Children's Ideas in Science

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CHAPTER 4

Heat and Temperature

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Introduction: The scientific point of view

Why is it that pupils seem to have so much difficulty in grasping some aspects of the scientific conception of heat and temperature? That this topic area has attracted attention from researchers recently is not surprising. The ideas are given prominence in science courses in many countries and are encountered, in some way, at virtually all age levels, yet there are many aspects of heat and temperature phenomena which are counter-intuitive, or at least troublesome, for many pupils. For example, school children are often puzzled that a thermometer will record a similar reading for all objects in a room even though a metal saucepan feels much colder than a plastic mixing bowl. Or they are surprised that an ice cube wrapped in wool or shredded newspaper will 'last longer' than one placed in metal foil.

Many children appear to have constructed various simple explanations to account for everyday situations they encounter involving heat and temperature. These explanations may subsequently become an integral part of the child's explanatory framework when she or he is faced with similar sorts of problems in a school setting.

Before discussing the findings of the research on pupils' beliefs, it is important to recognize some of the confusion which seems to surround their use of the term 'heat', confusion which probably stems in part from everyday usage of the term. The word 'heat' and its literal and metaphorical derivatives are commonly used as nouns, verbs, adjectives and adverbs. It is the use as a noun, which creates most of the conceptual confusion from a scientific and more specifically from an energy point of view. For example, we frequently hear expressions such as 'close the window and keep the heat in' (or conversely 'keep the cold out'). In classrooms we may hear pupils saying that 'heat is gained or lost' by an object when it comes into thermal equilibrium with some other substance, or that heat 'travels along a metal rod' when the metal rod is heated by a flame at one end.

These expressions illustrate a tendency to imply that 'heat' is substantive in nature. In the examples above 'heat' is described in terms of its ability to make objects hotter; to be stored in objects and transferred from one object to another; and to travel from one location in an object to another.

Why does it seem so natural to describe heat as a type of material substance which can cause predictable changes in other objects? (e.g. increase in temperature or an increase in volume). Some people think it may be a linguistic remnant from the Caloric theory of heat from the eighteenth and nineteenth centuries (when heat was conceptualized as a subtle, weightless fluid capable of penetrating all material bodies*). We know, however, that the notion of heat was more closely defined in the Caloric theory than in its present everyday meaning.[1] Others argue that there is a natural tendency to describe our common sense world in metaphorical terms wherein cause and effect relationships are seen in terms of interactions between types of matter.†[2] Regardless of the origin of this usage, it seems apparent that the predisposition to think of heat as in some sense substantial may be one of the important conceptual barriers that students must overcome if they are to be initiated into the current scientific way of thinking.

At this point, it is useful to review briefly the concepts of temperature, energy and heat from a scientific point of view, before describing studies of children's thinking about these ideas.

Temperature is one of the parameters that describes the state of a system. Knowledge of temperatures (along with other parameters) is essential information for predicting the changes which will occur in one system when it interacts with another system. Consider a saucepan full of water as an example. The question can be asked: 'if the saucepan is heated on a stove what will happen to the water?'. It is impossible to answer the question if the temperature of the water is not known. If the water is at 100° C, then the water will pass from the liquid state to the gaseous state. If the water is between 0° and 100° C, then the temperature of the water will begin to increase.

Temperature is a macroscopic property which expresses the state of agitation or disordered motion of particles; it is therefore related to the kinetic energy of these particles.

The *energy* of a system corresponding to a state of particle agitation is referred to as a form of *internal energy* of that system—sometimes called *thermal energy*.

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*For a good description of the caloric theory see Conant[3] and Fox.[4].

†Lakoff and Johnson[5] have argued that one of the most powerful linguistic tools that we use to structure and interpret physical phenomena is a set of 'substance and entity' metaphors.

Heat is a parameter that describes the interactions between systems; more precisely, it is one process of energy transfer. It is the *difference of temperatures* between two systems which determines whether heat transfer will occur. For example, when a mass of water is heated by a gas flame, there is a difference of temperature between the flame (temperature of combustion) and the water. So, heat is transferred from one system (gas + air) to the other system (water).

It is important to realize that heat transfer is only one way of altering the internal energy of a system. For example a mass of water at temperature T_1 and internal energy E_1 could reach temperature T_2 and internal energy E_2 either by being heated (i.e. where heat transfer occurs, or by being agitated by a paddle wheel (i.e. Joule's experiment where work is involved). Since there are several pathways for passing from a state with an internal energy E_1 to another state with an internal energy E_2, it implies that the internal energy state of any system is independent of the type of energy transfer used to achieve that state.[2]

A system can thus change its *internal energy* without energy being transferred in the form of heat. In everyday usage however the word 'heat' has a less specialized meaning and this leads to a confusion between the energy which is *in* a system (i.e. internal energy) and a form of transfer of energy between systems (i.e. heat).

In addition there is also confusion over the use of the term *thermal energy* in teaching: sometimes it is used to refer to the quantity of energy transferred between systems (i.e. in the form of heat), rather than as we have done, to the energy of particle agitation.

Since much of our everyday experience entails some form of transfer of energy between objects at different temperatures, the physicists' concept of heat plays an important role in interpreting these experiences. For example, as body temperature is higher than normal room temperature, any time we touch an object which is at room temperature or lower, energy is transferred from our hand to that object. Likewise, any time we cook food or turn on a heater to increase the temperature of a room there is a transfer of energy. But it is important to reiterate that in these contexts our conventional language tends to suggest that objects contain heat, while from the physicists' perspective they have the potential (because of the difference in temperatures) to transfer energy to another object at a lower temperature.

In the next part of the chapter we review studies, based on interviews and written surveys, which have documented pupils' use and understanding of these ideas.

Part A:

An Overview of Pupils' Ideas

Gaalen Erickson

Introduction

The studies discussed below have used a variety of different methods for identifying pupils' ideas about temperature or heat. These methods vary from interviews with individual children, to paper-and-pencil questionnaires, to observational studies in classrooms. Each of these methods provides different types of data and address different sorts of questions about pupil thinking in this topic area and so are interesting in themselves. However, since this chapter is organized around different topic areas, in many instances the data presented on any one topic are likely to have been generated by two or more different researchers who may have employed quite different techniques of data collection and analysis. The following descriptions, then, represent a summary of my interpretation of results from a number of different studies. Much of the work reported in the first section is based upon interviews with children ranging in age from 4 to 13. Later sections will refer to work done with older students, many of whom have received some formal instruction in the kinetic molecular theory.

Pupils' understanding of the concept of heat

Use of the term 'heat'

The terms 'heat' and 'hot' are usually a part of children's vocabulary from the age of 2–3 onwards. While these terms are used to describe some aspects of their many encounters with hot objects, it is not until they are 8 or 9 years old that they begin to talk about 'heat' in terms of a 'state of hotness' of a body along a continuum from cold to warm to hot.[6] Typically, when children aged 8–12 are asked: 'What does heat mean to you?', they tend to associate it with living objects, sources of heat, the degree of hotness of an object, and the effects of heat on objects such as phase changes, expansion, etc.[6,7,8] For example, when an 8-year-old was asked to give an example of heat he replied:

> Heat rises up, the sun has it. It has I think, the sun has, ... heat rises off the gas and it is hot and the sun burns it and it shines and comes down and makes the Earth hot.

