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ABSTRACT

In the domain of research on physics education, results on students' conceptions show difficulties in physics learning. This paper aims to propose theoretical elements to interpret such learning difficulties related to physics teaching in the case of heat and temperature. Sections in this paper include: (1) Introduction; (2) Epistemological analysis of the evolution of physics; (3) The learner's modeling of the physical world; (4) Elaboration of students' knowledge structure; (5) Structure of physics knowledge to be taught; and (6) Evolution of students' knowledge structure with teaching. (PR)

SYMPOSIUM : More on heat and temperature: recent advances in our understanding of conceptual change in the domain of physics

ANALYSIS OF LEARNING IN THE CASE OF A TEACHING ON HEAT AND TEMPERATURE

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1 - Introduction

In the domain of research on physics education, results on students' conceptions show difficulties in physics learning (Driver, Guesne & Tiberghien, 1985). Some work shows that young pupils (12 year old) and university students give similar incorrect answers with the same types of reasoning (Johsua & Dupin, 1986). Other work shows that students can solve rather difficult physics problems dealing with complicated mathematical relationships between physical quantities but that students are not able to interpret or predict real events in simple practical situations (Rozier, 1988). This paper aims to propose theoretical elements to interpret such learning difficulties related to physics teaching in the case of heat and temperature.

To interpret these learning difficulties in physics acquisition we take the point of view of didactics, that is, we introduce explicitly the role of physics knowledge in our study of learning. As a matter of fact, it appears as a gap between the meaning constructed by the learner and certain aspects of physics knowledge, particularly concerning physical quantities, their relationships and their meaning in the framework of physics. In this perspective, it is necessary to take into account the relations between the learner's acquisition and physics education. Our theoretical approach has been constructed from work on students' learning and work using the epistemology of science with each influencing the other. In this paper we start from the latter point in order to understand more explicitly how meaning is constructed from the physics point of view.

2 - Epistemological analysis of the evolution of physics

The general aim of physics is to interpret and predict the physical world. These processes of interpretation and prediction put into play a specific way of seeing the world even if they deal with complex mathematical formalisms and/or complex experiments. These processes imply a construction of an understanding of the physical world, where we assume that theories play a crucial role.

The role of theory appears when theories change; this is why in our analysis we focus on their historical evolution.

2.1 Importance of the theoretical construction

According to most epistemologists, the links between the questions at the origin of research and their theoretical background are so strong that when the theoretical background is different, there may be incommensurability between the theories (Kuhn, 1972; Thuiller, 1988). Kuhn's example about Copernicus is enlightening with respect to the different meanings of words which, in fact, are given by the theory : people who consider that Copernicus was mad because he stated that the Earth revolves, do not speak the same language as him. Kuhn considers that "when these people said 'Earth' they meant 'fixed position'. Their Earth cannot move. Copernicus's innovation did not only consist of making the Earth move". This was a new way of considering problems of physics and astronomy: the meaning of the concepts Earth and movement must necessarily change. "Without these changes, the notion of Earth moving was considered to be madness" (Kuhn, 1972, p.179).

There is a strong link between the formulation of the questions at the origin of research and the selection of experimental facts. In an experiment, it is not possible to take into account all the objects and events which can be observed. For example when we have a simple electrical circuit consisting of a battery and a bulb, the sign of the trade mark is not selected as a relevant attribute of the battery! This exclusion appears so obvious that it is not necessary to make it explicit; but it is no more obvious when the duration of the battery is not selected. However when we choose the electrokinetics theory (which is taught in most of the secondary schools and at the beginning of university), the duration cannot be selected as fact. As a matter of fact, electrokinetics is valid only for a stationary state and time is not a variable of the model. For example, it allows the respective brightness of bulbs in different connections of battery and bulbs to be predicted by using the physical quantities such as current, voltage and resistance.

This example shows the important selection physicists do when they interpret the material world. Throughout the historical evolution of physics knowledge, the mastering of this selection was more and more precise and explicit. The separation between phenomena at equilibrium independent of time and the phenomena which depend on time and outside of equilibrium is a basic selection incorporated in physics theories. Let us note that this way of dividing up the material world is far from an everyday approach to the material world.

The way in which the questions at the origin of research are determined and the facts (or events) to be interpreted and predicted are selected is deeply related to explanation. As with research questions, what is considered as an explanation has considerably evolved during the history of science. We assume that explanation is linked to the theory but it is very often tacitly shared by a scientific community at a given time. What is an explanation in the time of Aristotle is not relevant now. Since Galilee the nature of explanation has been transformed in relation to the role of the model and its relation to experiment. Historians of science show that Galilee was torn between two conceptions: (a) Aristotle's conception, which consists of starting from obvious and universal principles and then deducing logical conclusions; (b) more modern conceptions which consists of recognising the hypothetical status of results and the importance of experimentation (Thuillier, 1988). Therefore the underlying causalities are different in the modern approach; there is no more a direct cause as with the universal principles of Aristotle.

