heat content (such as in figure 1), this will ultimately be an impediment to understanding the physics.

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