Also, a 12-year-old girl volunteered the following response when asked what heat meant to her:

> Heat, it makes everything melt; lead, gold, iron, aluminium, zinc too I think.

In one study a large group of 12–16-year-olds were asked 'to say in a couple of sentences what heat is'.[7] Although some of the 16-year-old pupils described heat in terms of energy, most of the younger ones and about one-third of the older pupils equated the idea of heat with a hot body or substance or described it as being given off from a heat source. Examples of these types of response follow:

> Heat is energy; when it heats something up it will transfer the heat energy to what it is heating up.
>
> Heat is warm air.
>
> Heat is a warming fluid or solid.
>
> ... when you touch it it feels hot—if anything has got the heat in it.

Thus, even though many of the 14 and 16-year-old pupils have been exposed to formal instruction in this topic area, most pupils still seem to associate the term 'heat' with the meanings they have constructed for it during their everyday encounters with hot and cold objects rather than from those encountered in the classroom.

Pupils' intuitive understanding of the notion of heat as a transfer of energy

Research on the developmental acquisition of the notion of heat reveals that even at the age of two, children have developed a notion of a 'hot body' which is capable of producing feelings of warmth in oneself.[6] But it is not until the age of 5 or 6, that they actually disassociate these hot objects from feelings in themselves and differentiate between a heating source and the object which is affected by the source. They become aware of a movement from the source to an object. For example, to the question: 'Who makes the outside hot?', a child (6 years) answered:

> I don't know, the sun shines [she raises her hands] you see, like this [moves her hands] it gets from the sun to the air.[6]

These are, however, the primitive beginnings of the notion of heat transfer and the recognition of 'hotness' as a property of objects which can be altered. By 8 or 9 years of age many children appear to have constructed, from a variety of interactions with their physical and linguistic environments, a set of relatively coherent beliefs about the nature and behaviour of hot and cold objects in their immediate world. They have become aware of the process of heating and cooling and tend to discuss 'heat' in terms of the representation of the 'state of hotness' of a body along a continuum from cold to warm to hot. Many children also invent the entity of 'cold' as a counterpart to 'hot'.

In interpreting common situations, very often children use the verb 'to heat' and not the noun; they describe the situation in terms of action.[9] For example, in discussing a situation where an empty flask is supported just above an alcohol lamp with a thermometer suspended in it, a child of 9 years said:

> Well, I think the flask would be heated and that would heat the air and the air is surrounding the thermometer, and I think the thermometer would get hot. It's open at the top, and heat rises, so, ... it's just a guess.[9]

When we examine how pupils tend to describe the movement or transfer of heat from one object to another (or even movement within a single object) we find different ideas being used. In some instances pupils seem to use a substantive description of 'heat' which implies an inherent motive force. Hence, as the above example suggests, 'heat rises' of its own accord. Other expressions where heat tends to be treated like a substance include the use of more metaphorical terms such as 'fumes', 'rays' or 'waves'. It may be that the use of these terms emerge from direct observations of some phenomena (e.g. the appearance of 'heat waves', or 'fumes' rising from an electric toaster and from a pavement on a hot day) or from common linguistic expressions.

An example which suggests a physical mechanism for the movement of heat is provided by Ron (12 years old). He described a situation where a metal rod was being heated at one end by a candle.

> The whole rod gets hot because 'the heat builds up in one part until it can't hold anymore and then moves along the rod.[10]

In other instances, however, many pupils seem unwilling to imbue heat with its own internal motive force and instead invoke some intermediate agent or medium (most frequently air) to convey the heat from one subject to another or even from one location to another in the same object.

Those researchers who have engaged children in discussions about various phenomena involving heat transfer have documented many properties which tend to be associated with heat. A very common property which is used extensively to make predictions and explain observations is the relative strengh/weakness of the 'heat' in that given situation. Hence the observation that some objects (e.g. wooden or plastic blocks) do not seem to get very hot when placed on a hot plate is explained in terms of the heat not being very strong and unable to penetrate those substances. For example, explaining how a metal block is heated, Ricky said:

> The heat, the heat isn't very strong. And it won't go through the metal very easily.

And comparing the rate of heating of wood and metal he said:

> Cause wood isn't as strong as metal. ... The heat will go through this wood faster than it will through the metal.[9]

Here, the strength is not only a property of heat but also of metal. Often, the property (such as strength or weakness) which is attributed to 'heat', is related to a property of the substance in which heat is moving.

As we will see in subsequent sections, this way of thinking about heat influences the sorts of judgement and predictions which pupils make in more school-related tasks: such as pencil-and-paper tests or questionnaires.

Pupils' understanding of the mechanisms of heat transfer

Two common mechanisms of transfer are normally discussed under this general heading—conduction and convection. I shall deal with each of these separately.

Conduction

Virtually all pupils are aware that one hot object is capable of 'heating up' another cooler object when they come into direct contact. The earliest experiences of this sort are personal such as when a child touches a hot stove, a light bulb or other hot object and discovers heat transfer in a memorable fashion. This perceptual experience is transferred to other contexts and thus researchers report that pupils of all ages rapidly refer to the 'movement of heat' from one object to another. The substance notion of heat is used extensively by children to account for this transfer phenomena. Typically, the mechanism hypothesized for transfer (for example, a flame heating a metal rod) is a transitive one, and is illustrated by one pupil who during an interview explained that the whole metal rod gets hot (even though it is only being heated at one end by a candle)

> because the heat keeps moving from one point of the rod to the next until the whole rod is hot.[11]

When pupils are asked to explain the results of typical conduction experiments—placing several objects made of different materials in contact with the same heating source—several common response patterns seem to emerge. The observation that metals become hot much more quickly than wooden or plastic objects is explained by pupils in terms of a metal's inherent attraction for and tendency to hold heat. For example, several pupils discussed these conduction phenomena as follows:[11]

> A metal just pulls in heat... I can't remember the word... and it sucks it in and keeps the heat.
>
> Well heat... it will be attracted to it... like pulls the heat towards it... as if it was like a magnet.
>
> ... metal holds heat... heat easily gives into it... wood doesn't hold heat.

Another common explanatory mechanism employed by younger pupils (up to age 13) to account for conduction phenomena is the strength criterion mentioned earlier. For example, some subjects predicted, without actually testing these predictions, that air would heat up the fastest and metal the slowest because of their respective 'strengths'.[7] Similar claims were found in the context of classroom discussions about the effectiveness of various insulating materials.[10] This belief that air readily transmits heat because it is weak, obviously becomes a serious source of confusion when the data from insulation experiments are actually obtained and discussed.

A related conduction situation, that of touching different objects at room temperature, is usually not seen by pupils in terms of a heat transfer from their hands to the object. Rather, their explanation of their sensation that metals feel colder than wood or plastic is, as in the other instances of conduction, attributed to an *ad hoc*, inherent property of metals. Some pupils explain that metals feel colder because, in this context at least, they attract cold or they lose their heat to the surrounding air. Less inventive subjects simply assert that metals are by nature a cold substance; that metals feel colder because they have smooth, shiny surfaces. If pupils were able to 'see' this phenomenon in terms of a transfer of energy from their body to the object, this sort of situation would likely be less of a problem than it seems to be at present.