An analysis of Newton's approach shows the type of explanation which is acceptable at a given time. Newton does not pretend that his mathematical model coming from universal gravity theory represents exactly the physical world: specific aspects have been selected. His theoretical construction is predictive for the selected aspects and can be considered as an explanation to the extent that its physics consequences can be verified. It takes the status of theory. However, many contemporaries could not follow Newton because the physical cause (reason) of gravity was not made explicit (Cohen, 1987).

This epistemological analysis presents the main functions of the scientific theory that we take into account in our analysis of physics learning. In brief, we consider that scientific theory contains the explanatory system, the meaning of interpretation and prediction is constructed through the theory. Therefore paradigms in Kuhn's sense -the set of beliefs, recognised values and techniques which are shared by the members of a given group of physicists, research questions, basic principles (conservation, symmetry, ...), and laws- are part of the theory. A fundamental aspect of scientific theory is its hypothetical status which is a foundation aspect of modern science. It implies the validation process.

2.2 Roles of three levels : theory, model and experimental field

When physicists interpret and predict experimental facts they do not apply directly a theory to the situation but, by using the chosen theory, they construct a model of the experimental situations. We refer here to a French epistemologist, S. Bachelard (1979) who considers that the model is always relational; it is an intermediary:

> "The model in its most abstract sense functions in an ostentive way (We keep the French word 'ostensive' which means what is shown, what can be perceived) and in its most concrete meaning allows theoretical aspects to become apparent . In every model there is a bipolarity of :
> - the theoretical aspects and
> - the ostensive aspects ".

"The model is not an imitation of phenomena, ... it represents only some properties of reality".

In this perspective, we consider that, in physics, interpretation and prediction imply a modelling process which puts into play three levels : theory, model, experimental field of reference (fig 1).

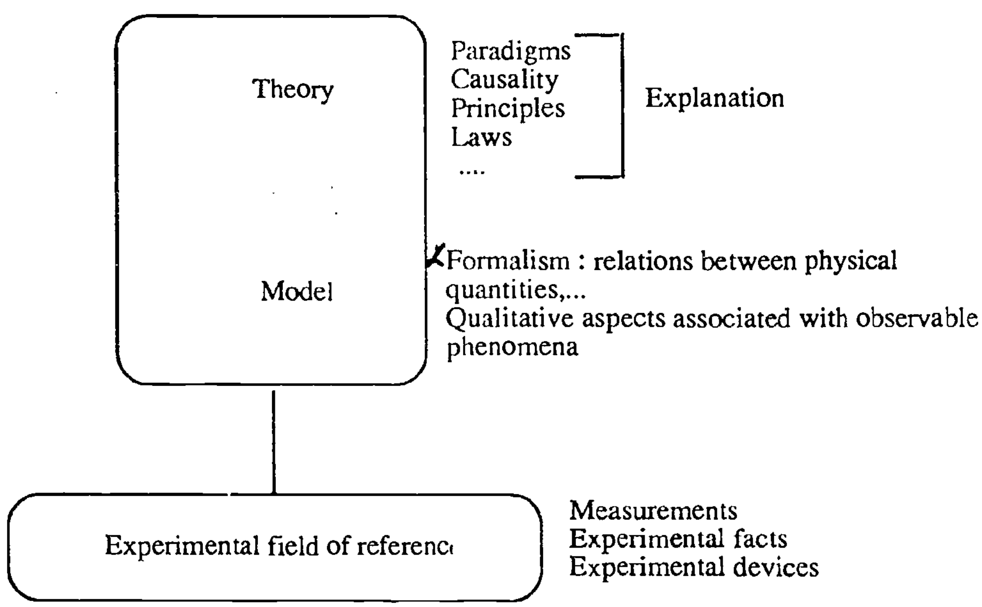

Figure 1 A view of modelling in physics

Here we do not have the ambition of giving a formal definition of these levels. We will specify their meanings in an operative way. We have already described what corresponds to theory.

Models consist of qualitative and quantitative functional relations (implying mathematical formalisms) between physical quantities in order to represent the selected aspects of a set of material situations. This level of the model can be divided in several sublevels. Each has an internal coherence and is compatible with the others; each of them has a specific syntax.

The experimental field of reference corresponds to the experimental situations which belong to the domain of validity of the theoretical construction (theory + model) brought into play in modelling. This field consists of the experimental facts, the experimental devices and the measurements. It is also possible to consider that measurements are in-between the level of objects and events and that of the model. The type of language associated with this level is that used in describing facts in terms of events and objects, it is the natural language but the words have the meaning giving by physics (e.g. light, heat, ...) and not that of everyday language.

We assume that the three different levels are necessary in the functioning of physics knowledge, they constantly interact (figure 2).

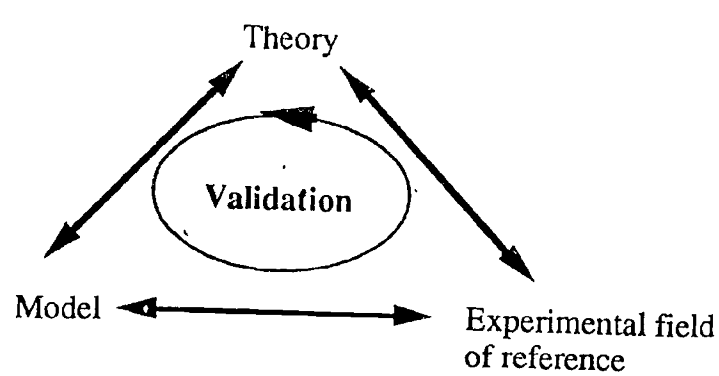

Figure 2. Three levels involved in validation process

We should note that, in physics, the level of the model is very developed. Models use mathematical formalisms, they are a long "detour" between the objects and events and the theory. This "detour" is a hard cognitive task but allows for a large field of validity and not an "ad hoc" model for a specific case.

3 - The learner's modelling of the physical world

After this short analysis of physics knowledge, we discuss the following question : what is the meaning that the learner constructs when interpreting and/or predicting material situations ? Let us note that we can no longer use the word "experimental situation", which depends on physics theory. We make the hypothesis that a relevant common point for the analysis of physics modelling and learner's approaches consists of the real world : the material situation.

At this point we make several hypotheses on the learner's cognitive activities. First we assume that when s/he is interpreting (or predicting) material situations s/he constructs a "model" of the situation (which could be analogical and/or propositional), this model depending on his/her own point of view. In other terms we associate the cognitive processes involved with a modelling activity.

In this modelling process, like in physics, the learner selects of the objects and events which are relevant according to his/her point of view that we assume as belonging to a theoretical level. Underlying such an hypothesis it is assumed that the learner is coherent from his/her point of view with respect to the situation which includes the social context. These hypotheses agree with the findings of psychological research (Brown, 1989; Carey, 1985; Vosniadou, 1989). For example, Brown (1988) states that young children not only can transfer their knowledge on "deeper bases than mere-appearance matches" (p.376) but also for the primacy of relational information in which causality plays a fundamental role. Moreover, Brown takes "an hypothetical continuum of knowledge such as theory, causal explanation, meaningful solution, arbitrary solution". For her, "a theory would be defined as a coherent explanatory network of interrelated concepts" and "a causal explanation would refer to a principled understanding of part of a larger system, such as the fact that inanimate objects need to be pushed, pulled, or propelled into action." (p.370). This convergence on the role of theory, particularly causal explanation in even young children's knowledge processing, confirms our hypothesis that the learner's modelling is based on theoryL[1].

Concerning modelling by individuals, we refer to cognitive psychology. Two concepts can be compatible with what we consider as a model : representation and mental model.

[1] In the following we use theoryL, modelL and field of applicabilityL when these notions are associated to the learner and we keep theory, model and field of applicability when these notions are associated to physics or "physics to be taught".

These concepts do not have a unique definition (Richard 1990, Gentner & Stevens 1983, Johnson Laird 1983). However, the common points are important enough. In our case, at this step of our research, we assume that a model is a mental construction done in a given situation in order to solve a problem according to a theoretical point of view chosen in relation with the needs of the situation and depending on the acquired knowledge. For physics knowledge and for individuals, there is a model level to the extent that it retains the main characteristics : that of being an "intermediary between the theoretical aspects and the ostentive aspects" (S. Bachelard 1979). Or in other terms, the model is the link between the theory and the objects and events (experimental/empirical field); it is a representation of the selected aspects of what is studied.

The model is constructed under constraints which are not necessarily of the same type in the case of physics as for students, in particular concerning the theoretical standpoint, the coherence between the levels and internal coherence of a level. For example, in everyday life the main constraint on the model is the perceived result of the action which is related to a cause in a linear relation (Guidoni 1985). These models can be "ad hoc" with the situation and still compatible with linear causal reasoning. This causal relation belongs to theoryL in our approach. Thus, in the case of learners who, at least for young ones, acquired their knowledge in the context of everyday life, we can suppose that the meaning of words, such as heat, temperature is radically different from that in the physics framework, even if, in some specific situations, the meaning seems similar. As we shall discuss later, in many common heating situations, the students' principle is "what is hot heats". This principle, which belongs to theory$_L$, can lead to the same result as the principle from physics that "if a difference of temperature between two systems then there is a spontaneous transfer of heat from the system at the higher temperature to the other one". However, these two statements are at odds in the case of wool or cotton. Although they seem warm to the touch, they do not heat a cold object. These words represent concepts in both cases but not the same concepts; their meaning is not given by the same theoretical standpoint, in particular, the underlying causalities are different.

Although, it is obvious that the content of physics theories and models and the content of theory$_L$ and model$_L$ can have almost nothing in common, we consider that in both cases, we have a theory level and a model level, the similarities bearing on their roles.

A first type of validation of our hypothesis on the learner's modelling of the physical world is to use these levels to interpret learners' approaches.

In this paper, we draw on our previous research results (Tiberghien, 1980, 1985, 1989a,b,c). The methods used in the two main pieces of work were different. In the first one, we obtained data with a group of eleven students at the second year of secondary school (13 years old, 5th grade), outside regular teaching. We performed interviews before and after the teaching with each student and we video-recorded one group of two students throughout the teaching. In the second one we used six classes in the framework of a regular teaching at the same grade (13 years old, 5th grade, 300 individuals) but with an experimental content on heat and temperature. Data consisted of questionnaires given before and after teaching in these classes and in six other ones with regular teaching content and with interviews (2 students in each class before and after teaching) and all the written exercises done by students.