Convection

Pupils also appear to possess an intuitive notion of convection which is most often anchored in terms of previous perceptual experiences. For example, most subjects are able to respond to a question such as: 'How does a radiator heat up a room?', with explanations like: 'heat gets out of the radiator; that's just like smoke which gets away and gets into the whole room, and the radiator is the same, it's the smoke that you can't see that gets into the whole room'.[8]

Another example of these sorts of intuitions is provided from a two-month case study of a 13-year-old boy.[12] When asked to explain 'how heat travelled from one place to another' the boy responsed by writing the following:

> Most heat travels through some kind of rays. There are other kinds of heat like fire which gives off heat (I do not think these have anything to do with rays). Gas heats water. ... The heated water flows through pipes into a container. ... The rays from the hot water are very strong because they are new. The rays from the sun are old by the time they reach the Earth, though they were much stronger when they left the sun than the hot water which the boiler warmed by the gas.

This short excerpt illustrates a number of interesting intuitions about mechanisms for heat transfer other than conduction. While some subjects to appear to require some intervening medium (usually air) 'to carry the heat', others, as the above description of heat rays indicates, seem quite content to accord heat with an inherent propensity for movement.

In summary, the research in this area suggests most pupils are very aware of the transfer of heat from objects at a higher temperature to those at a lower temperature and they also possess a number of intuitions about plausible mechanisms for this process. Most of these mechanisms draw heavily upon the 'heat as a substance' metaphor in order to explain a variety of phenomena involving heat transfer. Furthermore, many of these explanations rely heavily upon simply ascribing plausible properties to heat (e.g. 'heat is strong', 'heat rises') or to the interacting objects (e.g. 'metals get hot quickly because they attract heat').

Pupils' understanding of the concept of temperature

Introduction

As with the term heat, temperature is a word that even very young children recognize, as they encounter it frequently in discussion about the weather and at later ages (e.g. 5-7 years) in the kitchen while observing or engaging in cooking activities. But unlike 'heat', they do not tend to use the term spontaneously in conversation. Rather, they tend to make observations about the relative 'hotness' of objects in qualitative rather than quantitative terms.

It has been observed that by 8-9 years of age, pupils seem to have developed a notion that temperature is related to levels or degrees of heat as expressed by a scale such as that used for reporting the air temperature or the dial setting for a heating device.[6] Others have noted that while pupils in the age range 8-12 are able to use and read a thermometer to take temperature readings, they tend to make judgements about the temperature of an object based more on the nature of the material than on the temperature of the surrounding medium.[13] Some pupils thought that objects of different materials in the same room were at different temperatures. For many pupils, metal objects were colder than wood objects. For example, a child who was asked if a casserole, full of water, left for a long time in a room would be colder, hotter or the same as the water inside it, said: 'The casserole will be colder than the water...it depends on what the casserole is made of'.[8]

It seems then, that up to the age of 12 or 13 pupils are familiar with the term temperature and are able to use a thermometer to assess the temperature of objects, but they actually have a fairly limited concept of the term and rarely use it spontaneously to describe the condition of an object. When asked to make specific judgements about the temperatures of different objects or systems of interacting objects most pupils are able to do so, but as we will see in the next section they frequently use a very different framework from that of physicists for making these judgements.

Pupils' understanding of the notion of temperature changes

This section will be subdivided into two parts: the first will focus on the pupils' understanding of temperature as an intensive rather than an extensive property of objects. The second is concerned with pupils' understanding of temperature during phase changes.

Temperature as an intensive property

In certain experimental situations, many pupils appear to believe the temperature of an object is related to its size. For example, more than 50 per cent of the 12-year-old children who were interviewed in one study thought that 'a larger ice cube would have a colder temperature than a small ice cube' and hence the larger ice cube would take longer to melt.[11] In another study[16], groups of 8 to 14-year-olds (totalling 324 pupils) were asked the following question: 'What can you say about the temperature of the ice blocks?' (Preceding this question was a diagram of a large and small block of ice.) Fifty per cent of the younger group (8 to 9-year-olds) used size as the criterion for temperature, whereas only 15 per cent of the 13 to 14-year-old group did.

These predictions follow quite logically from another apparent belief among pupils that temperature is simply a measure of the amount of heat (or in some instances cold) possessed by an object. It is reasonable to conclude, then, that larger objects contain more heat (cold) and hence are likely to have a hotter (colder) temperature.

Items that have been used extensively on many large-scale achievement tests ask pupils to predict the final temperature of a mixture of two quantities of water given the initial temperatures of the components from which the mixture is made. Detailed research studies on this question have found that the extent of the difficulties experienced by children depend upon the form in which the temperature problems are presented.[14,15] Two basic types of situation were used:

(1) similar amounts of water at the same temperature are mixed; and
(2) both similar and different amounts of water at different temperatures are mixed.

For the two types of situation, both qualitative and quantitative questions were asked. Figure 4.1 shows one example of these questions for each case, and Figure 4.2 gives the types of results obtained. In each case, qualitative tasks are easier than quantitative ones. And, the mixing of water at different temperatures is more difficult than the mixing of water at the same temperature. For example, it is not before the age of 12 or 13 that a task like that shown in Figure 4.1d is solved. Another study which used the same type of questions found an even smaller percentage (from 10 to 25 per cent) of their 13 to 14-year-old age group responding correctly to this type of quantitative problem.[16] The pupils' responses were categorized according to 'strategies' used to solve this problem and it was found that while the younger group (8 to 9-year-olds) preferred an 'addition strategy', the older group tended to opt for a 'subtraction strategy'—a strategy which at least acknowledges that the final temperature should lie somewhere in between the initial temperatures. Similar results were also obtained with

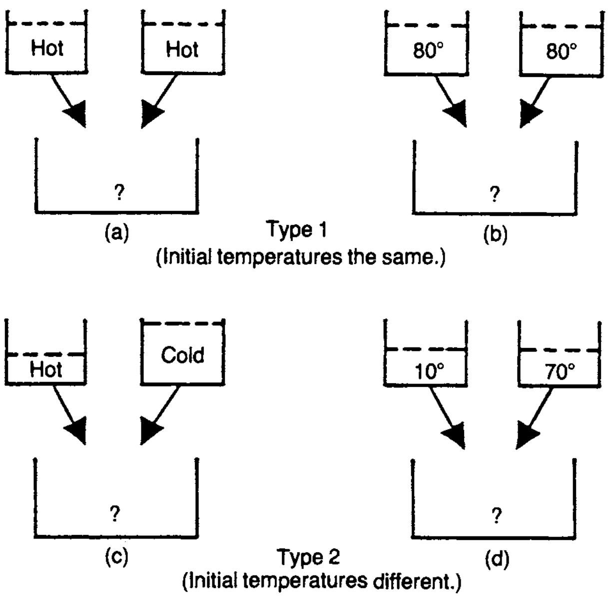

Figure 4.1: Four water-mixing questions requiring qualitative and quantitative responses.
(After Stavy and Berkovitz[14].)