In the following, first we present how we reconstruct the students' knowledge structure with modelling as an analytical framework that implies to specify theory$_L$, model$_L$ and experimental field$_L$, then we discuss two types of learning.

4 - Elaboration of Students' knowledge structure

Since we state that the relevant common point in "physics knowledge to be taught" and the learner approaches consists of the real world (the material situation), an initial question bears on the choice of the set of material situations from which we study learners' approaches. In the "knowledge to be taught", the situations involved in the regular teaching on heat and temperature were : heating and boiling water, freezing water and melting ice, uses of thermometers in comparison with touching, heating bars of different materials at an extremity and observed effect (melting wax for example) at the other one.

In our theoretical approach, we state that the learners have elaborated their own theory of the material world. Here our aim is to reconstruct at least a part of the theory that they use when they are confronted with these situations. But if we restrict ourselves to the types of situations involved in the teaching, we cannot reconstruct learners' theory for a main reason. We are working with rather young learners who have not learnt physics before, so their knowledge of the situations have been constructed mainly outside school education. Thus, the field of applicability of their theory has no reason to overlap that of "physics knowledge to be taught". Consequently, we have to enlarge the set of situations and we need to make conjectures about the relevant set to take data. We assume that the everyday situations of heating and insulating, using similar techniques to that used in teaching situations, are relevant to investigate learners' approaches.

4.1 Students' theoretical point of view and their structuring of the material world

The use of our modelling as an analytical framemork for defining the learner's knowledge structure requires us to identify a set of material situations (objects and events level) associated with the same kinds of interpretations or in other terms a field of experiments coonstituding the experimental field of reference of theoryL[2].

We analyse our data by categories of interpretations or predictions within two kinds of frames of reference at the theory level :

- taking into account the age of the learner (13-14 year), we use Aristotelian causalities as a frame of reference : material, efficient, formal and final (Kuhn, 1971). For university students, these forms of causalities would probably not be sufficient.
- "physics knowledge to be taught"[3] with the equilibrium principle (as an explanative principle), and the relations established between temperature and heat or the properties given to physical quantities or real objects alone or in interaction.

We are aware that these two frames of reference may appear to be at different levels : the Aristotelian causalities are content independent whereas the second reference is the teaching content itself. The reasons of this choice relate to our hypothesis. We state that most of the students at 12-13 year old (at least in France) have acquired their knowledge about the material situations used in our investigation in an everyday context. We assume that the students' explanative system is close to the commonsense one and that it can be

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[2] The situations which were used in the questionnaires and interviews put into play :
- heating sources such as camping gas, oven, cooker, radiator
- heated objects : foodstuffs (flour, salt, water, chocolate, sugar), other objects such as nails, iron powder, sand, metal (or wood, plastic,..) foil or bar, room in a house.
- insulating situations such as keeping hot or cold liquid or solid object (marble, ice, coffee, hot water), insulating a house.

In the following we eliminate the situations of heating or insulating house which concern another space dimension.

During interviews and during teaching, the real situations with material objects were involved, in questionnaires they were described by words and drawings.

The questions about these situations bear on :
- prediction : what will happen to this "object" if it is heated or put in the oven, put in the room, .. or what will the temperature be ?
- interpretation : what is going on ? why ?

In the teaching sequences, the questions are more complex : in some cases the students had to conceive experiments by themselves to answer some questions about interpretations.

[3] We mean by "knowledge to be taught" the result of the process which starts from the scientific knowledge and leads to the knowledge which has to be taught (this knowledge is written in the textbooks or in the programmes decided by different authorities according to the countries) (Chevallard, 1985)

categorised in terms of Aristotle causalities. This is a way of reconstructing at least a part of the theoryL.

Concerning the "knowledge to be taught", we need to have an explicit theoretical level. Unhappily this is not provided in the textbools or in the offical programmes. As it appears in didactics, we need to reconstruct or at least reformulate our analytical framework according to our epistemological choices : here, our reformulation is based on modelling and the theory, as an explanative system, consist of the principles involving the physical quantities of temperature and heat. Let us note that it is far away from Aristotelian causalites or more generally from linear causality.

In fact, it appears that a large majority of learners have a theoryL based on causal reasoning. Consequently, "physics knowledge to be taught" is not relevant for constructing theoryL of the majority of students. At this stage of our work, we intend to reconstruct the theoryL shared by the majority of learners. Obviously, these reconstructions will have to be refined according to different learners. In the following, "learner" will mean what is shared by an important part of students.

4.1.1 Aristotle causalities

(1) Material : This type of causality is used when students consider that cotton, wool are hot, or heat "because it is wool", i.e. to be hot or to heat is a property of the wool.

(2) Efficient : This cause is very often involved when there is a change, as when, for example, a battery lights a bulb ; the cause of the lighting up is the battery itself or a property of the battery (energy, electricity). Or, a ball hits another motionless ball which starts moving : the movement of the first ball (or the kick given to the second ball by the first one) is the cause of that of the second ball, etc.