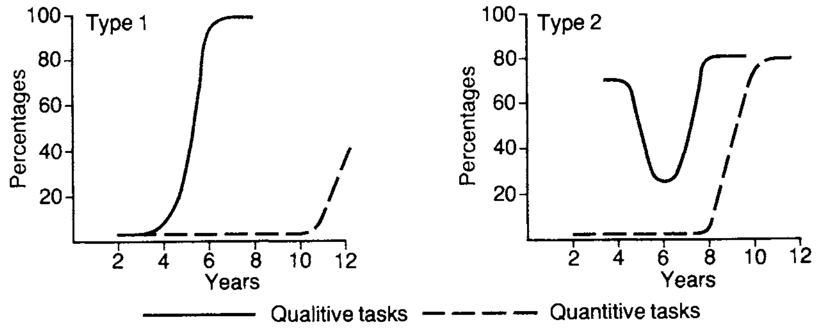

Figure 4.2: The success rates of pupils at different ages on the two types of water-mixing questions (after Strauss[15]).

another group of pupils aged 12 to 16 years, where even the 16-year-olds used the additive or subtractive strategies with about the same frequency as an averaging strategy.[7]

These results are somewhat perplexing since it would appear that most pupils, even at a very young age, possess a good intuitive grasp of this notion of intensivity when discussing phenomena in qualitative terms. It has been suggested that the main difficulty in problem contexts of this sort is the conflict which exists between two representational systems for temperature (qualitative and quantitative) and hence when the problem supplies quantitative data, most pupils employ those strategies normally used with quantitative data—that is, addition and subtraction.[15] Another complementary explanation for the popularity of an 'additive strategy' is the linking of the frequently expressed belief that temperature is simply a measure of the amount of heat possessed by an object with the operation of mixing together two quantities of water which then leads to a prediction of an overall increase in temperature. Whether one or both of these explanations adequately accounts for pupils' conceptual difficulties on this sort of problem, the fact remains that considerable confusion is still in evidence even among 16-year-olds.

In order to overcome this problem one study[14] undertaken with 10-year-old pupils as part of a larger curriculum project, used a conflict-inducing strategy which was quite successful in encouraging pupils to distinguish between the ideas of temperature and heat. The conflict was introduced by means of deliberately juxtaposing two different representational systems, a system in which predictions of various water mixing experiments were requested in qualitative terms, such as hotter or colder, and a system in which predictions were requested in numerical terms.

Temperature and phase changes

A 'standard' laboratory exercise is to plot a time-temperature graph of water (or some other liquid) from room temperature to its boiling point. Although pupils can readily observe that the temperature of the boiling liquid remains relatively constant regardless of how vigorously or how long it is heated, this observation appears to be counter-intuitive to many pupils and exclamations such as 'this thermometer is not working properly' are frequently encountered.

A survey of over 400 Swedish pupils has shown that the majority of 12 to 15-year-olds predicted that the temperature of boiling water would remain at 100° C so long as the switch setting on the hot plate remained constant.[17] If this setting was increased, then 80 per cent of the grade 6 and 54 per cent of the grade 9 pupils predicted that the temperature of the boiling water would increase. In another study a similar type of response was noted, although it was not nearly as pronounced for one of their 14-year-old groups.[16] It would seem that pupils can easily learn the 'fact' that water has a boiling point of 100° C and that it may remain invariant in certain conditions (e.g. over time); however, most do not appear to have any clear understanding of why the temperature remains invariant during a phase change. This understanding would seem to require some explanation of what is happening to the liquid, at the molecular level, in order for temperature invariance to make sense. While the phenomenon of boiling is explained in most text books in terms of a kinetic molecular theory of matter, many pupils appear to have difficulty understanding this explanation.

The following brief excerpt from an interview which was conducted with a 12-year-old illustrates this need to relate phase change to some theory of matter (he subscribed to a 'cell' theory of matter), so that the invariant temperature of boiling water, which he had read about in a book, would make sense to him.[10]

I: Can we heat this ice cube up?
S: Yes.
I: How hot do you think we can get an ice cube?
S: Until it melts do you mean?
I: Well how high a temperature do you think we can get the ice cube?
S: Well it would melt at 32 degrees. But uh, you can boil it. Water will get uh, when water starts to boil it can't get any hotter. So when that ice cube starts to boil the cells won't expand anymore. That's what a uh, man told me. No, it's in this science lab book, my brother's lab book. It says once water starts to boil it might be boiling just slowly but it won't get any hotter. It might boil more rapidly, but it's not getting any hotter.
I: Why do you suppose that is?
S: The cells cannot expand anymore. The cells have reached their, you know, like after a while you can't blow a balloon up any farther or it will burst. You can call a balloon a cell. When, it's like we had a balloon over at Simon Fraser [University] and when we stuck it in liquid oxygen it would contract, it would go ssshh crumple. Take them out in the air and they would go, you know, back to the same point. You can heat them, you know, and they will expand until they burst. But water, it just stops at a certain point.

Others have examined the conditions which bring about these phase changes for a variety of different substances.[13] When pupils were questioned about whether these solids could become a liquid given a sufficiently high temperature, a majority of 12-year-old pupils indicated that some solids (e.g. iron, gold and lead) could indeed become a liquid; while other solids (e.g. aluminium, diamond and salt) could not. The reasons offered for these predictions were usually based upon either some type of previous direct or vicarious experience (e.g. 'because it is necessary to melt gold to make gold bricks') or an appeal to some observable property of the substance (e.g. 'because it is hard').

Pupils' understanding of the differentiation between heat, energy and temperature

As we discussed at the beginning of this chapter, heat describes the transfer of energy between two interacting systems at different temperatures. Temperature and energy describe the state of a system; but, temperature is an intensive parameter whereas energy is an extensive parameter and hence it is directly related to the amount of substance. This extensive property of energy seems to be more accessible to pupils in an everyday context. In one study which used two questions drawing upon familiar contexts—the melting of two ice cubes of different sizes and the boiling of different amounts of water using a similar heating source,[16] over three quarters of 11 to 14-year-olds responded correctly that the larger quantities of ice or water would require 'more heat' to melt or boil respectively.

It seems that many pupils have an intuitive notion of the extensive property of energy particularly when the problem setting and language is familiar to them. But as far as having a clear notion of energy or being able to distinguish it from the notion of temperature, much confusion is evident. Pupils of all ages (12-16) also experienced difficulty in differentiating between 'heat' and 'temperature'.[7] When asked to describe the difference between heat and temperature, the most common type of response (accounting for more than 25 per cent of pupils at all age levels) was that there is no difference between them. Other typical responses were that temperature is either 'a measurement of heat' or it is 'the effect of heat'. Some examples from pupils' responses to this question are:

> Temperature you measure heat with, but heat is hot... you can feel heat.
>
> Temperature is the amount of heat in that space... it tells you the hotness of the water.
>
> Temperature is the amount of heat, and heat raises the temperature.
>
> I don't think there is one, is there [referring to the question of a difference].

> Well temperature, it's just like a thing—like the sun—when you get the sun shining you get a temperature then. But heat, you've got to get something to make heat. But for temperature, it just comes, it's just natural temperature.

There are, clearly, many types of responses here that are similar to those discussed in earlier sections.

In this part of the chapter we have reviewed studies which have given some insight into the kinds of ideas children have about heat and temperature. In the next part we draw on studies of particular classrooms to describe the way pupils' ideas change with teaching.

PART B:

The Development of Ideas with Teaching

Andrée Tiberghien

Introduction

I describe here the way pupils' interpretations of phenomena concerned with heat and temperature change as a result of teaching. The situations which will be considered are those commonly included in introductory science schemes involving ideas of heating, cooling and thermal insulation. Our observations and comments are mainly based on studies which have been undertaken for a number of years with French children aged between 10 and 14, learning about aspects of heat and temperature as part of an introductory physics course.[18]

Temperature

Very often the idea of temperature is not taught as such, except for the temperature of change of state. Therefore, I will begin by considering the evolution of pupils' conceptions concerning this notion.

Temperature of change of state

Many pupils start learning about the stability of the temperature of change of state by melting ice or boiling water. Here I consider what they think about these phenomena and what they learn about them.

Results before and during teaching
Most pupils, aged between 10 and 13, do not know about the stability of the temperature of change of state of water or ice unless they have already been taught about it (in this study 20 per cent or less knew

about it or could give the temperatures at which water boils or ice melts).

The case of boiling water

For pupils the term 'boiling' is very often associated with the appearance of bubbles in heated water; the verb 'to boil' does not seem to have a specific link with the temperature of water. However, this is not a great problem for pupils as long as the teacher is aware of the issue and explains the meaning of boiling from the physicist's point of view.

When pupils boil water as an experiment, it has been noticed that those pupils who watch the thermometer are surprised by the rapid increase in temperature. Sometimes they are afraid that the thermometer will break. They are very surprised at the speed with which the reading on the thermometer goes up; often more than with the stability of the temperature when the water is boiling. The following comment made by a pupil after seeing that the temperature remained constant is typical:

> The water will be hot enough, very, very hot, the hottest that it can be... and then it is going to stop (11-year-old).

This pupil attributed a property to the water, i.e. he considered the temperature of change of state as a property of substance.

The case of melting ice

The results of several studies[13,16,17,18] in different countries are similar. The pupils are no more familiar with the temperature of melting ice than they are with the temperature of boiling water. Indeed, the analysis of different results show that pupils do not interpret the properties of ice and water in the same way. For example, let us consider the comments written by pupils during the following activities:

(1) the water is in a vessel which is heated on a bunsen burner; and
(2) the ice is in a vessel which is immersed in warm water

For pupils it is clear that *before* boiling, the purpose of the bunsen burner was *to heat* the water, whereas before melting the purpose of the warm water was *to melt* the ice (instead of warming or heating the ice). Therefore, ice has the property of melting or of cooling something; very seldom do they consider that the ice itself can warm, heat or cool, i.e. it can change temperature.

Results after teaching

When we consider the results after teaching on the stability of temperature of change of state, there is an improvement, particularly for boiling water and melting metals. For example, the following question regarding the apparatus in Figure 4.3 was given to pupils before and after teaching:

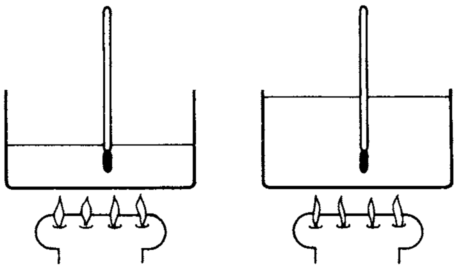

Figure 4.3.

In Eric's container there is a little water, and in Stéphane's container there is a lot of water. The two camping stoves are set at the same level. The two thermometers are the same.

(1) When the water is boiling in each of the containers, is the temperature read by Eric:
  (a) higher than the temperature read by Stéphane;
  (b) equal to the temperature read by Stéphane;
  (c) lower than the temperature read by Stéphane; or
  (d) I don't know.

(2) (a) What temperature does Eric read?
  (b) What temperature does Stéphane read?
  (c) I don't know.

At the beginning of the year 20 per cent of the pupils gave a correct answer to the first question, and at the end of the year 70 per cent of 300 pupils gave a correct answer. To the second question, less than 10 per cent gave a correct answer at the beginning of the year, but this increased to almost 60 per cent at the end of the year.

For a similar question about the melting of ice, there was less improvement over the year, though the progress made was still significant.

It is necessary to note that these results were obtained after a period of teaching in which the pupils carried out several experiments by themselves with ice, water and, in some classes, naphthalene. They also discussed the melting of metals and they were given exercises on both these points. However, despite these experiences, it was noted that these pupils still had difficulty in applying ideas about the temperature of change of state.

Responses to the following questions asked after teaching illustrate these difficulties.

Adele puts a piece of zinc in an oven at 1000 °C. She reads the temperature of the zinc every minute. She got 30°, 70°, 200°, 420°, 420°, 420°, ...

(1) Why does the thermometer have several readings of 420 °C?
Adele goes on to read the temperatures.

(2) Can you tell if:
   (a) the temperature always stays at 420° C;
   (b) the temperature is going to rise again to 1000° C; or
   (c) I don't know.

The responses to the first question were:

'zinc is melting' (about 40 per cent of the pupils) and
'it is the highest possible temperature for zinc' (about 20 per cent of the pupils).

The responses to the second question were:

'the temperature always stays at 420° C' (70 per cent of the pupils); or
'the temperature is going to rise again to 1000° C' (17 per cent of the pupils).

These results suggest that, if the pupils accept the stability of the temperature, they may not ascribe it to the phenomenon of change of state, but rather to the maximum temperature that a substance can have when it is heated. In a certain way, they do not take into account that the liquid metal is an 'object' which is heated and, therefore, its temperature should increase until thermal equilibrium is reached. As we shall see in the next section, these points cause difficulties for pupils.

Remarks on the acquisition of the notion of temperature
This last difficulty shows that the notion of the temperature of an object is only partially acquired by many of the pupils. Here, I would like to emphasize two points concerning the notion of temperature.

First, scientists recognise that when an object is heated, its temperature increases of necessity except if there is physical or chemical transformation. However, the causal relation 'when a substance (or an object) is heated, its temperature increases' is not recognized systematically by all pupils. For some of the pupils this relation *depends on the substance.* Often, they establish a link between the heating and visible modifications (change of state, bubbles, change of colour, etc). For example, before teaching, only about a third of the pupils think that the temperature of sand, sugar and water increases when they are heated. Many of them predict that sand will not be hot 'because sand cannot heat', whereas water can heat up. For them the ability to be heated is a 'natural' property of particular substances.

After teaching more than 50 per cent of the pupils recognized that the temperature of these three substances increases when they are heated, but it remains a difficult concept for them. For example, it was noted that more pupils recognized the stability of the temperature of boiling water than recognized the increasing temperature of the three substances (sand, water, sugar) when they were heated. Very often in teaching, we consider that pupils are already familiar with such notions as the increase in temperature with heating, but it appears that this is not the case for them with every substance.

The second issue concerns thermal equilibrium. When several objects are in prolonged contact in the same room (or any other place which can be considered as a thermostat) they are at the same temperature. Pupils, however, have difficulties in recognizing the equality of temperatures at thermal equilibrium. For example, two plates (one made of metal, the other of plastic) in the same room are not considered by the majority of pupils to be at the same temperature, even after teaching.[19] Likewise, different materials (flour, nails, water) placed for several hours in an oven at 60° C are at different temperatures for the majority of the pupils. Typically, flour is at less than 60° C because flour does not heat up very much, nails are at more than 60° C because the iron heats faster, and water is at 60° C because it takes the temperature of the surroundings. Even if in this case there is some progress (from about 10 per cent before teaching to over 30 per cent after teaching) it remains a problem. Before, and sometimes after, teaching we find the same kind of interpretation as in the preceding case: that some substances cannot heat up. It appears that even after teaching, some pupils have difficulty in assimilating this notion.