(3) Formal and Final : These two causes are often used together and we do not try to distinguish them systematically (Kuhn 1971). For example, when students invoke the function of an object to predict or interpret (because pots made of metal have the function of a coffee pot, then metal will keep something hot).

The efficient causality may put into play a theoretical construction including a variable which does not correspond to a direct perception. Depending on the spatial arrangement and duration in time, young students may or may not invoke a mediator between the cause and the effect. When the objects or events considered as cause and those considered as effect are distant and are going on for a time, then a mediator is invoked. In theses cases there appears to be an intellectual need for a mediator which "transmits the cause". For example, in heating situations it is often named as "heat" or "hot air" or for electrical circuits, "electricity" or "current" or "energy". This causal mediator does not correspond to a direct perception and it has a specific property - that of displacement which is different from cause or effect. For example, neither battery nor lamp or brightness move but the mediator named electricity, current or energy does.

In other cases of spatial arrangements for example in the case of heating when source and heated object are in direct contact, or in the case of movement when a ball hits another fixed ball, a mediator is more rarely invoked. Similarly, when the object related to a cause intervenes only at an instant and not simultaneously with the duration of effect - for example when an object hits another object, the cause, which is the object which does the hitting, stops being involved during the movement itself. In this case a mediator is rarely invoked.

The above mentioned findings have been obtained with young students (8-14 year old) and are in agreement with studies done with students at University level, both in electricity (Johsua et al, 1986; Duit & al., 1985), and in thermodynamics (Rozier 1988).

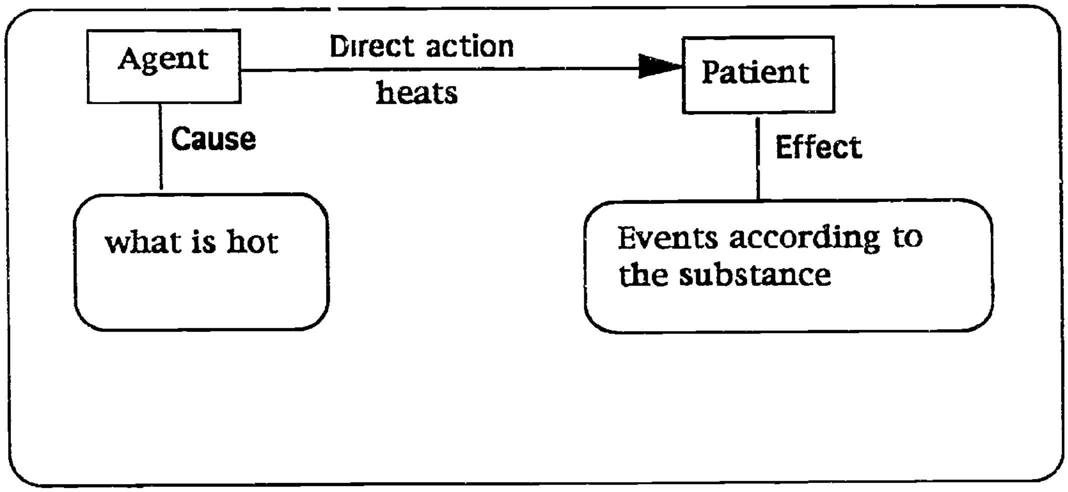
4.1.2 Learner's knowledge structures

These Aristotelian causalities lead to structure the set of material situations in three parts :
- heating situations in which the source of heating and the object to heat are in contact;
- heating situations in which the source of heating and the object to heat are at a distance;
- insulating situations.

For each part, the same type of causality occurs with the same type of cause and effect.

In the first case, heating situations in which the source of heating and the object to heat are in contact, our results show that pupils use causal reasoning between an "agent", the source of heating which has to be hot and a "patient", the object associated with the effect of heating (effective causality). The events, which happen as the effect of heating, **depend on the substance** involved; for example gold melts, wood burns, water can become hot, boil, evaporate. We show also that, after instruction, most of the pupils keep the same type of reasoning. They adapt their new knowledge of the stability of the temperature of boiling water by giving another property to the water; it has a maximum temperature when it is heated (see figure 3).

Theory$_L$ Level



Model$_L$ Level

water	salt	wood	wax	sugar	metal gold	iron,..	
x	*		x	x	x	x	becomes hot
			*	x	x		melts
x							boils
x							evaporates
							changes of color
				x			burns
			x	*			gets a maximum t°
x					x	x	(added after teaching)

* An alternative proposition is shared by some students. In the case of salt, after seeing that the salt keeps the same aspect (white) they try to touch it saying that nothing changes (including its "hotness" state)

Experimental field$_L$ Level

Heating situations in which the source of heating and the object to heat are in contact

Figure 3
Knowledge structure of heating situation with "in contact" spatial arrangement (object (cause) and events (effect) are in contact).