Let us consider two examples which illustrate the difficulties of using the notion of thermal equilibrium in different situations. The first example illustrates pupils' use of different and even contradictory explanations for two experimental situations. To a question asking if the temperatures of different objects next to each other in the same room are the same or not, a pupil responds:

> They are in the room, therefore all of them have taken the temperature of the room. ... If one puts any object... in the room, this object is going to take the temperature of the room... irrespective of the material of which it is made (Nathalie, 13 years).

However, in response to a question about the choice of the best material in which to wrap a cold ball-bearing in order for it to remain cold for as long as possible, the same pupil chose aluminium foil and explained:

> ... because the material, like wool, has a tendency to heat something... because it is the material, it is like that... when it is aluminium, it is metal, therefore it remains at the room temperature.

The second example illustrates an incorrect use of thermal equilibrium. To a question about the handles of different spoons in hot water, a pupil responds:

> the iron seems hotter (when you touch it), the end of the wood is almost

> not (hot). ... I think that they are at the temperature of water... because they have been in the same water, at the same temperature, for the same time (Cécile, 12 years).

This pupil knows that different materials in a room are at the same temperature although they feel different. She applies this knowledge to another situation, though here ambient air intervened and she did not take it into account.

To summarize, it was noted after teaching that pupils had made more progress in their understanding of the stability of the temperature of change of state, particularly in the case of boiling water or melting metals, than they had with the following ideas:

(1) the increase in temperature of an object (or substance) when it is heated (without physical or chemical transformations); and
(2) the equality of the temperature of several objects in prolonged contact, i.e. at thermal equilibrium.

Knowledge of these difficulties leads naturally to a consideration of the *content* of the teaching and we will return to this matter at the end of this chapter.

Heat

In this section, we deal mainly with the notion of conduction, in so far as conduction is the process of the transfer of energy. Moreover, nowadays, the words conductor and insulator are much used, particularly in the media. Many of the pupils, even before teaching, know these words even if they do not use them very often. What do they mean by them? Does the use of these words imply a notion of the conduction of heat, and if so what are their ideas?

First, let us consider the meaning for the physicist. Being a conductor or insulator is a property of substances. This notion is connected with one of the processes by which energy is transferred: that of heating, which corresponds to the transfer of increased thermal agitation. This process can exist only if there is matter. The notions of conductor and insulator *cannot be separated* from the notion of heat and consequently *from the notion of energy*. Indeed, it seems very difficult to consider a transfer without specifying what is transferred (i.e. to deal with heat without considering energy). As we noted previously, heat is a characteristic parameter of interaction and, therefore, when we use the notions of conductor and insulator, we are dealing with systems in interaction.

Types of interpretations given by pupils of several experimental situations

A number of studies undertaken by researchers have involved asking pupils about situations, which to a physicist involve the notion of the conduction of heat.[18,19,20]

The situations presented to pupils included the following:

(S1) which materials are good for the thermal insulation of a house?
(S2) Which materials are good for the thermal insulation of a heated (or cooled) steel ball-bearing?
(S3) Which materials are good for the thermal insulation of a hot drink or of ice?
(S4) Why do metal and plastic plates feel different to the touch?
(S5) Why do the metal and plastic parts of bicycle handlebars feel different on a frosty day?
(S6) Why is the handle of a metal spoon hotter than the handle of a wooden or plastic spoon when they are placed in hot water?

Explanations given by pupils before and after teaching fall into several main categories *which are not exclusive*:

(1) the material retains warmth or cold, better or less well;
(2) the material has the property to be cold or warm because of its nature;
(3) the material is hot (or cold), so consequently it heats (or cools);
(4) the material becomes hot or cold, more or less quickly;
(5) the material retains, lets in or lets out hot or cold air, better or less well;
(6) the material absorbs, retains, lets out, stores, ... attracts, repels heat, better or less well;
(7) the material transmits heat, more or less quickly; heat propagates, moves in the material, more or less quickly; the material transmits thermal agitation, more or less quickly;
(8) the material takes the temperature of its surroundings; and
(9) the material is a conductor or an insulator.

Pupils' interpretations before teaching

Interpretations before teaching

Before teaching, pupils tended to give the first five categories of the above explanations depending on the experimental situations.

The explanation 'the material retains heat or cold, better or less well' predominates in situations in which there is a container whose function it is to keep the inside at a given temperature for as long as possible (situations S2 and S3). For example, a pupil chose aluminium to wrap the ball-bearing with (S2) and said:

> the aluminium keeps cold or better (Cécile, 11 years).

Another pupil chose an aluminium container for a hot drink because:

> the iron preserves better (11-year-old).

In that case, the container has the property to preserve the hot or cold state of the object which is inside it; it could be said that it is similar to the case of canned foods where the can could have the function of preserving the food in it.

The explanation that 'the material has the property to be cold or warm' is also quite common in this same type of situation (S2 and S3), and in the situation in which touch is involved. For example, in the case of the thermal insulation of a hot drink or ice (S3) a pupil chose a metal container with ice in it because:

> the iron container is colder than an ordinary glass (11-year-old).

Another pupil chose a glass wrapped in cloth for his hot drink because:

> the glass wrapped in cloth will be hotter than the others since it is wrapped in cloth (11-year-old).

In these cases, pupils relate two properties which they ascribe to the material: the property to be cold (or warm) (i.e. the explanation type 2) and the property of keeping something cold (or hot) (explanation of type 1).

The second type of explanation is also found very often in situations where touch is involved (S4):

> it's metal and metal is cold (11-year-old).

The third type of explanation, 'the material is hot (or cold), so consequently it heats (or cools)', is also mainly found in situations in which there is a container (S2 and S3). Pupils establish a casual relation of this type, because the material is cold (or hot), it cools (or it heats). For example:

> metal cools things, metal is cold (Marie-Noëlle, 12 years).

The fourth type of explanation, 'becomes hot (or cold), more or less quickly', is mainly found in situations where metal is heated and when the question concerns the material itself (S6). For example:

> I've been told that metal heats up faster than any of the other three.

In that case, the material doesn't have the property to remain in a given state of hot or cold.

The fifth type of explanation, 'material retains, lets in or lets out hot or cold air, better or less well', is found in the case of the insulation of a house, where the house is similar to a container whose function is to keep the inside at a given temperature as long as possible (S1). In that case, the majority of pupils do not use the previous categories of explanation; they tend to take into account the transfer of air between the outside and the inside and because of this, they consider an action from the outside on the inside. For example (in situation S1):

> it (the material) lets the cold air into (the house) (Cécile, 11 years).

These first five types of explanation *are only in terms of properties of objects or events* (it is hot (cold), it retains the warmth (cold), it heats, it becomes hot (cold), etc.). The pupils do not use parameters, as the physicist does, to describe experiments (temperature, heat, energy, etc.). In addition, except for the last example, in which the air intervenes as an intermediary between the outside and the inside, there is neither the idea of transfer nor the idea of interaction or even action between objects or systems. The thinking of the pupils is very much divorced from the interpretation of the physicist.

The other explanations listed earlier are given mainly after teaching. It is important to note that the explanation 'the heat goes through, moves...' is found mainly in situations where there is a material substance between the source of heating and the place where the temperature is considered, such as in the situation where spoons are left in hot water. The situation very frequently used during teaching, in which a bar of metal is heated on one side and temperature is examined on the other side, produces this kind of interpretation.

Comments on differences between the physicist' and pupils' interpretations

As we have already noted, most of the pupils give interpretations which are very different from those of the physicist. In considering the choice of a container to keep a drink hot or ice cold for as long as possible, if responding in an analytical way rather than by recall, a physicist would:

(1) *Identify* the interacting systems: the hot drink (or ice) the container, ambient air;
(2) *redescribe* the state of the systems with the parameter temperature;
(3) *compare* the temperatures of the different systems;
(4) *recall* a piece of knowledge which comes from the *principles* of thermodynamics: heat propagates from a region at higher temperature to a region at lower temperature;
(5) *deduce* that heat will propagate from the hot drink to ambient air (or from ambient air to ice) and from the hot drink to ambient air through the container;
(6) *recall* the piece of knowledge that, in a conductor, the heat transfers faster than in an insulator; and
(7) *choose* the most insulating material for the container.

In what way does this differ from the explanations given by the majority of the pupils?

The first difference which is very often found is that pupils do not take into account all the systems which interact (including in this case the ambient air); secondly, they do not redescribe the systems by using parameters of state (or by interaction parameters)—in this case temperature. Most often they describe or interpret situations in terms of:

(1) events: it is heating, it cools, etc.;
(2) properties that they have ascribed to the object: the substance of the object, or the fact that it is cold, hot, solid, hard, thick, etc.; and
(3) function of the object: it has been made to perform a specific function, e.g. for drinking coffee or keeping food, etc.

Pupils tend to associate:

(1) a property of the object with an event (it is cold so it cools);
(2) one property of the object with another (it is made of metal so it will retain heat);
(3) the recognized event with another one (it becomes hot so it will heat); and
(4) the object with another analogous situation (there is aluminium in the vacuum flask, so the container made of aluminium will work the same way).

It appears that the physicist who interprets these experiments reasons in a different way from the majority of 12 to 15-year-old pupils.

The physicist identifies *systems*, then, in order to analyse the interaction, *describes* the systems using *parameters* such as temperature. Pupils, on the other hand, take into account only *objects* (not a real difficulty when systems and objects are the same), and in order to interpret the situations, very seldom do they describe them in terms of parameters, instead they use *properties*, *functions* or *events*. These two fundamental differences are evident at the beginning of a teaching sequence when pupils start reasoning about experimental situations.

Learning of the notion of heat

Before considering our results concerning what 12-13-year-old pupils learn about heat as a result of teaching, it may be helpful to outline the main features of what is taught on this topic. It is very difficult to say what is actually taught in any class but here we outline the objectives of the teaching given by teachers who participated in this research:

(1) there is transfer (propagation of heat) between two points which are at different temperatures; there is (spontaneous) transfer from the place which is at the higher temperature to the place which is at the lower temperature;
(2) different materials conduct more or less heat; there are conductors and insulators;
(3) in the case of conduction, the transfer occurs without movement of matter;
(4) in the case of convection, there is transportation of matter;
(5) several objects in prolonged contact have the same temperature (when there is only one thermostat).

Here we will not examine the case of convection because conduction is the process of energy transfer which corresponds to heat and also because there are few results on pupils' understanding of convection.

After teaching, it is striking to find out that pupils tend to use the words heat, cold, conductor and insulator in almost all types of explanations and in almost all the situations. However, these words can have *very different meanings*, which vary not only from one pupil to another, but even for the same pupil according to the situation.

Cases where there is little or no significant change in pupils' explanation

Let us examine the case where pupils' explanations are of the same type before and after teaching, only words are added. In the following examples, these explanations were given for the same question concerning the choice of a container which has to keep a drink hot or ice cold for as long as possible. A pupil (12-years-old) chose an iron container with ice in it and said:

> the iron keeps the cold better than the others. It is an *insulator.*

He made the same choice for the hot drink and explained:

> because the iron container keeps the cold, it can keep the heat.

Another pupil (also 12-years-old) chose an iron container and said:

> the iron will keep the ice. ... It is a good *conductor.*

and for the hot drink:

> for the same reasons.

At the beginning of the year, this last pupil made the same choice for these questions, and gave a similar explanation for the hot drink:

> the iron keeps things better.

So, before and after teaching, we found the same type of explanation; material retains warmth or cold well or not as well, the only difference is the addition of a word, 'conductor' or 'insulator'.

These examples illustrate one type of learning which is found in a substantial number of pupils after teaching on heat. These pupils *do not change their minds*, their type of interpretation is the same, *they just accumulate a piece of knowledge*, in this case the words 'conductor' and 'insulator'.[21]

Cases where there has been noticeable development but still with significant difficulties

Example of conceptual change

Let us take a typical example where there has been some development even though after teaching the type of interpretation is not very close to the physicist's one.[8,20] For example, in considering the choice of container before teaching, Marie-Noëlle (12-years-old) said:

> Surely not this one (in cardboard and plastic)... beause in my fridge it is not cardboard, it is not this material, it is iron or plastic.

And, after touching a metal container, she said: 'metal cools'. Of the cardboard-plastic container, she said:

> the cardboard container, it is warm enough.

Concerning a casserole full of hot water, left for a long time in a room, she said:

> the casserole will be colder than the water... it depends on what the casserole is made of.

The analysis shows that she used:

(1) Events and properties: coffee pots are metal; in the fridge, there is no cardboard but metal or plastic; metal is cold;
(2) Causal reasoning: because a material seems cold when you touch it, its temperature is above the ambient temperature; because a material is cold, it cools; because an object has a specific function, it has some properties.

Sometimes, she used the heat as an existing intermediary in an interaction but not often and only in very favourable circumstances.

We should note that almost all of these statements are correct, but the statements that link them are not.

During the teaching, this pupil made several experiments, the results of which were in contradiction to her predictions. However, even after several sessions, we observed that in the same session, she stated that cotton and aluminium are at the same temperature and she stated that cotton is warm so ice wrapped in it will melt more easily than in metal.

> I think that, that [metal] will keep it [the ice] frozen most easily, because that [cotton] is hotter and keeps the heat better.

Then, she carried out the experiment, and after she stated:

> The cold of the ice goes into the material [metal] and goes away, and there [the cotton] it keeps it. That one [cotton] keeps the heat more than that one [metal]. Here [metal] it's all right, it goes away, the heat or the cold.

After teaching, she compared materials using the criterion that heat transfers more or less quickly according to the material (insulator, conductor); for example: 'it is a conductor... heat of hot water will go in the sides, it will go through'.

She also distinguished between heat and a hot object and she ascribed to heat the property to move in a material. So she used a new idea; heat, as an entity which implies an action of one object (hot water, for example) on another one (container).

After teaching, she still reasoned in terms of the properties of an object but she did not use the same properties. She had modified her ways of explaining. She had, as least partially, restructured her ideas.

However, she can draw on several types of interpretation. So, during the same final test, in order to answer a question about the different sensations she felt when she touched metal and cotton, she used the fact that the movement of heat is more rapid in some materials than in others:

> The metal spreads out the heat quickly, while the cotton's heat stays in the same place.