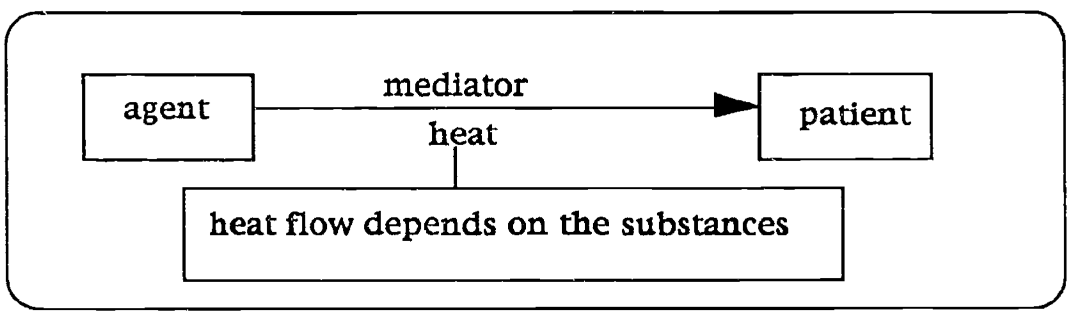
In this structure we consider that pupils have a theory which comprises the linear causality and the following "principles":

- what is hot heats (it is possible to add : what is cold cools)
- when something is heated (or cooled) the events which happen depend mainly on the substance.

The first statement supposes a reference to the states of being hot or cold, these states being implicitly defined in reference to our perception of our normal environment.
The theory is directly applied to the objects and events and then it is very close to our perception.

In the second case of heating, we still have causal reasoning between an "agent", the source of heating (or cooling) which has to be hot (or cold) and a "patient". Moreover, a mediator is invoked with the property to move from the source to the effect (figure 4)

Theory$_L$ Level



Model$_L$ Level

Heat flows in the metal (iron, gold, silver, ...) Heat does not flow in the wood, plastic After teaching the words "conductor" and " insulator" are added attached respectively to "flow" and "does not flow".

Experimental field$_L$ Level

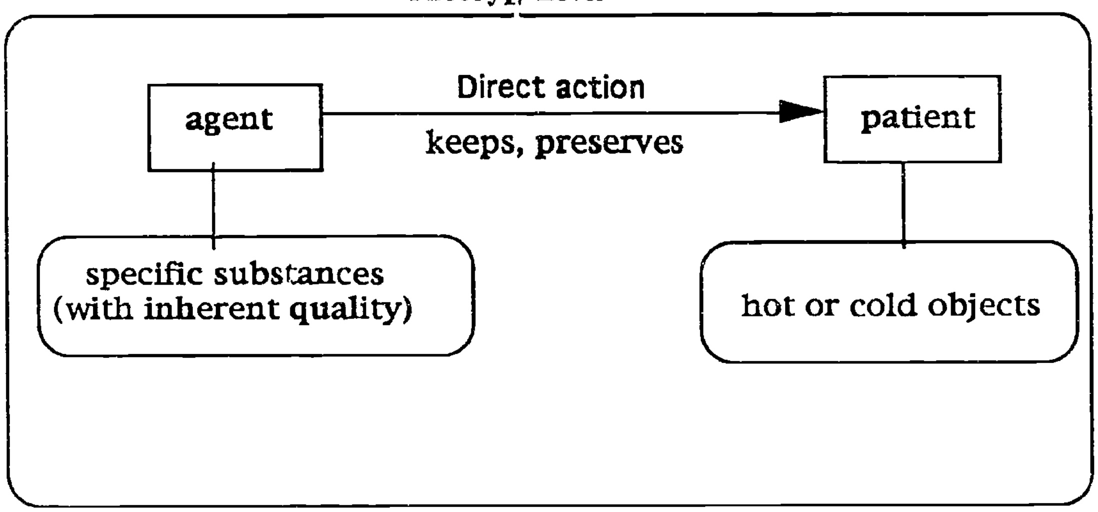
Heating situations in which the source of heating and the object to heat are at distance

Figure 4
Knowledge structure of heating situations with "at distance" spatial arrangement (object (cause) and events (effect) are at distance).

At the theoretical level we still have causal reasoning and the same principle : what is hot heats. But we have now a new concept : heat which transmits the property of heating (or cold). We consider that this concept intervenes at an intermediate level between theory and objects-events in relation to the type of substances involved. The substance is characterised by qualities[4] such as conductor and insulator of heat.

In the third case, insulation, the "agent" (the cause) is the substance that the container, which has the function to insulate, is made of. The "patient" is the hot or cold objects which have to be insulated. The action is to keep or to preserve (figure 5). An important point is that the agent is the substance of the container which in the other cases of field of ¬plicability were patient.

TheoryL Level



ModelL Level

Cotton	keeps well	hot objects
Aluminium	keeps well	cold objects

Experimental fieldL evel

Insulating situations

Figure 5

Knowledge structure of insulating situations

[4]We use the word quality to make explicit that it is inherent to the substance.

At the theoretical level we still have causal reasoning and the principle : "what is hot heats (or cold cools)" associated with another principle : "certain substances are warm by nature and others are cold by nature". The model level is still very close to the objects and events.