But, for a question based on an everyday experience (pick a material for a container to keep soup hot the longest), she referred to a different situation:

> Coffee pots keep in the heat well. Aluminium keeps in the heat well.

Comments

Pupils use the words 'heat' and 'cold' with several meanings. Let us examine some of them. For example, mainly in situations in which touch is involved (S4 and S5), the explanations are of the type:

> Metal *absorbs* more cold than plastic does.

In situations concerning the insulation of a house, typical explanations are of the type:

> We try to insulate houses... in order that heat does not escape and cold does not go in (Nathalie, 12 years).

In situations in which spoons are placed in hot water, many explanations are of the type:

> ... metal is a conductor, *it conducts the heat* up into the metal... it transfers heat... transfers heat along it.

or,

> Water has heated the whole... it has heated the end, then it has gone up... heat has gone in the whole spoon (Béatrice, 12 years).

All these types of explanation take into account an entity, the heat. In all these cases, *this entity has the property to make the material (or object) hot*, and in its absence, the material is cold. Very often, cold is also an entity which has the property to make something cold (heat heats and cold cools). But there are important differences between the types of explanations. In the case where the material absorbs, retains, loses, or prevents heat from escaping, the heat has the property of being stored in an object (or material), and it should be noticed that most of the pupils who 'store' heat (or cold) do not consider that heat has a mass. In the case where the material transmits heat or heat goes through, or propagates in the material, the heat has the property of movement and *it is not necessarily stored.* Moreover, in that case, recognition of transfer from one object to another presupposes that one of the objects has an influence on the other; in other words there is an action of one object on the others.

Therefore, when heat transfer is taken into account, the pupil's interpretations are nearer to those of the physicist than before teaching. For example, these pupils recognized, at least partially, the interaction between the objects, and also used the rapidity of the movement of heat in order to compare materials. But, significant difficulties still remain. The use of the idea of heat transfer *does not necessarily imply a correct explanation,* because, in particular, it also requires: first, a correct choice of the systems (or objects) which interact, and secondly to take into account the difference between the temperatures as a condition of transfer.

Therefore, even if after teaching the word 'heat' is frequently used, we have to be careful not to infer that for pupils this idea of heat as an interaction parameter predominates in their explanations of all the situations in which a physicist would use it. The interpretations given by a substantial number of pupils of the different experimental situations show that the *idea of heat as a characteristic of interaction* is not as essential in explaining the phenomena as are the properties of materials.

Some difficulties in the reorganization of pieces of knowledge

Let us examine the different explanations given, after teaching, by the same pupil in different situations. First, in the situation with several spoons in hot water, this pupil said:

> the iron is a conductor... the iron one will be the hottest because it will conduct more quickly (Jean-Claude, 12 years).

In the situation where he has to choose a material in which to wrap a cold ball-bearing, which is supposed to have been taken out from a freezer, he chose aluminium foil and said:

> because metals keep the cold... the aluminium is a conductor.

The interviewer asked, 'the fact that it (aluminium) conducts, does that make it possible for it to keep the ball-bearing cold for the longest time?', and the pupil answered:

> Yes, because it will take the temperature of the marble... and it will keep it for a long time.

This example illustrates an interpretation which is given quite often. It is based on the following reasoning:

— a conductor heats (or cools) quickly;
— something hot (or cold) heats (or cools);

With only this reasoning, the pupil is right to choose aluminium foil, since aluminium becomes cold (or hot) faster and will cool (or heat) what is inside. These statements work in the majority of real life situations. However, they may lead to incorrect conclusions. They ignore two essential points:

(1) it fails to take into account all the systems which interact, in this case the ambient air;
(2) it does not fulfil the condition that heat goes from the hotter place to the less hot place.

To learn that a conductor heats (or cools) quickly is seen as progress, but it is not sufficient.

The case where pupils' interpretations after teaching are close to the physicist's interpretations

This section will show that the idea that an object takes the temperature of the other objects with which it is in contact, can be very helpful in using correctly the notion of transfer of heat in a material. For example, after teaching, a pupil gave as an explanation for his choice of thermal insulation for a house:

> the polystyrene... is a good thermal insulator... they [polystyrene, wood] prevent cold for coming in... the lead will take the temperature... of the cold [outside] and therefore will put it in the house, ... it [heat] goes through the piece of lead (Sébastien, 12 years).

In the situation in which he had to predict the temperature of different objects on a table, he stated:

> [same temperature]... because there is the same temperature on the two sides of the material, nothing has an effect upon the other.

In the situation with spoons in hot water:

> [an insulator]... means that it does not take the temperature of the surroundings, but, on the contrary, iron will take the temperature of the surroundings at once.

These types of explanations are close to these of the physicist in so far as there is use of the parameter temperature in order to redescribe situations and to predict what will happen.

It should be noted that these kinds of explanations are not frequently found. In this case, even before teaching, the pupil concerned already used in most of his explanations an entity (which he called energy) moving at various rates according to the material. Perhaps this kind of interpretation could be a step forward in the learning of this concept.

Implications for teaching

The results show the very significant difficulties that pupils have in acquiring the notion of temperature. Very often, pupils think that temperature depends primarily on the substance (or material) and possibly on the surroundings. This has a number of implications:

(1) In some cases pupils do not recognize that the same object can have different temperatures.
(2) They reason in terms of substance and case by case, i.e. according to the experimental situation; they do not establish a systematic causal link between the heating of a substance and the fact that its temperature increases.
(3) They do not recognize that several objects in contact (with only one thermostat) move towards the same temperature.

However, typical teaching programmes do not take these difficulties into account; they often assume that pupils have already acquired the notions in question. More appropriate teaching which might help pupils to acquire these notions and to overcome the difficulties identified would involve the following components:

(1) Various experiments in heating and cooling of very different substances. These would give pupils the opportunity to see what is happening to these substances *and* to take their temperature, the temperature of the surroundings and, if possible, of the source of heat (or cold).
(2) Several activities with boiling water, melting ice and other changes of state including, of course, taking temperature readings.
(3) Discussions, tests, etc. in order to help pupils to generalize the notions which have been taught to appreciate their range of application.

Such teaching could help pupils to learn, at least partly:

(1) to use the parameter temperature in order to redescribe an experimental situation (when it is pertinent);
(2) to use the principle (sometimes called the zeroth law of thermodynamics) that two bodies which are in contact for a long time, are evolving towards thermal equilibrium; when there are two bodies in thermal equilibrium with a third then there is thermal equibrium between all three;
(3) to know that temperature is one of the parameters which determines the physical state of a substance;
(4) to learn the range of application of the temperature of change of state and consequently the range of application of the increase of temperature of a substance when it is heated (without change of state or chemical reaction).

The introduction of the notion of heat appears to give students significant problems for several reasons. Very often this notion is introduced before that of energy and, therefore, a transfer is being considered without being explicit about what is being transferred. The use of the notion of heat also implies the use of the notion of temperature and this notion has not yet been acquired by a majority of the pupils. The pupils' attainments *after* the teaching of conduction of heat and insulation show that a substantial number of them used these notions incorrectly in different experimental situations. So, more generally it would seem that an *intermediary* step could be used in teaching the notion of heat. The pupils could be introduced to a notion of interaction between objects in so far as they learn that the temperature of an object depends *necessarily* on its surroundings.

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