4.1.3 An example of analysing learners' interpretation by "knowledge structure"

A first step in the validation of these structures is to interpret the apparent inconsistency in learners' knowledge functioning shown in a lot of work on children's conceptions (Driver, Guesne & Tiberghien, 1985). For example, for three different situations presented in the same interview, the same student said :

- in the case of a metallic sheet heated in the centre by a candle flame, "*Heat is going to heat the sheet... heat goes everywhere*"
- in the case of spoons, made of different materials, put in hot water, "*the metal heats faster... The heat goes in, heats the metal faster than the wood .. Wood, it does not heat a lot because it is a bad conductor of heat*; (the interviewer suggests : if the spoons were put in ice) "*the metal spoon will get cold faster than the wood one because it is always, it is a bad conductor for heat and for cold as well.*"
- in the case of choosing a material to wrap a very cold or very hot ball,

for the cold ball, (choice: aluminium foil) "*because aluminium foil keeps the cold"; for the hot ball, (choice cotton) "it keeps the heat ... aluminium is bad conductor for the heat and cotton is bad conductor for the cold.*"

Another student, still during the final interview, when asked to design an experiment in order to choose which of two metallic sheets will be the more insulating, said : "*transmission of heat goes faster in this sheet ... but it does not prove that it is that which would allow to keep the cold or the hot for a longer time*".

In these interpretations we have in both cases an efficient causality between the property of a material and its rapidity to get cold or hot but the function of the material is drastically different in the different situations. In the first two, the metal is the patient: it becomes hot or cold; in the last two the metal is the actor, it keeps the "cold" or the "hot". The learner's representations of these situations are inconsistent with "physics knowledge to be taught" but if we refer to our learner's knowledge structure, there is no more incoherence. In these examples, for the learner the situations correspond to different field of applicability (figures 4 and 5). In the first cases the material which is conductor of heat or cold or which transmits heat is the patient (Heating situations, fig 4) and in the other cases (insulating situation), it is the agent (conductor different for heat and cold, keep cold or hot). Consequently for the learner there is no requirement that the same material has the same properties in its two different functions. In that sense we can say that learner's models ($model_L$) are "ad hoc" with respect to the particular situation. These $models_L$ are very close to the objects and events directly perceived, only the mediator (heat or cold) is invoked.

A second step is to analyse to what extent they can provide an account of the evolution of students' knowledge structures with instruction. Consequently, we need first to analyse the content of teaching.

5 - Structure of physics knowledge to be taught

The content of teaching (figure 6), even if it is very poor in comparison with that proposed by physics at the level of first two years of university, shows that the theory is not based on linear causal reasoning and includes a model with physical quantities, such as temperature, conductivity (even if this last one is only qualitative at this level). This model is not directly linked with objects and events.

Theory Level

State of matter

depends on

temperature

If
difference in temperature
between objects (systems)in contact (issued from principles of thermodynamics)

then

transfer of heat
conduction

until

equality of the temperature of objects in contact
(one aspect of the principle of thermal equilibrium

Model Level

Relations between substance and temperature of change of state

Relations between state of a substance and its temperature

Relations between substance and its conductivity

Figure 6
Structure of teaching content
(only temperature and not pressure belongs to the teaching content at this level)

6 - Evolution of students' knowledge structure with teaching

The comparison between students' knowledge structure and teaching content structure (figure 3-5 and 6) shows that the gap is very deep. The theory levels are drastically different. To illustrate this gap we present a case of learning which has been analysed in reference to Aristotle causalities. Then we discuss a type of learner's interpretation compatible with the "knowledge to be taught".

6.1 Example of learning analysed in reference to a theory level based on Aristotle causalities

As we saw, in the case of thermal equilibrium and conduction, a part of the students have different types of interpretation according to the types of situations : heating with or without an intermediary, or insulating[5]. Our study has given us the opportunity to analyse an evolution by observing two students during the 11 sessions[6] of an experimental teaching unit on heat and temperature (Tiberghien, 1980). Here we present the evolution of one of them as a study case. Before instruction, she had clearly two types of interpretations for heating and insulating[7]. Her knowledge structures fit with those we proposed in figures 3-4 and 5. For example during the interview before teaching, she chose a metal container to keep ice frozen for a long time with the argument : "*metal cools things, metal is cold*". During the first teaching sessions she performed experiments **several times** of which the results were inconsistent with her predictions made just before the experiment. For example, during the third session she took two ice cubes, wrapped one in aluminium foil and the other in a piece of wool. In spite of several experiments giving contradictory results, she predicted : "*That one (ice in wool) will melt more quickly than that one (ice in aluminium); because that (the wool) gives heat*". During the seventh unit, she studied the difference in perception when we touch two different materials such as cotton and copper. Previously, she studied the equality of temperature of objects in contact and remembered it. To try to solve the problem of difference in perception, she proposed to perform two experiments :

- to wrap an ice cube in a copper foil and another one in cotton;
- to heat these two same materials at one end and to touch them at the other end.

Before these experiments, she stated that cotton and copper are at the same temperature, but she predicted again, in spite of several similar experiments performed in the previous sessions, that ice will stay for a longer time in cotton than in copper : "*I think it (the copper) will keep it (the ice) frozen most easily, because it (the cotton) is hotter and keeps the heat better*".

When she observed the results of the two experiments, she said :

"*the cold of the ice goes in the material (the copper) and goes away, and there (the cotton) it keeps it. This one (cotton) keeps the heat more than that one (copper). Here (with copper) it goes away, the heat or the cold.*"

To interpret this explanation, it is necessary to distinguish the objectives of :

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[5] In this case of apparent inconsistency, obviously, we do not pretend that all the students have the same type of interpretations. We take it because it is shared by a part of the students and it is a typical case of apparent inconsistency.

[6] They were videotaped and transcribed

[7] In this teaching unit, we consider only one physical quantity : conductivity and not "specific heat". So only very rough predictions are allowed.

- insulation : the insulated object should stay for as long as possible in the same state of coldness or hotness, and

- the underlying mechanism allowing the interpretation.

The new interpretation involves **the displacement of cold (or heat) as a supplementary step** to interpreting how the state of cold (or hotness) is kept. The causal reasoning is more complex and there is a change in the **object roles :**

- the cold (or the heat), involved in the action, comes from the "insulated object" (ice) and which therefore has an active role. Then, this object has a double status : related to the cause since it gives heat or cold and related to the effect since its state is the objective of the insulation.

- the container (or its substance) still has an active role but a **different** one. This role is related to a new intermediary mechanism : the possibility of displacement of heat or cold. It is no longer related to the direct action of keeping the coldness or hotness or even of heating or cooling (figure 7).

These changes of role, with the introduction of a mechanism in the case of insulating similar to that which occurs in the case of heating, allow the student to give the same interpretation for the two types of situations. We hypothesise that this student has moved to another learning step. A new relationship is used in the case of insulating; the object which was associated to the cause, intervenes in the action and it is no more a direct action of "keeping", an intermediary mechanism is involved. The change is located in the selection of objects, their roles and in the way in which they are related. The student is still at the theoretical level "action $\rightarrow$ change". However, the student applied another rule : "heat flow depends on the substance" to new situations for which she used a model based on inherent qualities of matter. It does not imply, obviously, that she will never use the previous type of explanation (Tiberghien, 1980).

Situation	CAUSE	ACTION	EFFECT
Before seventh session			
Heating or cooling of specific objects	Source of heating or Source of cooling	heats or gives heat or cools or gives cold and heat (cold) moves more or less according to the substance of the intermediary object	heated object becomes hot or cooled object becomes cold
Insulation of objects	**Container or its substance**	keeps or prevents heat cold to go away	object to be insulated stays hot cold
After seventh session			
heating, cooling **AND** insulating	Source of heating Source of cooling or heat cold of the object to be insulated	gives heat gives cold and heat (cold) moves more or less according to the **substance** of the intermediary object (which is **container** in the insulating case)	object (to be heated or cooled) becomes hot or cold or object to be insulated stays hot or cold

Figure 7

Change in roles of objects in causal relations

This example illustrates learning which consists of giving the same interpretation for two kinds of situations previously interpreted differently (heating with intermediary and insulating situations). This learning could not have been recognised if we had taken "knowledge to be taught" as frame of reference. However it is a very important learning situation. It can be noted that many teaching situations could develop this type of learning.

Even if this learning is without radical change in theory, *it needs a new organisation of knowledge as far as there are new semantic relations between the model and the experimental field (events).* We consider that this learning is a type of conceptual change that we call "semantic conceptual change" because the causal relation is still the same but its meaning is different (Tiberghien submitted).

6.2 Learner's interpretation analysed in reference to "physics knowledge to be taught"

At this level of teaching, some students acquired the notions of two differentiated physical quantities namely heat and temperature instead of one. For example for the insulation of a ball, a student said: " (same choice for the hot and cold balls : a wool blanket) *because it is a good insulator*". The interviewer asked about the hot ball : will it get colder after a certain period of time ? and the student answered : "*yes, ... because in the end, eventually it will take the temperature of the ambient air ... it (the heat of the ambient air) will pierce the blanket a little*". This answer illustrates the capacity to go from the level of objects and events (to which the question corresponds) to the level of a model dealing with physical quantities such as heat and temperature. This capacity of dealing with these two levels allows us to assume that a meaning of heat and temperature level has been constructed. Two notions are used: "to take the temperature" and "heat which goes through or pierces". As a matter of fact it is really two notions to the extent that they have different properties. A majority of students at this level of interpretation (very few compared to the total number of students) use very often, the verb "to take" associated with temperature, whereas heat is attached with movement verbs. This is a new step of learning which needs *a restructuring at the theory$_L$ level.* The type of explanation is deeply modified in comparison with the previous case since it implies the thermal equilibrium principle and not causal action of an object. This analysis allows us to interpret our results which tend **to show that this principle is a necessary step in the learning of conduction since it belongs to the explanative system**; as a matter of fact, it provides meaning.

In this case, the acquisition of the theory$_L$ is coherent with physics. This acquisition is likely at a meta-knowledge level and should be studied for itself. We call it "theoretical conceptual change".

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